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Complex power distribution analysis in plates covered with passive constrained layer damping patches

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ABSTRACT

The vibration of a plate partially covered with a passive constrained layer damping (PCLD) patch is studied from an energetic point of view. The damped plate is excited by an acoustic plane wave. The study is done with a numerical two-dimensional multilayer plate model. Results of the present model are compared to those obtained with three-dimensional finite element models. It is shown that the present model gives accurate results, even for the layer's inner behavior. It is less expansive in terms of computational cost; hence, it can simulate efficiently the structure for higher frequencies. Mathematical formulas for complex mechanical power are presented, and the link with strain and kinetic energies and dissipated power is detailed. Both local and global complex power balance are established, and corresponding expressions for the discretized problem are formulated. Conservative and dissipative powers are studied for the PCLD damped plate. After a global balance analysis versus frequency, a local study has been carried out in order to quantify the relative contribution of the components of strain and stress tensors to the total strain energy and dissipated power; the individual layer's contributions is also investigated. The in-plane distributions of powers are mapped, showing the location where dissipative phenomenon occurs and where strain energy is stored. Finally, three criteria based on the previous power quantities are proposed in order to quantify the mechanical damping efficiency of the patch.

1. Introduction

Passive constrained layer damping (PCLD) patches have been widely used since they were first introduced in 1939 by a British patent [1] for damping vibration in the automotive industry. Nowadays they remain an easy, cheap, and efficient way to reduce vibration and noise in a structure. For years, it has been used almost exclusively in the aeronautic industry; however, Rao [2] recently presented many new fields of applications of these treatments. Since the 1950s, many papers have presented studies of vibration damping of plates and beams by means of constrained layer damping devices. Most of these papers deal with plates fully covered with a PCLD treatment, which can be considered as sandwich plates. However, in the case of partial treatment of the plate, definite optimization of the patches layout is not established yet. Amongst the existing optimization algorithms, Zheng [3] presents a comparative study of four of them: a sub-problem approximation

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method, a first-order optimization method, a sequential quadratic programming algorithm, and a genetic algorithm. The disadvantage of those iterative optimization algorithms is their high computation cost; therefore, most of them are limited to two-dimensional beam treatments. Other algorithms, such as gradient based methods developed by Lee [4] or Alvelid [5] and cellular automata developed by Chia [6,7], were applied; yet, no algorithm led to a definite general design rule regarding the layout of the damping patches.

Numerical simulation of structural vibrations is classically carried out by means of displacement approaches. The Finite Element Method (FEM) has been extensively used for these studies. Indeed, this method is particularly efficient to study the vibrational behavior of rods, beams, plates, shells, solids and any assembly of such elements, giving the possibility to study complex structures like automotive, aircraft, train or ship bodies, engines, buildings, wind turbines, etc. Nevertheless, the mesh of the structure must be sufficiently refined to let the shape functions of elements match the displacement field. When the wavelength is small compared to the dimensions of the studied structures, the use of a lot of elements and degrees of freedom is necessary. Then the computation cost can be very high, sometimes so much that the study is not feasible any more.

As an alternative to displacement-based approaches, methods based on energy or power were proposed. Statistical energy analysis (SEA) [8] is a method suitable to predict space- and frequency-averaged behavior of structures when the modal density is high, which generally corresponds to small wavelength/dimensions ratios. The SEA method is different from the FEM for at least two reasons: the SEA method solves a – relatively small – set of scalar energy balance equations, and is based upon statistical assumptions concerning distribution of energy versus modes and/or substructures; the FEM solves a – relatively big – system of linear equations corresponding to the discretization of partial differential equations (PDE) in a continuous media (the structure's domain) and is of deterministic nature. Another class of methods, the power flow analysis (PFA) [9], in which unknowns are powers, solves a heat conduction type PDE in the structure's domain. Hence, this approach can be formulated with the help of classical PDE solving tools, like the FEM. The PFA method has been applied to rods, beams [10,11], and to one-layer plates [12]. However, the required power diffusion equations seem to be difficult to formulate for heterogeneous structures. Nevertheless, these methods emphasize the relevance of the power flow concept for the study of damped structures.

Energies, powers, and energy flow can also be computed from a classical displacement study and can improve the comprehension of the damping of complex structures as shown by Pavic [13,14]. The aim of this paper is to present PCLD treatments from an energetic point of view, which could be a help for the design of the optimal layout of the patches. In this study, a PCLD damped plate is studied with the help of a model [15] based upon a zig–zag type plate theory [16] and the Rayleigh–Ritz method. Formulas that link the complex mechanical power to the time-averaged strain energy and to the time-averaged dissipated power are presented. The setting of a local and a global power balance is detailed. Formulas for computing all these quantities from matrices and vectors of the discretized problem are presented. These formulas are used to investigate the mechanism of damping. Agreement of the results, given by the studied model, is shown by comparison with two other FEM simulations: a classical three-dimensional study carried out with the Cast3m FEM software and a study realized with the shell elements of the code ACTRAN. Dissipative and conservative parts of the mechanical power are examined in several ways: global balance, global bending/shear repartition in each layer, and two-dimensional spatial repartition. Based upon the global power balance, generalized damping factors are proposed.

2. Present plate model

2.1. Considerations on plate models

A plate damped with PCLD patches is formally a multilayered plate with spatial inhomogeneities. Both static and dynamic behaviors of such structures have been studied in early works [17,18], and, because of their complexity, they have been and still are extensively studied, causing the developments of many models [19,20]. The goal of all these models is to reduce the plate to a two-dimensional structure by eliminating the thickness dimension; this implies the consideration of bending (and possibly shear) generalized displacements and forces. The classical laminate theory (CLT) is efficient for thin plates, and the (first-order) shear deformation theory (SDT) is appropriate for plates of moderate thickness. For the SDT, shear correction factors have been proposed by various authors [21–24] in order to take into account the transverse shear stresses variations, which strongly depends on the adjacent layer modulus and the laminate stacking sequence. These works gave different results, which point out the difficulty of the task, especially when dealing with the dynamic behavior. Higher order shear deformation theories [25–27] and also alternative approaches like the so-called zig–zag theories [19,28] have been formulated. All these models are perfectly compatible with the finite element method (FEM) or with Rayleigh-Ritz approaches. Commercial finite element (FE) codes classically propose CLT and SDT based elements. However, plates with PCLD patches exhibit a very high elastic modulus ratio between the elastic layers and the viscoelastic one, which is not compatible with these classical plate models. For this study, the SDT (with or without shear correction factors) has been tested and compared to other approaches including the present model, and a poor agreement was found (results are not presented in this paper). On the contrary, the present model is based upon a zig–zag type model [16], and it is shown in this document that it is very accurate for the PCLD problem.

2.2. Specificities of the present model

The present model, as described by Loredo [15], allows one to simulate the behavior of a rectangular multilayered plate with one or several multilayered patches. It is based on an out-of-plane assumed displacement field obtained by means of