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An effective coating material solution and modeling technique for damping oriented design of thin walled mechanical components

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ABSTRACT

A multi-layer coating beam model is proposed to find, at the modelling stage, optimal coating architectures to be applied to mechanical components, in order to maximize the vibration damping in industrial operating conditions. Recent experimental works showed that application of coatings may influence vibration damping, and that dissipative actions can be mainly localized at the interlaminar interface. The aim of this paper is to present a mechanical model for numerically simulating the response of a uniform, multi-layered composite beam specimen taking into account of these interlaminar dissipative actions, so that reducing the need to experimentally evaluate the effectiveness of many candidate coating solutions. The model is based on a modified third order zig zag beam theory, where the contribution of the frictional actions is modelled by means of complex, elasto-hysteretic distributed actions localized at the layer interfaces. The resulting multi layered beam model degrees of freedom do not depend on the number of the coating layers and the proposed technique showed to be computationally effective to simulate the damping behaviour of different virtual specimens. A frequency and application dependent damping estimator is proposed and some application examples are presented and critically discussed.

1. Introduction

The development of composite components combining high damping with high stiffness and resistance properties can be of great interest for applications in the aerospace, automotive and machine tool industry among all. A known method to improve the damping behaviour of mechanical components is the use of coating technology [1–7]. Coatings can be applied on components to improve their dissipative properties while at the same time preserving as much as possible the other useful mechanical properties such as stiffness and resistance. Many different coating production techniques such as chemical deposition, anodizing, plasma spray, plasma vapour deposition, and many others are known, and the vibration damping behaviour of a coated component is expected to be influenced by different factors such as the coating materials, the multi-layered geometry and architecture, the interface between coating layers and between the coating and the component substrate surface finish [8–13]. The choice of the coating manufacturing technique may be greatly influenced by the substrate material, as an example plasma related production technology requires the use of materials that can sustain the relatively high temperatures of the production process. The thermal plasma spray production is a relatively fast production process working at high temperature [14] but care must be paid to the effects of the impact of the high temperature coating particles on the target substrate surface, so that application to polymeric materials is generally not possible. Technologies like plasma vapour deposition (PVD) or reactive plasma vapour deposition (RPVD) can work at a lower temperature and can be employed to deposit metallic, ceramic and polymeric coating layers [3–4,7]. PVD based technologies make it possible to finely control the coating layer thickness and composition, but are time consuming processes so that the final obtainable coating thickness is usually low. Other production techniques such as hot melt can be easily employed to apply polymeric material coatings, they are relatively fast but require a curing process, and allow the production of high thickness coatings.

The increase of the vibration damping response of mechanical components can be obtained by means of the application of a surface coating layer having high distributed internal hysteresis [8,13,15] or by properly designing a multi-layer coating architecture [4,7] that maximize the frictional actions at the interface between the layers under operating conditions [16]. The use of coating materials with high internal hysteresis such as polymers or polymeric-based materials, requires a high coating thickness to maximize the damping effects, so that altering the composite component geometry. Moreover, such coating materials generally exhibit temperature dependent, poor mechanical

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properties such as stiffness and resistance, negatively influencing the composite component mechanical properties. Multi-layered coating architectures may be more effective than the a single-layer coating having the same thickness with respect to the damping maximization target since constrained layer damping (CLD) [4,7,17] effects maximize the work of dissipative actions at the interface between layers in flexural vibrating conditions. The vibration damping behaviour of a multi-layered coating composite component depends on the materials, the overall coating thickness, the number and relative thickness of the layers, the substrate surface texture, the interface coupling actions between the coating layers and between the coating and the substrate [13,18–19]. The deposition of multi-layer coatings requires more prototyping and production steps with respect to a single-layer, so that a time and cost more expensive product development process is expected.

To investigate the damping behaviour of known and innovative coating solutions, physical prototypes must be produced and experimentally tested to verify the effectiveness of the solutions. The use of dynamical measurements, in both free and forced vibrations, is known in literature as an effective experimental tool to investigate the dissipative properties of coated standard specimens, within a wide range of component shape and coating materials [16,18,20–22]. The damping behaviour of coated components can be compared with the damping behaviour of uncoated ones to directly asses the effectiveness of the investigated coating solution.

In this work known new experimental results concerning some known and innovative coating solutions, produced by means of the multilayer, Cyanoacrylate-based glue technology, are tested, in order to validate the basic assumptions presented in this paper and also to prove that engineering solutions to be applied in real industrial applications can be found, being also more effective than previous solutions reported by these same authors in past research [16,18,19]. Geopolymer-based [23] coating applications were initially considered but later discarded because of the low structural adhesion properties exhibited with some commonly used metal substrates. Since only damping oriented applications are considered in this work, technological aspects such as inter-layer coating adhesion, residual stress analysis, coating structural characterization are not taken into account in this paper. The main task of this work is to help designing coating solutions to be applied to the contact-free, external surface of thin walled mechanical components such as a mechanical pump or motor casing. Composite beam specimen solutions are made by applying a multilayer coating to the substrate, obtained by alternating thin metal layers and adhesive Cyanoacrylate-based polymer thin layers. The layer mechanical properties such as stiffness, interlaminar adhesion and viscosity can be tailored by properly choosing the metal layer elastic modulus and thickness and the Cyanoacrylate composition.

When experimentally investigating the effect on damping of different coating solutions it is necessary to produce a high number of testing specimens and to realize a high number of test measurements. Since the production and experimental validation of a high number of different coating solutions may be time and cost consuming, a numerical model being able to make virtual prototyping and measuring on standard specimen configurations could significantly reduce the product development time and cost. An effective model for coated, multi-layered beams must be able to take into account of the many different factors such as the coating materials, the multi-layered geometry and architecture, the interface between coating layers and between the coating and the component substrate surface finish.

Research work on mechanical modeling of multi-layer beam and plate components is well known in literature [24–30]. Equivalent single layer and layer wise theories are known [31,32]. In the first case the parameters of an equivalent single layer beam are evaluated by means of averaging assumptions. In layer wise theories kinematic assumptions and constitutive relationships are defined for each layer, taking into account of the anisotropy due to the different layers. Equivalent single layer beam theories are easier to compute but less accurate than layer wise theories. Nevertheless, a disadvantage of some layer-wise beam theories is that the required model number of kinematic variables and the computational load increase with the number of layers [33]. Some layer wise theories, i.e. the zig-zag beam and plate theories, can give a good compromise between the computational efficiency of equivalent single layer theories and the accuracy of the more complete layer wise theories.

Zig-zag theories make it possible to deal with a low number of state variables, not depending on the number of layers [25,34–35], while still taking into account of the anisotropy of the different layers. In both the equivalent single-layer and the layer-wise approaches, the damping behaviour is generally neglected or globally modeled by averaging the system modal viscous damping [36–39]. Contributions on locally modeling the system internal dissipative actions, located at the interface between the layers, are not known to these authors knowledge.

In this work an extended multi-layer beam model based on zig zag multi-layer beam theories, taking into account of local hysteretic friction, is presented. The dissipative actions are modeled by relaxing the kinematical displacement continuity at the layer interface and by introducing a complex elasto-hysteretic dynamical interface coupling at the interface between the layers. The effects on the damped response of distributed viscous ground-constraints are also taken into account. Some examples are reported and numerically investigated, and the formulation of some damping estimators is proposed. The results are reported, and a critical discussion follows.

2. Experimental results

In this section, measurement estimates of the frequency dependent damping behaviour related to some multi-layer thin-walled beam specimens prepared with known [16,18–19] and innovative coating technologies are presented and discussed.

All of the tested specimens are made from beams, length $L = 10^{-2}$ m, uniform rectangular cross section, width $b = 3{\cdot}10^{-3}$ m and

Table 1
Specimen data.

Solution	Substrate material	Substrate surface	Coating layers	N° of layers	Coating total thickness [μm]	Coating production technology
1	Al1000	Untreated Ra0.8	Cr + CrN multi-layer	4	4	RPVD
2	Al1000	Untreated Ra0.8	Cr + CrN multi-layer	20	4	RPVD
3	Al1000	Sandblasted Ra12	Al + Cyanoacrylate	4	140	Gluing and curing
4	Al1000	Untreated Ra0.8	Al + Cyanoacrylate	4	140	Gluing and curing
5	Al1000	Untreated Ra0.8	Al + Cyanoacrylate Gel	4	140	Gluing and curing
6	Al1000	Untreated Ra0.8	Al + Cyanoacrylate Gel	8	280	Gluing and curing
7	Steel C67	Untreated Ra0.8	Cr + CrN multi-layer	4	4	RPVD
8	Steel C67	Untreated Ra0.8	Cr + CrN multi-layer	20	4	RPVD
9	Steel C67	Sandblasted Ra12	Al + Cyanoacrylate	4	140	Gluing and curing
10	Steel C67	Untreated Ra0.8	Al + Cyanoacrylate	4	140	Gluing and curing
11	Steel C67	Untreated Ra0.8	Al + Cyanoacrylate Gel	4	140	Gluing and curing
12	Steel C67	Untreated Ra0.8	Al + Cyanoacrylate Gel	8	280	Gluing and curing