ESTIMATION OF DAMPING LOSS FACTOR OF FUSELAGE PANEL BY POWER INJECTION METHOD AND IMPULSE RESPONSE DECAY METHOD

Giovanni Bratti, giovanni.bratti@ibest.com.br
Augusto Amador Medeiros, augusto.med@gmail.com
Federal University of Santa Catarina - UFSC

Mario Alejandro González Montenegro, marioacustico@gmail.com
Federal University of Santa Catarina - UFSC

Arcanjo Lenzi, arcanjo@lva.ufsc.br
Federal University of Santa Catarina - UFSC

Roberto Jordan, jordan@emc.ufsc.br
Federal University of Santa Catarina - UFSC

Júlio Apolinário Cordioli, cordioli@emc.ufsc.br
Federal University of Santa Catarina - UFSC

Abstract. In recent decades, the air transportation has grown quickly, becoming one of the most important means of transport of passengers. In terms of the internal comfort of passengers and crew, aircraft internal noise is considered very important to airline companies, since interior noise can bring discomfort to passengers, interfere in the internal communication and produce fatigue of the crew. The vibro-acoustic behavior of aircraft structures, like fuselage panels, has significant impact on the interior noise of the aircraft, and it is frequently analyzed in mid to high frequencies by means of the Statistical Energy Analysis (SEA). To perform this analysis, complex systems are divided in subsystems, which are described in terms of their modal density, damping loss factor (DLF) and coupling loss factor to other subsystems. The DLF is considered a key parameter in order to get an accurate SEA model. Generally, the DLF of subsystems are obtained from experimental tests, with the Power Injection Method (PIM) being one of the main methods used in the literature. However, the method may display some problems when estimating the DLF of structures with non-uniform distribution of mass. In this paper, the DLF of a fuselage panel with and without viscoelastic material is measured using PIM the Impulse Response Decay Method (IRDM). The results from both methods are compared and advantages and disadvantages of each method are discussed.

Keywords: Fuselage panel, SEA, DLF...

1. INTRODUCTION

The Statistical Energy Analysis (SEA) is a standard numerical methods used to analyze the vibro-acoustic performance of structures in the aeronautic and aerospace industries (Davis *et al.*, 2005). The method is based on a statistical description of regions of the structure (called SEA subsystems), which are represented by their modal density, damping loss factor (DLF), coupling loss factor (CLF) and power input (Cordioli *et al.*, 2010). Although the other parameters can be calculated with reasonable confidence through analytical and numerical methods, the DLF is typically obtained through experimental tests.

Noise and vibration systems can be reduced by different ways. The traditional methods in acoustics make use of absorbers or damping materials, acoustic resonators, etc. Usually, the most common practice is by applying damping materials, or viscoelastic materials, in some parts of structures. The viscoelastic materials are widely used in aeronautic and aerospace applications, as well as in other industries, in view of possibility of obtaining high levels of damping (Rao, 2003).

The experimental methods currently used to measure the damping of a system include modal analysis curve fitting methods, time domain decays-rate methods, the Power Injection Method (PIM) and others. Each method has it's own advantages and drawbacks. The PIM is one of the main methods, however, the method may display some problems when estimating the DLF of structures with non-uniform distribution of mass. On the other side, decay-rate methods are usually limited to structure with small damping. This paper presents a experimental comparison between two methods widely used to estimate of DLF of a structure: the PIM and the Impulse Response Decay Method (IRDM). The structure considered was a fuselage panel, which two configurations was tested: with and without viscoelastic material applying in the bays. The principal objective of this paper is to verify the limitations of each method for this type of structure.

Furthermore, an analysis is performed with the IRDM to verify the upper limits os the DLF of a structure for witch the method may be used with confidence.

2. DESCRIPTION OF THE METHODS

2.1 Power Input Method - PIM

The power input method is a method utilized to estimate the DLF of a system, which can be defined as the ratio between dissipated energy and total energy per radians of motion, or (Cordioli *et al.*, 2010)

$$\eta(\omega) = \frac{P_{diss}}{\omega(U+T)}, \tag{1}$$

where U, T and P_{diss} are, respectively, the time-average strain energy, kinetic energy and dissipated power of the system, and ω the frequency in radians per second.

Assuming a stationary force excitation applied to the structure, there will be a stationary vibration response field in the structure, meaning that an equal amount of energy must be input from the excitation source to compensate for the dissipation energy from damping (Carfagni and Pierini, 1999). Therefore, it may be assumed that the power input to the structure is equal the dissipated energy in stead-state conditions. On the other side, assuming a resonant behavior of the structure, the total energy "$(U+T)$" is equal maximum kinetic energy (T_{max}), and Eq. (1) can be written as

$$\eta(\omega) = \frac{P_{in}}{\omega T_{max}}, \tag{2}$$

where P_{in} is the power input from the excitation.

In the case of a driving point, the power input to the system can be calculated based on the mobility (Y_{fv}) of the point where the force is applied (point mobility). The kinetic energy can be obtained from the system transfer mobilities (Y_{iv}). For structures with uniform distribution of mass, like a plate, assumption a linear system, the Eq. (2) can be written as (Carfagni and Pierini, 1999)

$$\eta(\omega) = \frac{\text{Re}\left(Y_{fv}(\omega)\right)}{\omega \frac{M}{N} \sum_{i=1}^{N} |Y_{if}(\omega)|^2}, \tag{3}$$

where M is total mass of the system and N is the numbers of measured transfer mobilities, in which all terms can be experimentally determined.

The structure that will be used in the analysis can be seen in Fig. 1. The panel has a non-uniform distribution of mass, and some modifications in Eq. (3) need to be done. In the case of the panel, the total vibratory energy is composed by the sum of the energy of each component. So, the DLF of the fuselage panel, calculated via PIM may be given by

$$\eta(\omega) = \frac{Re\left[Y_{jv}(\omega)\right]}{\omega \left(\underbrace{M_{bay} \sum_{j=1}^{N_1} \frac{|Y_{ij}(\omega)|^2}{N_1}}_{BAIA} + \underbrace{M_{str} \sum_{j=1}^{N_2} \frac{|Y_{ij}(\omega)|^2}{N_2}}_{STRINGER} + \underbrace{M_{fra} \sum_{j=1}^{N_3} \frac{|Y_{i,j}(\omega)|^2}{N_3}}_{FRAME} \right)}, \tag{4}$$

where M_{bay} is the total mass of the bays, M_{str} the total mass of the stringers, M_{fra} the total mass of the frames and N_1, N_2 and N_3 are the numbers of responses in each component, respectively. The number of points used to estimate the energy of each component is discussed in more detail in the following sections.

2.2 Impulse Response Decay Method - IRDM

Like other methods, the IRDM is based on the measurement of the system's decay rate when it is subjected to an impulse or an interrupted stationary excitation (Bloss and Rao, 2005). The system's response amplitude when plotted versus time will have a slope proportional to $e^{-\pi f \eta t}$, where f is the frequency, η is the loss factor, and t is the time. The decay slope between two instants in time t_1 and t_2 with amplitudes X_1 and X_2, respectively, in decibels, is given by (Lyon *et al.*, 1995)

$$20 \log_{10}\left(\frac{X_1}{X_2}\right) = 27.3 f \eta (t_2 - t_1). \tag{5}$$

Defining the decay rate, Δ_t, as the rate of decrease of the vibration level with time in decibels per second (Crocker, 1998), the loss factor may be calculated using

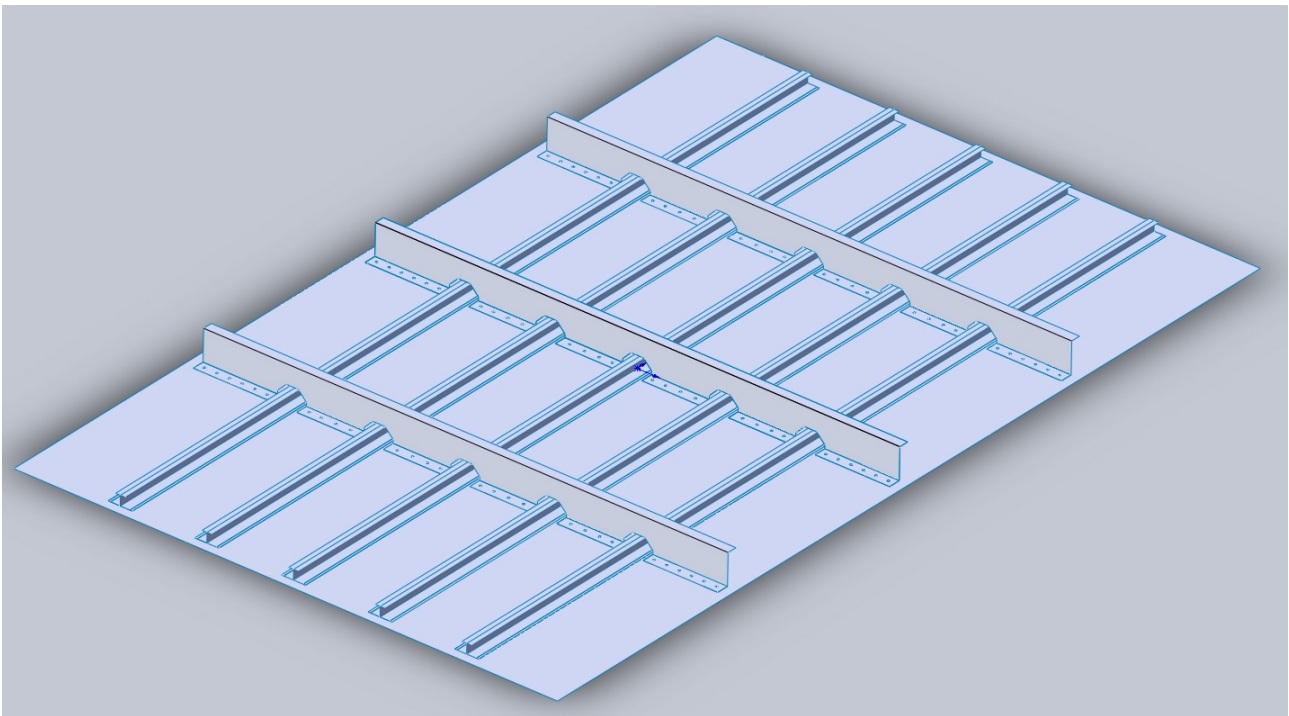$$\eta = \frac{\Delta_t}{27.3 f}. \tag{6}$$

Figure 1. Illustrate of panel without viscoelastic material.

The IRDM utilizes the impulse response $h(t)$ instead of the output response. The impulse response can be obtained from an inverse Fourier Transform (IFFT) of a system's frequency response function (FRF) (Bloss and Rao, 2005). The initial decay slope is found by plotting the system's response on a logarithmic amplitude scale, with a linear time scale.

A procedure for the calculation of the DLF using IRDM is proposed, and it is based on the following steps:

1. For each FRF, a vector was created with values corresponding to the values in the frequency band of interest, $Y_{ij}(f_{inf} : f_{sup})$, where f_{inf} is the low frequency limit and f_{sup} is the up frequency limit. The analysis was carried out in 1/3 octave frequency band.

2. A mirrored of the vector from the highest frequency of the analysis (not the band) was constructed.

3. The impulse response was obtained from each vector by applying a IFFT;

4. The initial decay slope, in dB/s, was found by plotting the system's impulse responses on a logarithmic amplitude scale, with a linear time scale.

5. This procedure was repeated for each frequency band and all measured FRF's. Finally, the curve for DLF of the system was obtained based on the average decay slope over all FRF's.

The procedure described above is illustrated in Fig. 2 and Fig. 3.

3. EXPERIMENTAL SETUP

As shown in Fig. 1, the fuselage panel used in the experimental tests is composed of a 2 mm aluminum skin with 3 frames and 5 stringers, these made from conformed aluminum sheets. The panel has 24 bays of dimensions 0.440 by 0.180 m and was suspended by bungee cords during the experimental tests (free-free boundary conditions - BC). The schematic of experimental setup can be seen in Fig. 4.

The panel was excited from 70 to 3100 Hz with a B&K electrodynamic shaker type 4809 and a B&K power amplifier type 2718. A B&K impedance head type 8001, connected to the shaker by a stinger and attached to the skin side, was used to measure both input force and acceleration. The shaker input signal was generated, and the impedance head and B&K accelerometers type 4517 were used to measure point and transfers mobilities, using a B&K Pulse front-end analyzer type 7539A.

The positions of the responses and excitations points were chosen randomly, and their respective quantities can be seen in Tab. 1. The data were collected and analyzed using PULSE LabShop 10.0 and the calculus was made in Matlab R2008b.

A correction for the transducer mass was applied to the transfer functions and the DLF was estimated by PIM and IRDM for the panel with and without viscoelastic material. A commercial viscoelastic material was used, which is
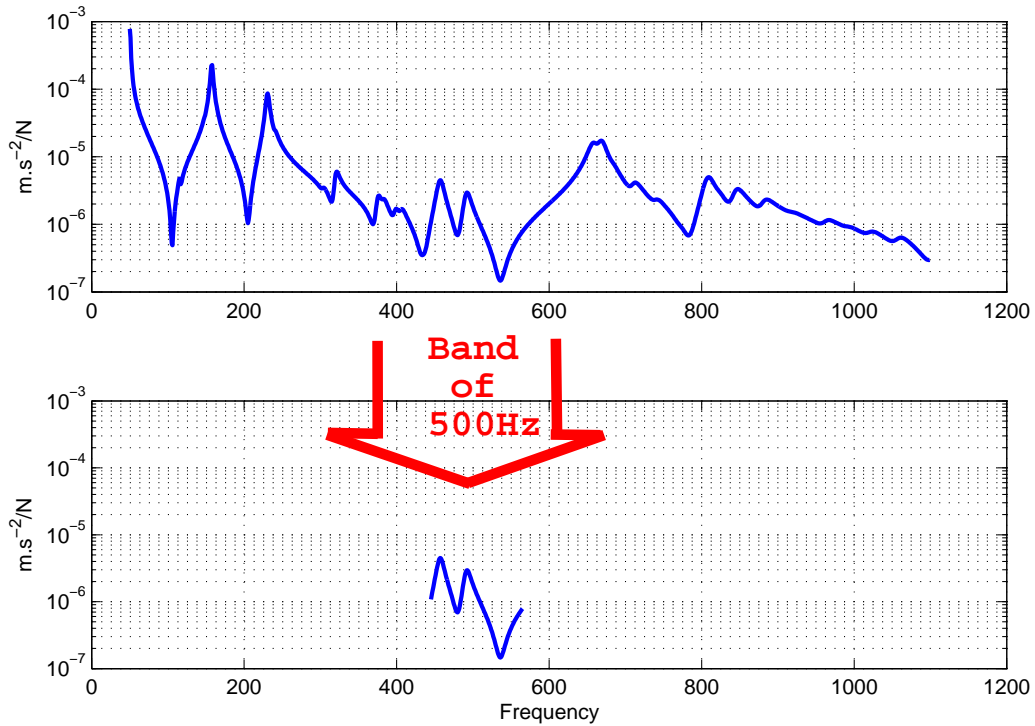
Figure 2. Procedure used to create a vector with only part of the FRF correspondent to the band of 500Hz.
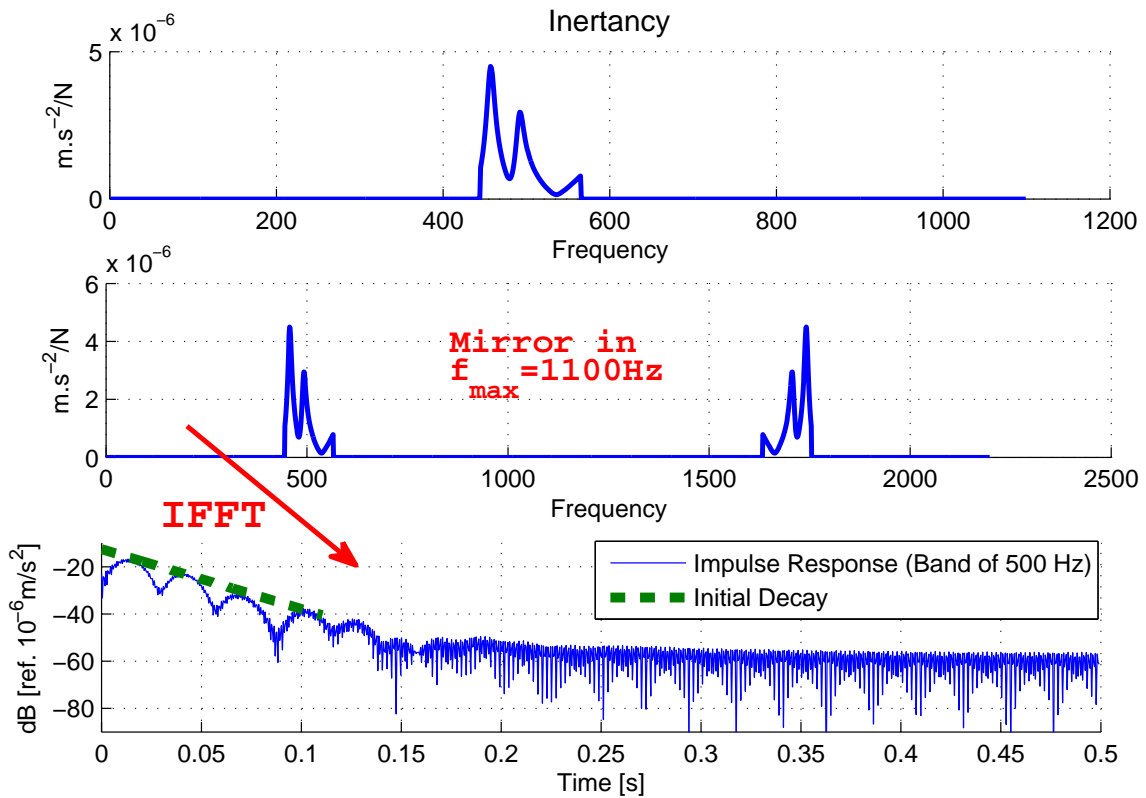

Figure 3. Illustration of creation of the new FRF, filtered at the band of 500Hz, and the obtaining of the impulse response at the same band.
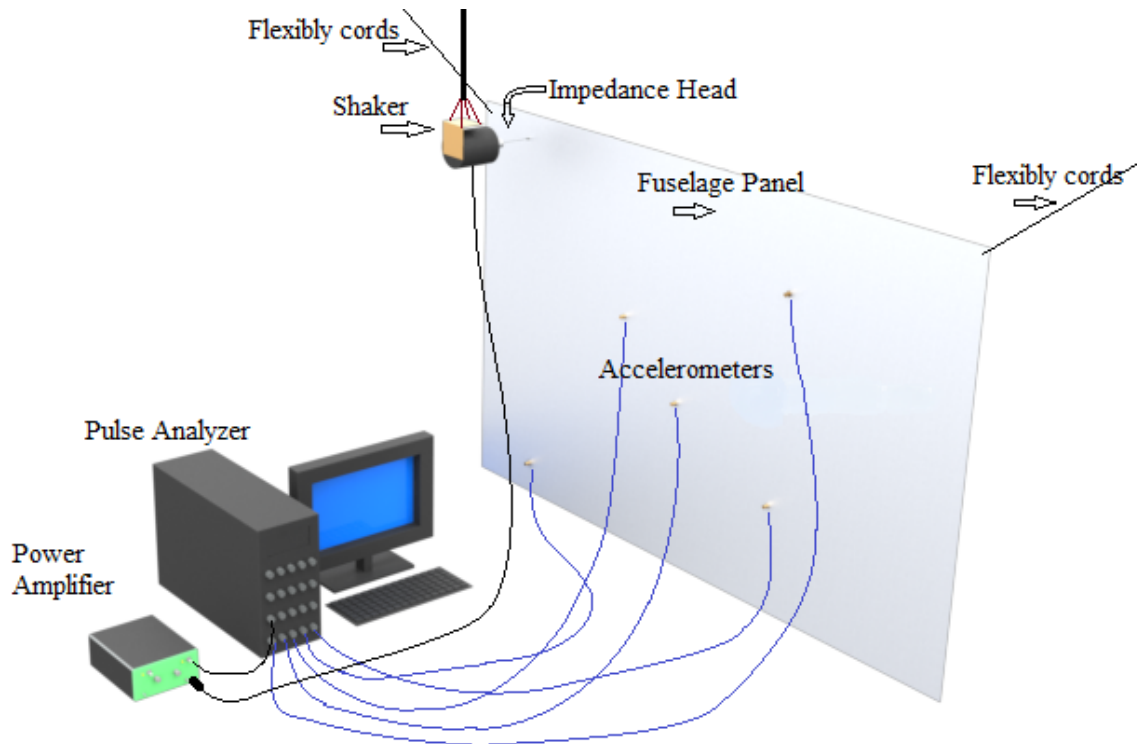
Figure 4. Experimental setup.

Table 1. Number of responses/excitations measured in the tests.

Configuration	Responses			Excitations		
	Bays	Stringers	Framers	Bays	Stringers	Framers
Without viscoelastic	10	1	1	4	1	1
With viscoelastic	48	15	9	4	2	1

composed of a 1.24 mm layer of viscoelastic and an aluminum constrain layer with 0.1 mm thickness. The materials were cut in rectangular parts and glued on the middle of the bays, as shown in Fig 5.

4. COMPARISON OF LOSS FACTORS FROM PIM AND IRDM

Figure 6 shows the comparison between two punctual inertances of the fuselage panel, with and without viscoelastic material applied. It is noticeable that there are a lot of modes in this frequency band and that some peaks were attenuated and others were shifted in frequency.

As the panel was excited in different points, the final DLF obtained by each method was calculated by the average between the loss factors calculated for each excitation. In the Fig. 7 we can see the results of the one-third-octave band averaged loss factor of the fuselage panel with and without viscoelastic material. Comparing Fig. 7 and Fig. 6 we can perceive that there is a big difference between the results in low frequency, where there are no (or there are a few) modes. These discrepancies at low frequencies, obtained for PIM results, is explained by Cordioli *et al.* (2010), where is believed to be due to the assumption in PIM method that the total energy of the system can be estimated from the kinetic energy. The assumption is valid at resonance frequencies and it is likely to underestimate the total energy away from resonances.

For panel without viscoelastic material, the differences in the results at low frequency is higher than for the configuration with viscoelastic. A reason for this difference is the fact that the PIM method needs a great quantity of points to estimate the DLF with precision, and for this configuration it was used a small amount of responses, as presented in Tab. 1. As the width of frequency band increases, the difference between the results of the methods decrease.

A detail that was investigated was the form that the FRF was truncated. Observing Fig. 2 and Fig. 3, we can see that the filtered FRF was obtained by the rectangular truncation of original the FRF in each frequency band. Shin and Hammond (2008) have presented in their book that the Fourier Transform of a window causes a characteristic decay in the other domain, and the authors mention that the rectangular window is considered poor with respect to the sides lobes, which have a slow decay. The difference of amplitude between the main lobe and the first secondary lobe is about ≈ 13dB, and the slope decay of the secondary lobes is approximate 6dB/octave, as can be seen in Fig. 8.

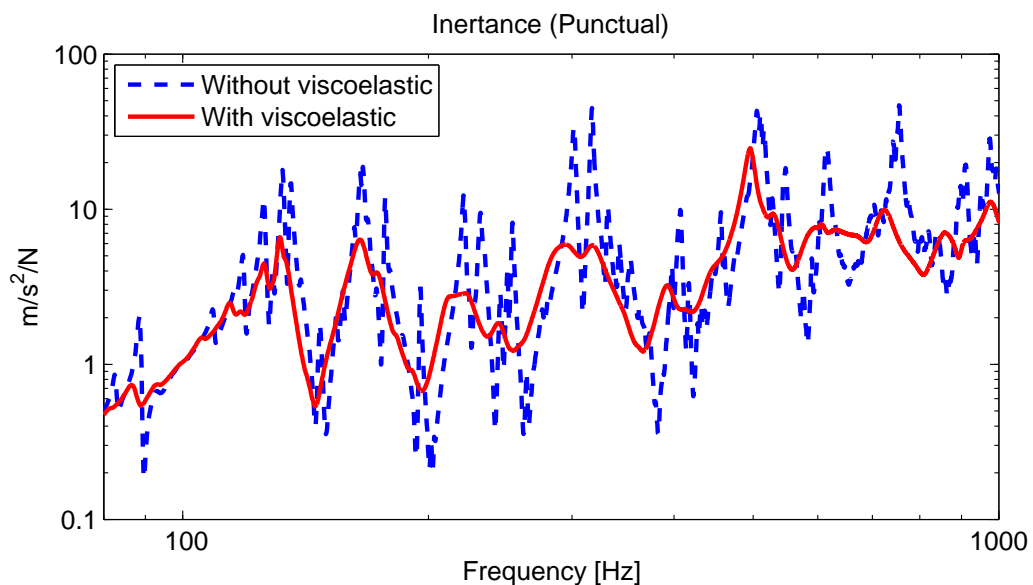Figure 5. Fuselage panel with viscoelastic material applied in the bays.

Figure 6. Comparision of experimental inertance (punctual) of the fuselage panel with and without viscoelastic.

Figure 8 shows that the hanning window has a side decay higher than the rectangular window and we can expect that the truncation form may influence the results of loss factors calculated with the IRDM. Based on this fact, the loss factors were calculated by IRDM with rectangular, hanning and parsen windows, as described in Sec. 2.2, where was created a vector with values of the window in frequency band, and the rest was written as being zero. So, the remainder procedure was ran normally and the results can be seen in Fig. 9. As we see, the results of DLF calculated to the windows was about
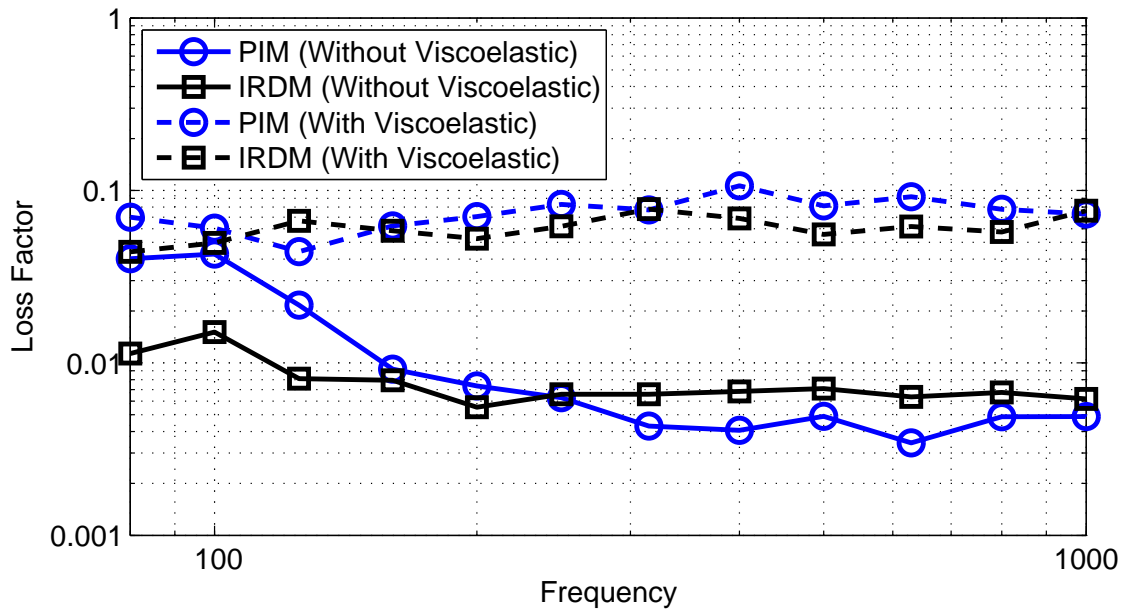
Figure 7. Comparison of loss factor obtained from PIM and IRDM of the fuselage panel with and without viscoelastic material.
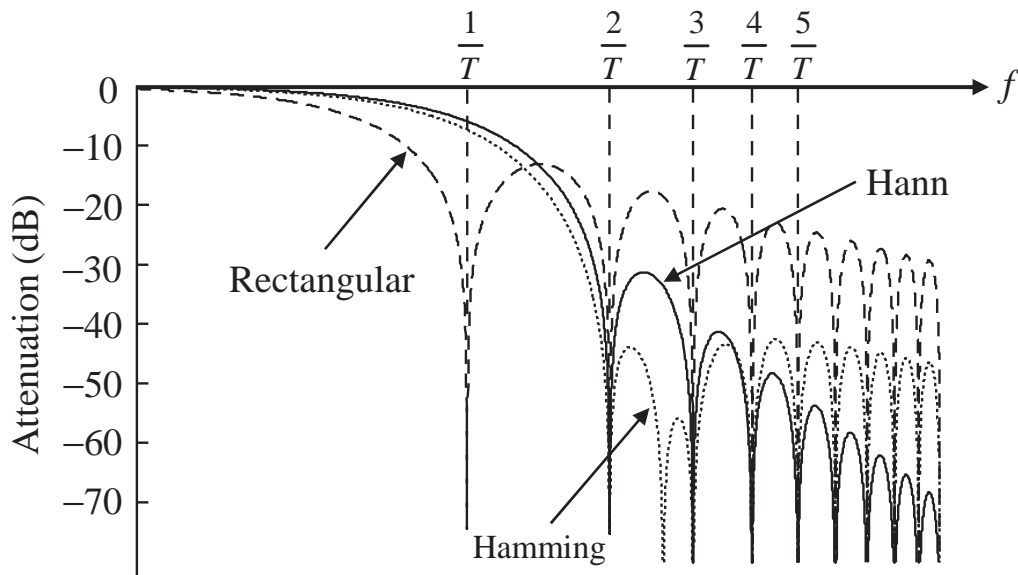

Figure 8. Fourier Transforms of some windows.
(Fonte: Fundamentals of Signal Processing for Sound and Vibration Engineers (Shin and Hammond, 2008))

$\eta \cong 0.10$.

The Fourier Transform of the product of two functions is given by

$$F\{w_1(t).w_2(t).\} = W_1(f) * W_2(f), \tag{7}$$

where $w_1(t)$ and $w_2(t)$ are any functions in time domain, $F\{\ \}$ is the Fourier Transform, the symbol "$*$" is the convolution operation and $W_1(f)$ and $W_2(f)$ are the Fourier Transform of the functions $w_1(t)$ and $w_2(t)$, respectively. So, we can calculate the impulse response as

$$\begin{aligned} h(t) &= F^{-1}\{W_1(f)\} * F^{-1}\{W_2(f)\} \\ &= w_1(t) * w_2(t), \end{aligned} \tag{8}$$

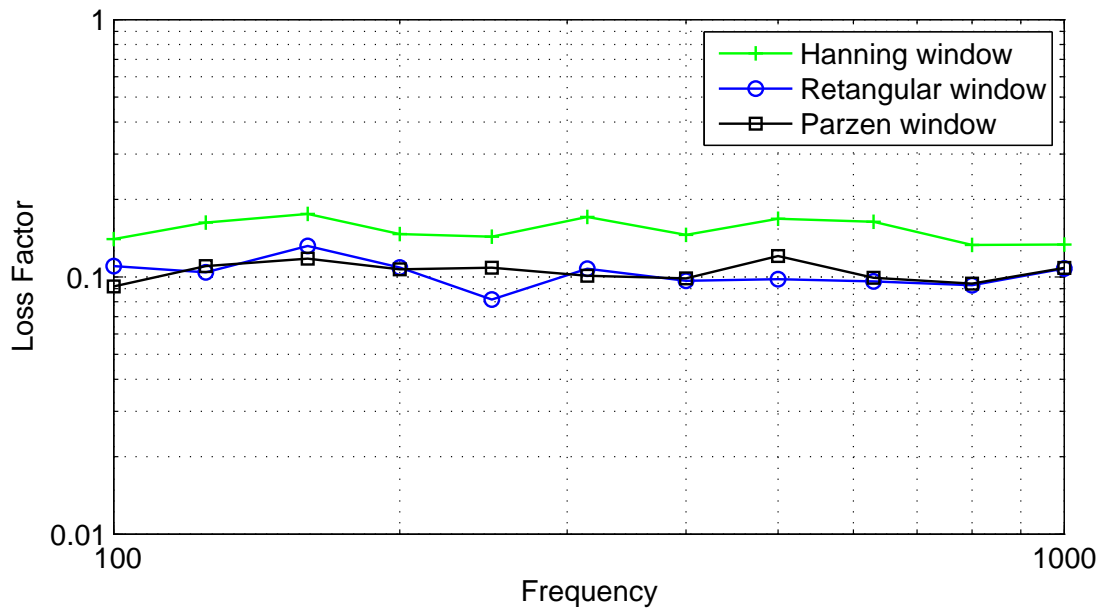where $F^{-1}\{\ \}$ is the inverse Fourier Transform.

Figure 9. Loss factors calculated to the rectangular window, hanning and parsen window.

Analyzing this information, we can conclude that the impulse response obtained in Sec. 2.2 is given by convolution between the IFFT of the original FRF with the IFFT of the rectangular window in frequency domain. In order to conclude, an analysis of convolutions between the functions was performed in order to investigate the dominant factor in decay of the impulse response. As shown in Fig. 10, three functions with different decay rates were created in time domain, in which $w_1(t)$ is a rectangular window, $w_2(t)$ a hamming window and $w_3(t)$ a hanning window. The convolution between these functions was calculated, using the Eq. (8), in order to investigate their behavior and if theirs decay have a tendency to follow the decay of some these functions. The results of the convolutions are presented in Fig.11.
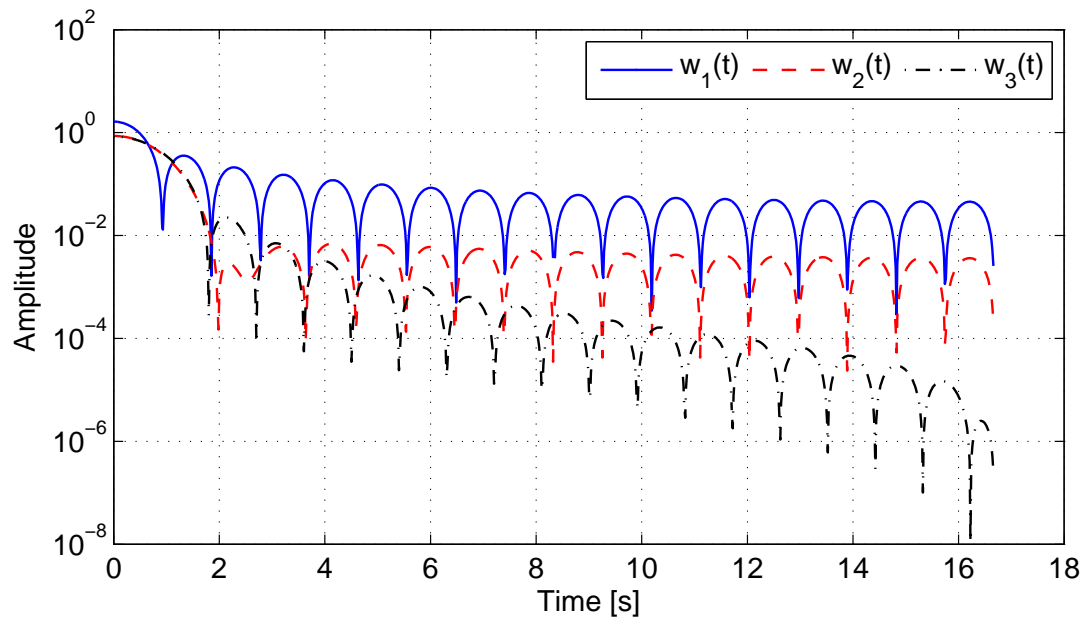

Figure 10. Functions used to analyze the convolution.

Observing Fig. 10 and Fig. 11, we can see that the decay of convolution between two functions tends to follow the decay of the function that has the lowest decay.
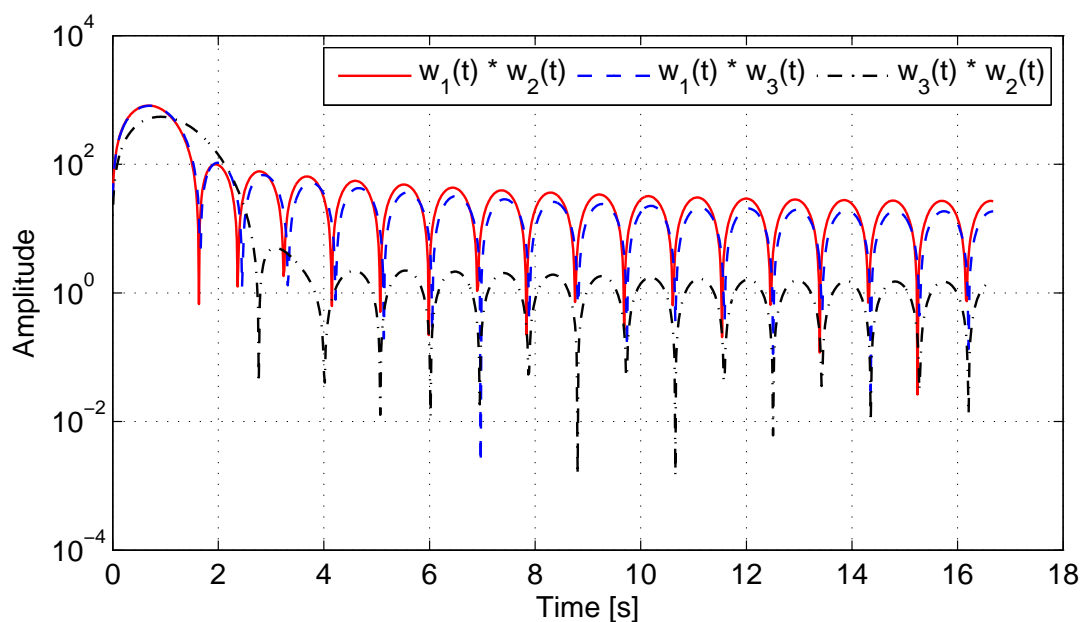
Figure 11. Convolution between the functions $w_1(t)$, $w_2(t)$ and $w_3(t)$.

5. CONCLUSIONS

The Power Input Method (PIM) and Impulse Response Decay Method (IRDM) were used to estimate experimentally the damping loss factor of the fuselage panel with and without viscoelastic material. It is possible to see that both methods show close results, but at low frequencies (few modes), without viscoelastic, due to the small number of response points, the PIM showed to be less accurate. Both methods present good results when there are modes within the analyzed frequency band.

The PIM is based on the comparison between the dissipated energy of the system and the maximum strain energy. This method has a strong dependency on the amount of response points; the greater the amount of points, the greater the accuracy. The doubts that stay open are: What is the amount of response point and excitation point necessary to get an accurate result with PIM? What are the proportions of points to distribute on the subsystems of a complex system?

The IRDM method, which uses the initial decay of the impulse response, can be faster than PIM because it requires only a little quantities of FRF's, but this method seems be limited to values of loss factor greater than 0.10, as shown in Sec. 4, in the convolution analysis between the functions.

6. ACKNOWLEDGMENTS

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