Determination of elastic mechanical characteristics of surface coatings from analysis of signals obtained by impulse excitation

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Abstract. Most of the surface coatings are based on the synthetic polymers, which are substances composed from very large molecules that form tough, flexible, adhesive films when applied to surfaces. The other components of surface coverings materials are pigments that provide colour, opacity, gloss and other properties. Surface coatings are two-phase composite materials: constitute a polymer matrix on the one side, and on the other side of the pigments and additives dispersed in the matrix. Their role is not only aesthetically but also to ensure anticorrosive protection or even improve some mechanical properties of coated surfaces. In this paper it will follow, starting from the mechanical properties of the substrate, the metallic sheet in general, to determine the new properties of the assembly of substrate and the two coating layers, also the determination of mechanical properties of the layers. From the analysis of vibroacoustic signals obtained by the impulse excitation of the sample, one can determine the elasticity modulus. These results come to validate the results based on finite element analysis (FEA) of the same samples.

1. Introduction
Coatings provide a layer that changes the surface properties of piece to those of the material being applied. The piece becomes a composite material exhibiting properties generally not achievable by either material if used alone.

Coating metal surfaces is a challenge both for experienced paint professionals from various industries, and for those concerned with residential or commercial painting works. There are two types of metals: ferrous and non-ferrous. Ferrous metals will rust in contact with corrosive environments, and it is very important to cover the surfaces of these metals.

Knowing the metal nature of the coated surfaces is a vital issue because it influences the performance of the coatings. At the same time, in a paint-metal system, the primer layer plays an important role as a link between metal and paint and forms a suitable base for the next layer. Since cracking is the most frequent cause of failure in coating metal plates, it can be said that the different loads of the two components affect the coating. It is also appreciated that the impact of the rigidity of the adhesive film may be one of the vital reasons for preventing cracking. To prevent further corrosion of the metal surface, the rigidity of the coating should be equal to that of the metal used [1].

The coating of mechanical surfaces by metallization or painting is done for various purposes: from the aesthetic shape of the parts, through the given color, to avoiding their wear or to prevent their oxidation and corrosion. With the coating the elastic properties of the composite system change [2].
Several methods have been developed to determine the mechanical properties of materials, with a general classification in static methods and dynamic methods [3], [4]. Among the most widely used dynamic techniques are ultrasonic resonance spectroscopy [5-8] and resonant vibrational techniques [9-11]. Recent advances in identifying methods for the elastic characterization of materials and recent patents are reviewed in the paper [12-13].

In this paper, the research on the determination of the mechanical characteristics of some materials by the impulse excitation technique is continued. The vibroacoustic signal resulting from the applied mechanical pulse was acquired by a condenser microphone or the movement of a sample point was recorded using a laser vibrometer [14-17].

The purpose of this paper is to determine the modulus of elasticity of some paints used for the protection of ordinary steel sheets used in the refrigeration industry. The elastic properties of the coating material can be determined by measuring the frequencies of the free vibrating bar excited by mechanical impulse, before and after coating.

2. Theoretical background
In the following, the samples are considered as homogeneous isotropic rectangular bar of constant section, consisting of a substrate and two coating layers, and no subject to external forces (Figure 1). To study the free vibration of the bar can consider different boundary conditions. The best known case in the literature is free–free conditions. It is assumed that the stiffness of the composite bar is equal to the sum of the stiffnesses of the component layers rigidities. Neglecting shear and rotary inertia effect, and assuming a perfect bonding at the interface the bending vibratory motion of the bar is governed by a differential equation with partial derive Euler-Bernoulli [18]:

\[ \left( \frac{EI}{(EI)_c} + (\rho A) + (\rho A)_s \right) \frac{\partial^4 Y(x,t)}{\partial x^4} + \left( \frac{EI}{(EI)_s} + (\rho A)_s \right) \frac{\partial^2 Y(x,t)}{\partial t^2} = 0 \]  

where \( Y(x,t) \) is the displacement of neutral axis of the beam at \( x \) distance to the left end, \( (EI)_c \) and \( (EI)_s \) are the stiffness’s of the two coatings, \( (\rho A)_c \) and \( (\rho A)_s \) are the masses per unit of length of the two coating layers, \( (EI)_s \) is the stiffness of the substrate beam and \( (\rho A)_s \) is the mass per unit of length of substrate beam, \( E \) are the longitudinal elastic modulus, geometric moment of inertia of the cross section of the bar with respect to the neutral axis, the area of this section and material density while the subscripts \( s \) and \( c \) refer to the substrate and the coating, respectively.

This differential equation can be solved analytically and allows the determination of the shapes and the frequencies of the vibration modes. The resonance frequencies can be determined from the characteristic equation for free-free boundary conditions:

\[ 1 - \sinh \chi X \cos \chi X = 0 \]  

where

\[ X = L \sqrt{\frac{2 \pi \chi_{cb}}{(2 \pi \chi_{cb})^2 + \left( \frac{(\rho A)_c + (\rho A)_s}{(\rho A)_s + (\rho A)_s \chi_{cb} (EI)_s + (EI)_s \chi_{cb} (EI)_c} \right)}} \]  

and \( \chi_{cb} \) is one of the bending resonance frequencies, \( L \) is the length of the composite bar.

The first two roots of the characteristic equation (2) are \( X_1 = 4.730 \), \( X_2 = 7.853 \), and for natural modes \( r > 2 \), it is easy to show that:

\[ X_r = \frac{(2r+1)\pi}{2} \]  

It is obvious that for uncoated sample, i.e. the sample is only substrate, can be write a relationship similar to that given by the equation (3):
\[ X = L \sqrt{\frac{1}{2\pi f_s}} \left( \frac{\rho A}{EI} \right)_s \]  

(5)

where \( f_s \) is one of the bending resonance frequencies of the substrate beam.

From equations (3) and (5) it can obtain the relation between natural vibration frequencies \( f_{cb} \) of the composite beam, and natural vibration frequencies \( f_s \) of the substrate, assuming that the two coatings are of the same material and have the same thickness:

\[ \frac{f_{cb}^2}{f_s^2} = \frac{2(EI)_c + (EI)_s}{(EI)_s} \left( \frac{\rho A}{EI} \right)_c \left( \frac{\rho A}{EI} \right)_s \]  

(6)

Figure 1 shows the design of the coated beam and how its dimensions are noted.

**Figure 1.** Coated beam and its noted dimensions

**Figure 2.** Beam cross section and its noted dimensions

For a composite beam with a rectangular cross section, Lopez has developed an analytical expression to determine the film Young’s modulus [11]. In this model, it was considered a single coating layer and the simplification by which the neutral axis does not change after coating.

In the following, it will be considered to paint the bar with two symmetrical sides with respect to the substrate and with the same thickness. In this case, the neutral axis can be considered as not changing.

The geometrical moment of inertia of the substrate beam is

\[ I_s = \int_{-h_s/2}^{h_s/2} y^2 dy = \frac{bh_s^3}{12} \]  

(7)

and the moment of geometrical inertia of the two layers of coating, considering them of the same material and having the same thickness is

\[ I_c = \int_{h_n/2}^{h_n/2} y^2 dy = \frac{(2h_c + h_n)^3}{24} - \frac{h_n^3}{24} = \frac{bh_n^3}{2} + \frac{bh_nh_s^2}{3} + \frac{2bh_c^3}{3}. \]  

(8)

The stiffness ratio of the bar after coating and the stiffness of the bar before to coating will depend on the thicknesses of the coating layer and the thickness of the substrate bar, as

\[ \frac{2(EI)_c + (EI)_s}{(EI)_s} = E_c \left( \frac{2I_c}{I_s} \right) + 1 = E_c \left( \frac{I_c}{I_s} \right) \left( 1 + 2 \frac{h_c}{h_n} \right)^3 - 1 \right]+1 \]  

(9)

The mass ratio per unit length of the coating layer and the substrate bar will depend on the ratio of the thicknesses of the coating layer and the thickness of the substrate bar and their densities.
\[
\frac{(\rho A)_s}{2(\rho A)_s + (\rho A)_c} = \frac{1}{1 + 2 \frac{\rho_c h_c}{\rho_s h_s}}.
\]  
(10)

By replacing equations (9) and (10) in equation (8), the ratio of the natural frequencies of the bar after coating and before coating is obtained. This ratio is a function of the thickness of the coating layer and the thickness of the bar.

\[
\frac{f_{ch}^2}{f_s^2} = \frac{1 + \frac{E_c}{E_s} \left[ 6 \left( \frac{h_c}{h_s} \right) + 12 \left( \frac{h_c}{h_s} \right)^2 + 8 \left( \frac{h_c}{h_s} \right)^3 \right]}{1 + 2 \left( \frac{\rho_c}{\rho_s} \right) \left( \frac{h_c}{h_s} \right)}
\]  
(11)

Then, the Young’s modulus of the coating can be calculated as:

\[
E_c = \frac{E_s}{6 \left( \frac{h_c}{h_s} \right) + 12 \left( \frac{h_c}{h_s} \right)^2 + 8 \left( \frac{h_c}{h_s} \right)^3} \left[ \left( \frac{f_{ch}}{f_s} \right)^2 \left( 1 + 2 \left( \frac{\rho_c}{\rho_s} \right) \left( \frac{h_c}{h_s} \right) \right) - 1 \right].
\]  
(12)

Assuming that the thickness of the coating is much smaller than the thickness of the substrate, i.e. the ratio \( h_c/h_s \ll 1 \), then the square and the cube of this ratio can be neglected and the equation (12) takes the form:

\[
E_c = \frac{E_s}{6 \left( \frac{h_c}{h_s} \right)} \left[ \left( \frac{f_{ch}}{f_s} \right)^2 \left( 1 + 2 \left( \frac{\rho_c}{\rho_s} \right) \right) - 1 \right].
\]  
(13)

This simplified model was given by Berry [19-20] in another way, but it can also be obtained from the Lopez model by developing Taylor series according to the ratio of the thicknesses of the coating and the substrate, and retaining only the terms of the first order.

Assuming that the thickness of the coating is much smaller than the thickness of the substrate, i.e. \( h_c/h_s \ll 1 \), and the density of the coating material is much lower than the substrate density then \( \rho_c/\rho_s \ll 1 \), then the equation (13) becomes

\[
E_c = \frac{E_s}{6 \left( \frac{h_c}{h_s} \right)} \left[ \left( \frac{f_{ch}}{f_s} \right)^2 - 1 \right].
\]  
(14)

This model leads to a very quick and simple formula for determination of Young’s modulus for the coating material into two very thin layers (on both sides) that have very small density compared with density of the substrate material. It can be used for thin, low density coatings (TLDC).

In the case of a free–free substrate beam with a rectangular cross-section, the Young’s modulus can be determined by the following formula [21]:

\[
E_s = k_s f_s^2 \rho_s \frac{L^4}{h_s^3} T_f
\]  
(15)
where \( k_1 = 0.9465 \) and \( T_f \) is the geometrical correction factor introduced to take into account the shear and rotary inertia effects. For a ratio between the length of the bar and its thickness \( L/h_s \gg 20 \), this correction factor can be simplified into the following expression:

\[
T_f = 1 + k_2 \left( \frac{h_s}{L} \right)^2
\]

(16)

where \( k_2 = 6.585 \).

3. Numerical simulation

Figures 3 and 4 give the geometric model of the sample. It consists of three parts: the substrate bar and two layers of coating, symmetrical to the substrate and of the same thickness. The substrate is a rectangular cross section slender beam with a length \( L = 250 \) mm, a width \( b = 40 \) mm and a thickness \( h_s = 2 \) mm. It is made of steel S 235 JR, with material properties \( E_s = 200 \) GPa, \( \rho = 7850 \) kg/m\(^3\), \( \mu = 0.3 \). The painting was bonded to the substrate by electrostatic field having the possibility of thickness control. For the sample considered in the modal analysis, the thickness of the two layers assumed by equal thicknesses was \( h_c = 0.0881 \) mm after one deposition in the electrostatic field, respectively \( h_c = 0.1882 \) mm after two depositions.

For the free-free boundary conditions the modal analysis, were applied to beam from Figure 1, by ANSYS program. The 3D hexahedron element was used to mesh the structure. Mesh on the beam is generated automatically by ANSYS, while is used the spatial hexahedral elements as in Figure 3. The element is defined by 8 nodes while each node has three degrees of freedom. The solid hexahedral element has a quadratic shifting behavior and is suitable for modeling of the finite element regular mesh. The maximum size of the element is 4 mm. The mesh, in Figure 4, is created of 748 elements and of 5634 nodes.

To extract the resonance frequencies of the substrate beam and composite beam, the type of solver and the solution method in program ANSYS is selected automatically. For this modal analysis the direct solver including the block Lanczos method is used.

A total of twenty vibration modes have been extracted. The first six modes correspond to rigid body modes and have natural frequencies approximately equal to zero. The following two modes of elastic body correspond to bending modes in plane. The next one mode corresponds to the first torsion mode. In higher order modes, the first out of plane vibration mode appears.

The first mode of bending vibration (Figure 5) is useful for determining the modulus of elasticity of the substrate in equations (15), respectively for determining the modulus of elasticity of the covering material in the equations (12), (13) and (14).

The first mode of torsional vibration can be used to determine the shear modulus of elasticity.
4. Experimental technique
To determine by measurements: the length L, width b and thickness h_s of the substrate beam, six measurements were made at six different points. To determine the thickness of coatings alleged equal, ten measurements were performed in six different points.

The substrate dimensions are its length L=250 mm, its width b=40 mm, and its thickness h_s=1.97 mm. The coating has the same length and width as the substrate and a thickness of a single layer has h_c=0.0881 mm after a single pass of the sample through the electrostatic field, respectively, h_c=0.1882 mm, after two passes.

The purpose of the impulse excitation technique (IET) is to measure the resonance frequencies of a sample impacted by a small hammer impulse (Figure 6). A beam can be excited in different vibrations modes: longitudinal, flexural and torsional. Experimental stand used in the vibration lab of the
department, is composed by: the sample 1, which is the mechanical structure to be analyzed, impulsive mini hammer 2, brackets to support the sample 3, elastic threads for support of the beam in boundary conditions the free ends 4, the acoustic sensor one condenser microphone 5, and the computer with acquisition board 6.

Before performing the test, the sample is placed on a support, elastic threads. The free limitation condition has been adopted for this procedure. The elastic threads are located at the nodal points of the sample, where the displacement is zero, i.e. for the first bending mode used in this study.

![Recorded signal](image)

**Figure 7.** Recorded signal

These mechanical vibrations are detected by an acoustic microphone and transformed by it, which is actually a capacitive transducer, in an electrical signal that is represent as a time function (Figure 7). Fast Fourier Transform (FFT) is used to represent the signal as a frequency function and to extract the resonant frequencies of the sample.

For the purpose of this paper, it is sufficient to determine in the Fourier spectrum the fundamental bending frequencies, before coating the sample with paint and after covering the sample. For this reason the recorded signal is filtered, using a band pass filter with ±70 Hz from the central frequency, about which value is obtained information from the modal analysis. In the Fourier Spectrum represented in Figure 8, for the signal recorded from the sample not coated with paint, only the frequency corresponding to the first vibration mode was retained. This resonant frequency value, density or mass and sample sizes are used to determine the Young's modulus of elasticity of the uncovered sample.

To determine the elasticity modulus of the paint, which covers the substrate sample, the equations (12), (13) and (14) are used.
In these equations the frequency of the first bending mode of the composite beam must be known. From a recorded signal, similar to the signal in Figure 8, after filtering it and applying the Fast Fourier Transform, the Fourier Spectrum is obtained, containing only the first resonant frequency of the composite beam.

In the Figure 9 the Fourier Spectrum gives the frequency of the first bending mode for the painted beam bar through a single pass by the electrostatic field. For two passes, the thickness of the cover width increases and the frequency of the first mode increases to \( f = 166.83 \)Hz.

The resonance frequency, density/ mass and sample sizes are used to calculate the elastic modulus of the paint material, and the results are shown in Table 2.

In a similar way, starting from the torsional vibration equation, relationships can be obtained for determining the shear modulus of the substrate and the paint layer, respectively. Between the three parameters that characterize the mechanical properties of a material: Young's module, shear modulus and Poisson's coefficient is a dependency relationship, and after experimental determination of the first two modules, Poisson's ratio can be determined. These issues are underway and are future research.

**Figure 8.** First resonant frequency from Fourier Spectrum for not coated beam
5. Results and conclusions

To determine the elasticity modulus of the paint, the equations (12), (13) and (14) are used. The results obtained are shown in Table 1, in which experimental determinations were made after deposition of the paint through a single pass of the sample through the electrostatic field.

Table 1. Young’s modulus of paint, after one pass of the sample through the electrostatic field

| Frequency before coating (Hz) | Frequency after coating (Hz) | E_s (GPa) | E_c (GPa) | E_c (GPa) | Berry method | Lopez method |
|------------------------------|------------------------------|-----------|-----------|-----------|--------------|--------------|
| 164.74                       | 166.4                        | 199.74    | 3.801     | 4.823     | 4.712        |

In Table 2 are presented the results of the elastic modulus of the paint determined experimentally from the sample covered by passing twice through the electrostatic field.

Table 1. Young’s modulus of paint, after two passes of the sample through the electrostatic field

| Frequency before coating (Hz) | Frequency after coating (Hz) | E_s (GPa) | E_c (GPa) | E_c (GPa) | Berry method | Lopez method |
|------------------------------|------------------------------|-----------|-----------|-----------|--------------|--------------|
| 164.74                       | 167.53                       | 199.74    | 3.994     | 4.987     | 4.621        |

The values of the elastic modulus given in the paint catalogs are in the range of 4.2 GPa and 5.3 GPa. By comparing the results obtained experimentally with those given in the catalogs it is found that the method is valid and gives good results for determining the modulus of elasticity of coating materials.
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