EXPERIMENTAL EVALUATION OF THE DAMPING PROPERTIES AND OPTIMAL MODELLING OF COATINGS MADE BY PLASMA DEPOSITION TECHNIQUES

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ABSTRACT

Coating layers, applied by means of different deposition technologies, can be used to produce composites with high damping properties. This is well known in literature and it is also verified by some experimental results reported in this work. The constitutive equivalent material model of coated specimens is identified and optimized by means of a generalized Kelvin model of n-th order, defined by means of the ratio of polynomials in the frequency domain. Dynamical measurements data obtained from coated single-layered and multi-layered samples obtained with different deposition techniques, are used to identify the optimal material model order and parameters. A robust identification technique that makes use of Forsythe orthogonal polynomials is employed for the numerical identification of the model parameters and a specific technique is introduced to eliminate the model non-physical components generated by measurement and model noise.

Keywords: damping, model identification, dynamical measurement, optimal model fitting.

INTRODUCTION

There is a great demand in industrial, aerospace and automotive mechanical applications for non-conventional composite materials suitable to design components showing high stiffness, high resistance and high damping behaviour. Coating layer technology can be employed to increase the global dissipative properties of an industrial component with limited influence on the other mechanical properties (Tassini, 2006; Yu, 2005; Ustinov, 2001). One or more coating layers can be deposited or grown in order to obtain a finished composite component with specifically designed characteristics. Different techniques are known (Rongong, 2004; Blackwell, 2007), for example plasma vapor deposition, plasma spray or the anodization process. When designing or analyzing the properties of a single or multi-layer coating, e.g. damping efficiency, corrosion resistance, or thermal insulation, many factors must be taken into account: layer composition, layer or multi-layer structure, deposition or growing technology and adhesion to the substrate.

The dissipative properties of a component can be significantly tailored by means of the adoption of layers showing high internal hysteresis or by maximizing the frictional actions at the interface between the different layers (Casadei, 2014; Wang, 2013; Kireitseu, 2007). A considerable number of applications was dedicated to study the influence of the coating characteristics, such as the coating material structure (Casadei, 2014; Guangyu 2014; Ustinov 2008) or the interface structure (Colorado, 2006) on the coated component damping behaviour and its temperature dependence (Khor, 2001).
Dynamic mechanical measurements can be used as an effective experimental technique for estimating the coated component damping properties. Forced and free vibration experimental methods were successfully employed to estimate the component dissipative properties by means of comparing the coated and uncoated component dynamical response (Reed, 2008; Pastias, 2004; Torvikt, 2009).

Single or multi-layered coated materials dynamic behavior can be considerably complex and classical material models (Zener, 1948; Nowick, 1972) may not accurately describe the coated component constitutive relationship (Amadori, 2016). Different higher order constitutive models can be adopted (Finley, 1989; Ramirez, 2007; Vasquez, 2010). Such models may require the use of not trivial constitutive equations and as a consequence a robust identification procedure must be considered for solving the generally ill-conditioned problem of parameter identification (Richardson, 1982; Amadori, 2016).

In this work, components made by single-layer and multi-layer coatings applied on a metal substrate by means of two different techniques, i.e. by an anodizing process and by a reactive plasma vapor deposition (RPVD) process, are considered. Coated and uncoated specimen dynamic mechanical measurement test results are compared and processed by means of a robust parameter identification and model condensation technique.

**IDENTIFICATION PROCEDURE**

The procedure used to identify the composite constitutive relationship, defined by the authors of this work in a previous paper (Amadori, 2016), is briefly outlined here. A generalized Kelvin model (also cited in literature as the standard linear solid model) is chosen to model the composite material constitutive equation. Since low order material models such as the Zener and Kelvin-Voight models can show limitations in predicting the dynamic behaviour of complex materials, high order models are taken into account in this work. A generalized Kelvin model of order \( n \), obtained by connecting \( n \) single Kelvin model units in series is shown in Fig.1, and starting from the relationship between the Fourier transform \( \hat{\sigma} \) of \( \sigma \) stress and \( \hat{\varepsilon} \) strain of the single Kelvin unit in the frequency domain:

\[
\hat{\sigma} = (E_i + j \omega \cdot \beta_i) \cdot \hat{\varepsilon}, \quad i = 1, \ldots, n.
\]  

The constitutive relationship for the generalize Kelvin model is:

\[
\hat{\sigma} = E(\omega) \cdot \hat{\varepsilon} = \hat{E} \cdot C(\omega) \cdot \hat{\varepsilon}
\]  

where:
The constant $E$ is the modulus of the material when the frequency value is zero and it can be obtained from static experiments or extrapolated from dynamical measurements estimates as the frequency goes to zero. $C(\omega)$ is a rational function with a $n$-degree numerator polynomial and a $n-1$ degree denominator polynomial. The estimate value of $C(\omega)$ in a wide frequency range can be obtained from dynamic mechanical measurements in a forced flexural excitation experimental set-up.

The contribution of the inertial actions is also taken into account and for a slender beam in a flexural experimental set-up with clamped-sliding boundary condition (Fig.2) and with a periodic force $q(t) = Q \cdot \exp(j \omega t)$ applied at the sliding end, the relationship in the frequency domain between the transverse displacement $\hat{\nu}(\omega)$ and applied force $\hat{q}(\omega)$ at the beam sliding end is approximated by:

$$\hat{\nu}(\omega) \approx \sum_{i=1}^{n_s} \frac{2(1 - \cosh k_s \cdot \cos k_s)}{\sinh k_s + \sin k_s} \cdot \left( \frac{2(1 - \cosh k_s \cdot \cos k_s)}{\sinh k_s + \sin k_s} \right)^2 \cdot \hat{q}(\omega)$$

$$M$$ is the beam mass, $I$ is the beam section moment, $L$ is the beam length, $k_s$ satisfy the following equation:

$$\sinh k \cos k + \cosh k \sin k = 0$$

Using Eq.4 and the corresponding displacement and applied force data, the material constitutive relationship $C_i = C(\omega_i)$ at $\omega_i$ excitation frequency can be estimated by finding the solution of the non-linear equation Eq.6:

$$\Theta(C_i) = \sum_{i=1}^{n_s} \frac{2(1 - \cosh k_s \cdot \cos k_s)}{\sinh k_s + \sin k_s} \cdot \left( \frac{2(1 - \cosh k_s \cdot \cos k_s)}{\sinh k_s + \sin k_s} \right)^2 \cdot \hat{\nu}(\omega) - \hat{q}(\omega) = 0$$
The solution is found by means of the Newton-Raphson method, the procedure showed to be stable and only a few iterations are generally needed for convergence.

The $C_i$ experimentally estimated values are used to identify the parameters of the constitutive relationship by means of an approach based on the least square error technique. The rational function $C(\omega)$ is defined in Eq.7 by means of the ratio of two polynomials expressed in a basis of orthogonal polynomials $\eta_s(j\omega)$ and $\mu_r(j\omega)$:

$$C_i = C(\omega_i) = \frac{1 + \sum_{s=1}^{n_s} \gamma_s \cdot \eta_s(j\omega_i)}{1 + \sum_{r=1}^{n_r} \delta_r \cdot \mu_r(j\omega_i)}$$  \hspace{1cm} (7)

Starting from Eq.6 and applying the least square error method the unknown $\gamma_s$ and $\delta_r$ coefficients can be obtained as the solution of two uncoupled systems of linear equations (Amadori, 2016). With the adoption of an orthogonal polynomial base, and in the specific case of a Forsythe polynomial base (Forsythe, 1957), high accuracy for the identification of both low and high order model can be obtained. The polynomial base coefficients $\gamma_s$ and $\delta_r$ can be unsuitable for further processing. It is more convenient to convert them to an equivalent monomial base, this can be done by means of known algorithms (Kelly, 1967).

This procedure has proved to be robust and the material constitutive relationship $C(\omega)$ can be obtained as the ratio of two polynomials defined by coefficients in a monomial base, as in Eq.3.

### MODEL CONDENSATION

Experimental measurements are affected by noise and the basic least-square error technique is not able to distinguish between system poles and virtual, non-physical poles resulting from such noise. High order model fitting estimates then generally result. This model can be further condensed, by finding an optimized model order and by eliminating the non-physical model components. The rational function $C(\omega_i)$ is manipulated in order to outline the system poles and residues.

By inverting $C(\omega_i)$ and defining it in standard partial fraction form:

$$\frac{1}{C(\omega_i)} = \sum_{s=1}^{n_s} \frac{R_s}{(j\omega - \psi_s)}$$  \hspace{1cm} (8)

where residues $R_s$ are computed from the $\zeta_s$ zeros and $\psi_s$ poles of $1/C(\omega)$. Since from Eq.2,8:

$$\hat{E}(\omega) = \frac{1}{E} \sum_{s=1}^{n_s} \frac{R_s}{(j\omega - \psi_s)} \cdot \hat{\sigma}$$  \hspace{1cm} (9)

computational and physical $\psi_s$, pole and $R_s$ residues subsets can be found by observing that poles and residues are expected to appear as complex conjugated pairs or real values. Poles with positive real part can be considered as computational poles and can be discarded. Couples of physical poles and residues are also assumed to present stability if the model order is increased. Unstable poles with respect to model order $n$ can be considered not physical and discarded. The model, condensed to a subset of $nr$ physical pole-residues $\bar{R}_s$ and $\bar{\psi}_s$, is expressed in the form:

$$\frac{1}{C(\omega)} = \sum_{s=1}^{nr} \frac{\bar{R}_s}{(j\omega - \bar{\psi}_s)} + \Lambda_m(\omega) ; \quad \Lambda_m(\omega) = \sum_{r=0}^{m} \lambda_r \cdot (j\omega)^r$$  \hspace{1cm} (8)
EXPERIMENTAL SET-UP AND TESTS

Specimens in the form of slender beams of rectangular cross section are tested with a dynamic mechanical analyzer (Fig.3) in a forced flexural excitation experimental set-up with clamped-sliding boundary conditions.

![Experimental apparatus. Dynamic mechanical analyzer (a) and specimen mounted in the flexural excitation experimental set-up (b).](image)

$A_{m}(\omega)$ is a $m$ order ($m=1,2$ generally works well) polynomial function used to estimate the contribution of the $nc=n-nr$ eliminated computational poles-residue pairs. The calculation procedure to obtain coefficients $\lambda_r$ can be found in the authors previous work (Amadori, 2016).

Two different coating solutions are considered in this work. In both cases coating layers are applied on a Al alloy (Al 1000) beam, length $10^2$ m, width $3\times10^3$ m, thickness $5\times10^{-4}$ m and density $2700$ kg/m$^3$. One set of specimens is obtained by means of the reactive plasma vapor deposition (RPVD) technique. A dual-layered coating is applied on two opposite faces of the beam. First a Ti metallic bond coat is deposited and then coated with an external hard coating layer formed by TiO$_2$ (Fig.4a).

![Schematic representation of the dual-layered structure of Ti+TiO$_2$ coating (a) and of the single layer Al oxide coating (b).](image)

Both the metallic bond coat and the hard coating layer thickness is 1µm. Other coated specimens are obtained by means of an anodizing process, the Al 1000 beam is coated on the two opposite faces of the beam by a single, 4µm thick, Al oxide layer (Fig.4b). Dynamic
mechanical test on the coated specimen sets and homogeneous Al beams are made at 0.01% maximum strain over a [0.01-200] Hz frequency range and 35°C constant temperature.

RESULTS AND DISCUSSION

The ratio of the imaginary and real part of $E(\omega)$ (Eq.2) is considered as a measure of the material dissipative properties (Nowick, 1972), and the results obtained for the uncoated and the coated specimens are compared. Fig.5 shows the estimated $\text{Im}(E(\omega))/\text{Re}(E(\omega))$ ratio of the dual-layered (Fig.4a) and of a homogeneous Al 1000 specimen, and the relative increase of the same ratio.

![Graph showing the ratio Im(E(\omega))/Re(E(\omega)) for dual-layered and homogeneous Al 1000 specimen, and their relative difference.](image)

Fig. 5 - Estimates of the ratio $\text{Im}(E(\omega))/\text{Re}(E(\omega))$ for dual-layer (Ti+TiO$_2$) coated specimen (red) and homogeneous Al 1000 specimen (green), and their $\text{Im}(E(\omega))/\text{Re}(E(\omega))$ relative difference % (blue).

Fig.6 shows the same results obtained for the single-layered (Fig.4b) specimen. It is shown that the coated specimen $\text{Im}(E(\omega))/\text{Re}(E(\omega))$ ratio increases with respect to the uncoated case. The dual-layer coated specimen only exhibits a meaningful effect at frequencies above 70 Hz, while a significant increase at all measured frequencies can be observed for the single-layer coated specimen. Since for both coating technologies a very small coating layer thickness, compared to the beam substrate thickness, is adopted, it can be assumed that this results are mainly due to the interface frictional actions acting during the imposed flexural test cycle.

The identification and the model condensation procedure are used to process experimental measurements data, and the results are shown in Fig.7 for the dual-layer specimen and in Fig.8 for a single-layer specimen. Condensed model fitting estimates of order $n=11$ are shown for both specimen solutions and compared with the estimated measurement values. In both cases a $n=43$ model order was taken into account as the starting point of the condensation procedure and a $n=11$ condensed model is obtained by eliminating all of the poles with positive real part and the ones not exhibiting stability with respect to the model order increase. Stability diagrams used to evaluate poles stability are shown in Fig.9.
Fig. 6 - Estimates of the ratio $\text{Im}(E(\omega))/\text{Re}(E(\omega))$ for single-layer (Al oxide) coated specimen (red) and homogeneous Al 1000 specimen (green), and their $\text{Im}(E(\omega))/\text{Re}(E(\omega))$ relative difference % (blue).

Fig. 7 - Dual-layer (Ti+TiO$_2$) coated specimen $E(\omega)$ estimates (green) and $n=11$ condensed model fitting estimate (red).
Fig. 8 - Single-layer (Al oxide) coated specimen $E(\omega)$ estimates (green) and $n=11$ condensed model fitting estimate (red).

Fig. 9 - Stability diagrams with selected poles (blue and red) of $n=11$ condensed models of the dual-layered (Ti+TiO$_2$) (a) and single-layered (Al oxide) (b) specimens.
To assess the effectiveness of the model condensation step, Figs.10-11 report the computational model fitting estimate results of the same order ($n=11$). It can be observed that in both the dual-layer and the single-layer solutions the condensed model is a significantly more accurate approximation of the experimental estimates and that the un-condensed model fail to accurately model the experimental estimates.

These results show that both coating solutions may affect the specimen dissipative properties. The integrity of the specimen layer interface showed to be nevertheless affected by cyclic loading, and preliminary results showed that damages and cracks may appear at the interface between the different layers, making the solution partially non-effective. Different coating process parameters and technologies will be investigated in future work to solve this specific problem.

CONCLUSIONS

A composite solution adopting many coating layers of different materials, may strongly increase the component structural damping, according to some engineering design specification constraints.

Two simple solutions are investigated, a dual-layer obtained by means of a thin coating of Ti and of Ti oxide and a single-layer obtained by means of a thin coating of Al oxide. Coated specimens show improved damping behaviour with respect to uncoated ones for both the solutions under study. Preliminary cyclic loading tests show that the component dissipative properties may decrease due to the formation of damage and cracks at the layer interfaces.

The obtained results are positive enough to justify further investigations. Different technological and processing solutions will be examined in order to obtain increased damping behavior by means of frictional actions at the layer interfaces.

![Graphs showing computational and experimental estimates of complex modulus](image)

*Fig. 10 - Dual-layer (Ti+TiO$_2$) coated specimen coated specimen $E(\omega)$ estimates (green) and computational $n=11$ model fitting (blue)*
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REFERENCES


