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APPLICATION OF THE METHOD EERA FOR IDENTIFICATION IN REAL TIME OF THE MODAL PARAMETERS OF AN ALUMINNUM PLATE

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Abstract: The aerospace structures must be submitted to some form of verification before the flight, to assure that the aircraft is free of any aeroelastic instability phenomenon, for example flutter. One of the essential elements to accomplish in flight flutter tests is the structural modal parameters identification process of the aircraft under test. The accurate and fast identification of the modal parameters allows determining, with antecedence and security, the flight conditions where the flutter phenomenon will occur. Currently the research in this area points in the direction of developing the technology that allows the identification, in real time, of the modal parameters associated to flutter. In this work the EERA - Extended Eigensystem Realization Algorithm method of modal parameters identification was carried out to be applied in real time. This is a method of identification in the time domain considered efficient and powerful, since it is capable of identifying complex dynamic behavior in structures. The method EERA was adpted and programmed in a dSPACE® signals acquisition and processing equipment. An experimental test, in real time, was carried out with an aluminum plate. With this test the modal parameters identified on-line were compared with those identified off-line, in a test carried out initially to validate the algorithm, thus proving the efficiency of the method for identification in real time.

Keywords: Identification, EERA, Modal Analysis, Real Time.

NOMENCLATURE

m = *number of output*
n = *degree of freedom*
r = *number of external excitations*
k = *sample instant*
M = *number of samples in a time window*
N = *number of samples in a time window*
$\boldsymbol{u}(k)$ = *input vector*
$\boldsymbol{x}(k)$ = *state vector*
$\boldsymbol{y}(k)$ = *response vector*
$\boldsymbol{A}_d$ = *system matrix*
$\boldsymbol{B}_d$ = *input matrix*
$\boldsymbol{C}_d$ = *output matrix*
$\mathbf{D}_d$ = *direct transmission matrix*
$\boldsymbol{G}$ = *block Toeplitz matrix*
$\boldsymbol{I}$ = *identity matrix*
$\boldsymbol{R}$ = *matrix of the left singular vectors*
$\boldsymbol{S}$ = *matrix of the right singular vectors*
$\boldsymbol{U}$ = *block Hankel matrices of inputs*
$\boldsymbol{X}$ = *matrix of the state sequence*
$\boldsymbol{Y}$ = *block Hankel matrices of outputs*
$\boldsymbol{0}$ = *null matrix*

Greek Symbols
Γ = extended observability matrix
Σ = matrix of singular values

Subscripts
s shifted
2n first 2n columns

Superscripts
-1 inverse
T transpose
⊥ orthogonal
† pseudoinverse

INTRODUCTION

The study of the dynamic behavior of aeronautical structures is of extreme importance in the aerospace industry, mainly due to continuous demand for lighter and consequently more flexible structures. In such a way, there is a great necessity for tools that make possible the knowledge of its dynamic behavior, as well as make possible to foresee this behavior. During the last decades the Modal Analysis consisted on the main tool used in the analysis of the dynamic behavior of flexible structures and can be subdivided in: Theoretical Modal Analysis and Experimental Modal Analysis.

The extration of information from experimental events is fundamental in order to have a more accurate understanding of the reality, allowing to formulate models and to develop theories that describe the observed systems. A way to make this is using the techniques of System Identification, considered the art of the mathematical modeling. System identification is a technique for establishing dynamic systems mathematical models from input and output measurements data (Klein, 1989). Some basic references about system identification can be cited: Eykhoff (1974), Ljung (1987), Maine & Iliff (1985) and Landau (1990).

The parametric identification of mechanical systems is one of the main applications of the techniques of system identification, specifically for the identification of modal parameters. Systematic modal identification methods such as the Eingensystem Realization Algorithm – ERA (Juang and Pappa, 1985) have allowed complexity increase of the structures that can be modeled by experimental measurements. The Extended Eigensystem Realization Algorithm (EERA) method is a modified form of the ERA that calculates the modal parameters by manipulating both input and output time histories. The development of these subspace identification methods is motivated by difficulties in estimating modal parameters for multiple-input multiple-output vibratory systems (Tasker, Bosse and Fischer, 1998). During the last few years subspace methods have attracted attention in the field of system identification, because they are essentially non-iterative (therefore, no convergence problems arise), fast and numerically robust (since they are only based on numerically stable techniques of linear algebra) (Favoreel et al., 1999). These methods accomplish substantial filtering of the data using eigenvalue or singular value decomposition and are particularly effective when there are closely spaced modes. In the EERA, the block Hankel matrices are built directly from the system input and output time history data, making the method faster and thus allowing identification in real time. The methods of identification in real time can be considered as particular cases of the traditional identification methods.

The identification in real time in the aeronautical industry is used when it is necessary to immediately observe the change that will occur in the modal parameters, making possible corrections in the procedures of the flight tests when the aircraft is still in flight. The advantages are: lesser cost, economy of time, minor disponibilization of resources and greater security in the tests. A typical example of application of these methods is the study of the conditions for the occurrence of flutter, allowing in such a way to establish the conditions of flight safety. The flight tests carried out for the study of flutter are dangerous due to the divergent oscillatory and destructive movements associated to the phenomenon. In De Marqui (2005), an application of the EERA method to identify the modal parameters that characterize flutter in a wing model was presented. Experimental wind tunnel tests with a rigid wing connected to a flexible device were carried out and the natural frequencies and damping factors had been identified considering the variation of the speed in the wind tunnel. The method EERA successfully identified the involved parameters in flutter. One another application of the identification in real time is in the active control of noise and vibration.

This paper presents a modal identification process in real time based on EERA. A brief mathematical description of the approach is given. The method EERA has bee applied to the data obtained from dynamic measurementes accomplished on an aluminum plate.

Extended Eingensystem Realization Algorithm Method - EERA

Any linear time-invariant dynamic system with n degrees-of-freedom can be modelled by the following discrete time state space equations:

$$\begin{cases} \{x(k+1)\} = [A_d]\{x(k)\} + [B_d]\{u(k)\} \\ \{y(k)\} = [C_d]\{x(k)\} + [D_d]\{u(k)\} \end{cases} \tag{1}$$

where $\{x(k)\}$ is the $2n$ dimensional state vector at the k^{th} sample instant, $\{u(k)\}$ is the r dimensional input vector, r is the number of external excitations, $\{y(k)\}$ is the m dimensional response vector, m is the number of outputs or responses of the system, $[A_d]$ is the $2n \times 2n$ system matrix, $[B_d]$ is the $2n \times r$ input matrix, $[C_d]$ is the $m \times 2n$ output matrix, and $[D_d]$ is the $m \times r$ direct transmission matrix.

Basically, the identification procedure using the EERA consists on the determination of the system matrix $[A_d]$ from the time history data of the inputs and the outputs. The identification of the system matrix $[A_d]$ using the EERA method is described by the following procedure.

The block Hankel matrices of inputs (U) and outputs (Y) can be obtained directly from the input and output time domain data, as observed in Eq. (2). The dimensions of these matrices are strictly connected to the length of inputs, N, and outputs time history, M, vectors (number of samples in a time window) that will be used during the identification process.

$$[U] = \begin{bmatrix} \{u(0)\} & \{u(1)\} & \cdots & \{u(N-1)\} \\ \{u(1)\} & \{u(2)\} & \cdots & \{u(N)\} \\ \vdots & \vdots & \vdots & \vdots \\ \{u(M-2)\} & \{u(M-1)\} & \cdots & \{u(M+N-3)\} \\ \{u(M-1)\} & \{u(M)\} & \cdots & \{u(M+N-2)\} \end{bmatrix}_{rM \times N} \quad [Y] = \begin{bmatrix} \{y(0)\} & \{y(1)\} & \cdots & \{y(N-1)\} \\ \{y(1)\} & \{y(2)\} & \cdots & \{y(N)\} \\ \vdots & \vdots & \vdots & \vdots \\ \{y(M-2)\} & \{y(M-1)\} & \cdots & \{y(M+N-3)\} \\ \{y(M-1)\} & \{y(M)\} & \cdots & \{y(M+N-2)\} \end{bmatrix}_{mM \times N} \tag{2}$$

One can verify that the block Hankel matrix of outputs are represented as (Verhaegen and Dewilde, 1992),

$$[Y] = [\Gamma][X] + [G][U] \tag{3}$$

where $[\Gamma]$ is an extended observability matrix, $[X]$ is a matrix of the state sequence, and $[G]$ is a block Toeplitz matrix of Markov parameters or impulse response, i.e.,

$$[\Gamma]=\begin{bmatrix}[C_d]\\ [C_d][A_d]\\ [C_d][A_d]^2\\ \vdots\\ [C_d][A_d]^{M-1}\end{bmatrix}_{mM\times 2n}\quad [X_d]=[\{x(1)\}\ \{x(2)\}\ \cdots\ \{x(N)\}]_{2n\times N}\quad [G]=\begin{bmatrix}[D_d] & [0] & \cdots & [0]\\ [C_d][B_d] & [D_d] & \cdots & [0]\\ [C_d][A_d][B_d] & [C_d][B_d] & \cdots & [0]\\ \vdots & \vdots & \vdots & \vdots\\ [C_d][A_d]^{M-2}[B_d] & [C_d][A_d]^{M-3}[B_d] & \cdots & [D_d]\end{bmatrix}_{mM\times rM} \tag{4}$$

By definition, the orthogonal matrix is written as (Van Overschee and De Moor, 1996),

$$[U]^{\perp}=[I]-[U]^{T}\left([U][U]^{T}\right)^{-1}[U] \tag{5}$$

Pre-multiplying and pos-multiplying Eq. (3) by the right and left terms of Eq. (5), respectively, it is simple to obtain:

$$[Y][U]^{\perp}=[\Gamma][X][U]^{\perp} \tag{6}$$

Applying the singular value decomposition in $[Y][U]^{\perp}$,

$$[Y][U]^{\perp}=[R][\Sigma][S]^{T} \tag{7}$$

where $[R]$ $(mM\times mM)$ is the matrix of the left singular vectors, $[\Sigma]$ are the corresponding singular values and $[S]$ $(N\times N)$ is the matrix of the right singular vectors. The columns of these matrices are orthonormal.

At this stage, a criterion to determine the number of necessary singular values can be stipulated. This number can be modified according to the difficulties involved in the identification process. This number will establish the dimension of the identified model and it must be modified according to the difficulties involved in the identification problem. Considering that the number of singular values is determined as $2n$, the matrix of singular values can be represented as:

$$[\Sigma_{2n}]=diag[\sigma_1,\sigma_2,\ldots,\sigma_{2n}] \tag{8}$$

So, the matrices can be written as

$$[\Sigma]=\begin{bmatrix}[\Sigma_{2n}] & [0]\\ [0] & [0]\end{bmatrix}\qquad [R]=[[R_{2n}]\ \ [R_0]]\qquad [S]^{T}=[[S_{2n}]\ [S_0]]^{T} \tag{9}$$

where $[R_{2n}]$ contains the first $2n$ columns of $[R]$ and $[S_{2n}]$ contains the first $2n$ columns of $[S]$.

Substituting Eq. (9) in Eq. (7) results,

$$[Y][U]^{\perp}=[[R_{2n}]\ \ [R_0]]\begin{bmatrix}[\Sigma_{2n}] & [0]\\ [0] & [0]\end{bmatrix}\begin{bmatrix}[S_{2n}]^{T}\\ [S_0]^{T}\end{bmatrix}=[R_{2n}][\Sigma_{2n}][S_{2n}]^{T} \tag{10}$$

The pseudoinverse of $[Y][U]^{\perp}$ can be obtained from Eq.(10) resulting in Eq. (11). Now, all elements in Eq. (10) are known, that is,

$$\left([Y][U]^{\perp}\right)^{\dagger}=[S_{2n}][\Sigma_{2n}]^{-1}[R_{2n}]^{T} \tag{11}$$

At this point, a shifted form of the block Hankel matrix of the output, or response, can be introduced as in Eq. (12). The dimensions of this new matrix are connected to the length of output time history vector (number of samples in a time window) that will be used during the identification process, but now this window is advanced one or more steps in time, as can be compared with the original block Hankel matrix of the output (cf. Eq. 2).

$$[Y_s]=\begin{bmatrix}\{y(1)\} & \{y(2)\} & \cdots & \{y(N)\}\\ \{y(2)\} & \{y(3)\} & \cdots & \{y(N+1)\}\\ \vdots & \vdots & \vdots & \vdots\\ \{y(M-1)\} & \{y(M)\} & \cdots & \{y(M+N-2)\}\\ \{y(M)\} & \{y(M+1)\} & \cdots & \{y(M+N-1)\}\end{bmatrix}_{mM\times N} \tag{12}$$

The shifted form of the block Hankel matrix of the output can be represented by (Verhaegen and Dewilde, 1992),

$$[Y_s]=[\Gamma_s][X]+[G_s][U] \tag{13}$$

where $[\Gamma_s]$ and $[G_s]$ are shifted versions of extended observability matrix and block Toeplitz matrix of Markov parameters, respectively:

$$[\Gamma_s]=\begin{bmatrix}[C_d][A_d]\\ [C_d][A_d]^2\\ [C_d][A_d]^3\\ \vdots\\ [C_d][A_d]^M\end{bmatrix}_{mM\times 2n} \quad\text{and}\quad [G_s]=\begin{bmatrix}[C_d][B_d] & [D_d] & \cdots & [0]\\ [C_d][A_d][B_d] & [C_d][B_d] & \cdots & [0]\\ [C_d][A_d]^2[B_d] & [C_d][A_d][B_d] & \cdots & [0]\\ \vdots & \vdots & \vdots & \vdots\\ [C_d][A_d]^{M-1}[B_d] & [C_d][A_d]^{M-2}[B_d] & \cdots & [D_d]\end{bmatrix}_{mM\times rM} \tag{14}$$

Following the same derivation used for Eq. (6), it is then possible to obtain Eq. (15). The term on the right side of this equation is easily obtained comparing the original and shifted versions of the observability matrices, that is, $[\Gamma_S] = [\Gamma][A_d]$.

$$[Y_s][U]^{\perp}=[\Gamma_s][X][U]^{\perp}=[\Gamma][A][X][U]^{\perp} \tag{15}$$

The block Hankel matrix of the output can be rewritten as,

$$[Y_S]=[Y_S][U]^{\perp}\left([U]^{\perp}\right)^{\dagger} \tag{16}$$

Considering that $\left([Y][U]^{\perp}\right)\left([Y][U]^{\perp}\right)^{\dagger}=[I_{2n}]$ and $\left([Y][U]^{\perp}\right)^{\dagger}\left([Y][U]^{\perp}\right)=[I_{2n}]$, Eq. (16) can be represented by:

$$[Y_S][U]^{\perp}=\left([Y][U]^{\perp}\right)\left([Y][U]^{\perp}\right)^{\dagger}[Y_S][U]^{\perp}\left([Y][U]^{\perp}\right)^{\dagger}\left([Y][U]^{\perp}\right) \tag{17}$$

Substituting Eq. (10) in Eq. (17), and considering the facts that $[\Sigma_{2n}]^{-1}=[\Sigma_{2n}]^{-1/2}[\Sigma_{2n}]^{-1/2}$ and the matrices $[R]$ and $[S]$ are orthonormal, then,

$$[Y_S][U]^{\perp}=[R_{2n}][\Sigma_{2n}]^{1/2}[\Sigma_{2n}]^{-1/2}[R_{2n}]^T[Y_S][U]^{\perp}[S_{2n}][\Sigma_{2n}]^{-1/2}[\Sigma_{2n}]^{1/2}[S_{2n}]^T \tag{18}$$

Equation (18) can be compared with Eq. (15) and then the following expressions are determined:

$$\begin{gathered}[\Gamma]=[R_{2n}][\Sigma_{2n}]^{1/2}\\ [A_d]=[\Sigma_{2n}]^{-1/2}[R_{2n}]^T[Y_S][U]^{\perp}[S_{2n}][\Sigma_{2n}]^{-1/2}\\ [X][U]^{\perp}=[\Sigma_{2n}]^{1/2}[S_{2n}]^T\end{gathered} \tag{19}$$

The system matrix $[A_d]$ is a minimum realization of the system. The dimension of this matrix is *2n* and it also determines the dimension of the identified system. This realization can be transformed to state equations in modal coordinates and then natural frequencies and dampings can be obtained. The above expression differs from the ERA expression only by the presence of the input term. When the responses are due to impulsive inputs, the expression is identical to the expressions observed in ERA.

Identification of Modal Parameters in Real Time using EERA

The experimental model used in this work is a square aluminum plate that was fixed in one of its sides between thick steel plates and all the set was fixed to an inertial base. Fig. 1 presents a photo of the plate, settings and the inertial base, and shows the environment of the test with the main used equipment.

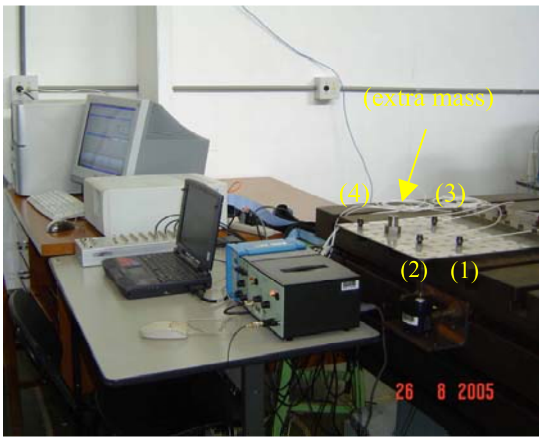


Figure 1 – Test environment.

For the accomplishment of the tests, the plate was marked with the localization of the single excitation point and the four acceleration measurement points. For the outputs, due to the availability of accelerometers in the laboratory, only four points had been chosen to get the data simultaneously. The localization of the input and output points had been determined in order that all the modes in the frequency bandwidth of interest were excited and measured.

Acquisition of the Experimental Data

The plate was excited using the B&K model 4810 electrodynamic shaker. The signal sent to the shaker was generated by a SignalCalc ACE four channels signal analyzer. The frequency of this signal used for excitation was a random one of limited bandwidth. The frequency bandwidth analyzed was limited between 0 and 250 Hz and the force sent to excite the structure was measured with a B&K model 8200 force transducer.

The vibration response was measured with four Kistler model 8636C10 piezoelectric accelerometers. It was used a Hanning window on the force signals and excitation. The force and acceleration signals, acquired in the time domain, were sent simultaneously to the acquisition and signals processing dSPACE®system.

In the tests, the SignalCalc ACE signals analyzer generated the input signal that was amplified by the B&K model 2706 power amplifier and fed to the B&K shaker that applied force to the structure. In order to measure the applied force, the B&K model 8200 force transducer was placed between the shaker and the structure. The accelerations were measured by the accelerometers fixed on the structure. All, transducer and accelerometers, had their signals amplified by the B&K model 2626 conditioner and amplifier and the Kistler Power Supply Coupler signals amplifier, respectively. The acquisition and the processing of these signals, as well as the identification of the modal parameters, were made by the dSPACE®system. For the identification, the EERA was implemented in the Simulink/MatLab® environment and then compiled for the system dSPACE® through the package RTW (Real Time Workshop), whose visual programming was carried out by the ControlDesk® software. The time between each acquisition used in this test was 0.001 second.

Experimental Tests and Results

The tests had as objective the identification, in real time, the natural frequencies of the aluminium plate. All the results presented in this work were obtained while the experimental tests were carried out, that is, the identification was done in real time. The interval of time used for acquisition and identification of each sampling in the test was 0,8s, that is, every 0,8s the signals proceeding from the identification process were updated. To do the identification with EERA, the dimension determined for the the block Hankel matrix of inputs was 91 lines (M=91 and r=1) by 182 columns (N=182) and for the block Hankel matrices of outputs (non modified and modified ones) 364 lines (M=91 and m=4) by 182 columns (N=182). The order of the estimated system was of $2n$=18.

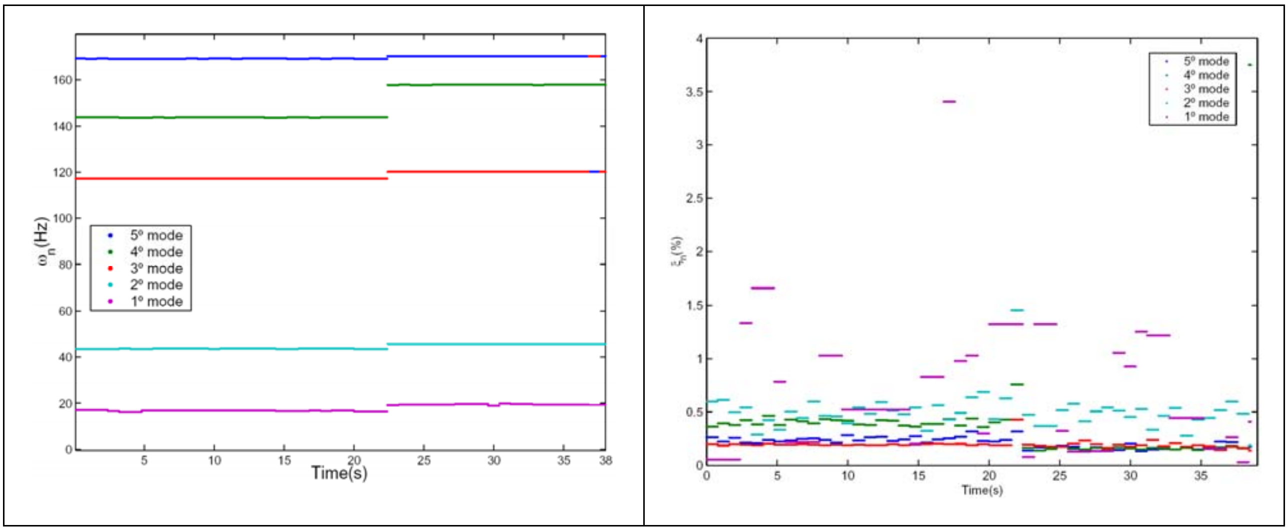
Initially, the structure was considered with an added extra mass of 212.42 gr and the objective of this test was to identify alteration in the modal parameters of the plate when this extra mass was removed. To do that, with the plate being exited, the data acquisition and the identification processes using EERA were started simultaneously and, after approximately twenty seconds, the extra mass was removed from the structure without interruption of signal capture and identification. The total duration of each run was approximately 40s.

Figs. 2 (a) and (b) present the results from the modal parameters identification process, where it is possible to observe the changes of the values of the natural frequencies and of the damping factors that occur around 23s, just after the extra mass was removed from the plate. It can be observed, as should be expected, that with a lighter structure, the values of the natural frequencies increase which can be also evidenced in Tab. 1. The alterations in terms of the natural frequencies can be better observed, whereas in terms of the damping factors the algorithm has difficulty in calculating it. The very low damping of the plate makes the overall damping difficult to be analyzed as well as to foresee which damping variation would occur and how it would change when its mass was modified. In this way, in this work, the results of the natural frequencies identification process will be the only to be presented.

Tab. 1 presents the values of the natural frequencies for the cases of the plate with and without addition of extra mass obtained in the experimental tests with off-line and on-line identification. The off-line results had been obtained in an experimental test carried out initially to validate the algorithm.

Table 1 – Values of the natural frequencies obtained by the EERA off-line and on-line, for the cases of the added mass and without the added mass.

With added mass		Without added mass	
off-line(Hz)	on-line(Hz)	off-line(Hz)	on-line(Hz)
17.75	16.78	19.50	19.46
42.75	43.62	45.90	45.60
115.75	117.21	121.10	120.14
143.00	143.70	157.50	157.86
168.00	169.20	172.40	170.20



(a) **(b)**

Figure 2- Identified modal parameters in real time: (a) natural frequencies;

(b) damping factors.

Next, a test was carried out during approximately 40s, where, during the first twenty seconds, the five modes of interest of the plate were identified and then, without interruption of the signal capture and the identification process, the extra mass was added to it. In this, one can observe that, in Figs 3 (a) and (b), when the mass is added the values of the natural frequencies diminish, as it was expected.

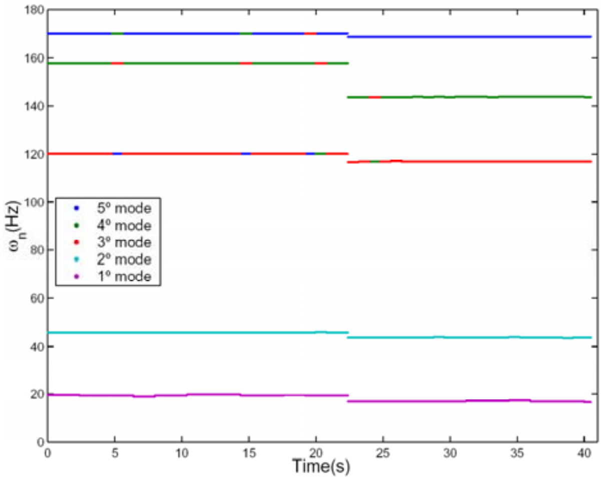


Figure 3- Identified natural frequencies in real time.

Away from the mass of 212.42 gr., located as it is shown in Fig. 1, another mass of 250.05 gr was added on the plate extremity, next to the exciter, as it can be observed in Fig. 4.

Figure 4 - Localization of the two masses added on the aluminum plate for the accomplishment of the tests.

In these tests, the frequencies of the plate were identified considering the two added extra masses but only the 250.05 gr. mass was removed and Fig 5 presents the results obtained in these identification processes.

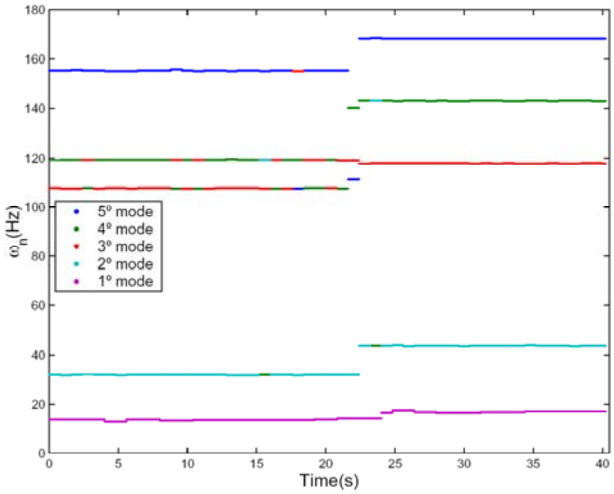


Figure 5. -Identified natural frequencies in real time.

It is observed in the Fig. 5 that during the identification process there is a variation in the order the modes are identified, what probably is due to the noise generated because of the fact the masses and the structure being slack. Just after the removal of the mass at around 24s, the changes in the values of the modes were identified, with exception for the first mode which variation will only be identified 1.6s later, that is, after two steps of the process of acquisition and identification.

Fig. 6 present the results of Average Power Spectrum – APS applied to the total set of FRFs obtained in this test, considering the two masses added to the structure. This graph alows the visualization of the natural frequencies of the structure with the two added extra masses.

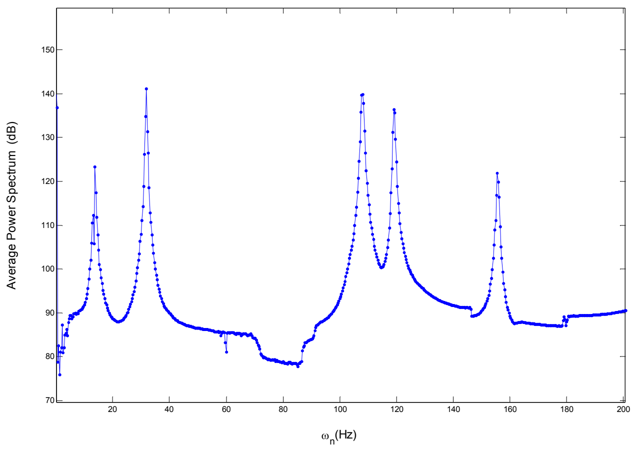


Figure 6. Average Power Spectrum (APS) obtained with two mass added to the aluminum plate.

Tab. 2 presents the natural frequencies values of Fig. 5 with all the extra masses on and the corresponding ones identified using the FRFs of the signals of Fig. 6.

Table 2 - Values of the natural frequencies (Hz) considering the two extra masses added to the structure.

Natural frequencies obtained by the FRFs	Natural frequencies obtained by the EERA in real time
13.75	13.55
31.84	31.90
108.12	107.70
119.06	119.20
155.53	155.50

The accelerometers and the masses positions were modified accordingly to Fig. 7. In this case the values of the natural frequencies had a bigger variation as it can be evidenced in Tab. 3.

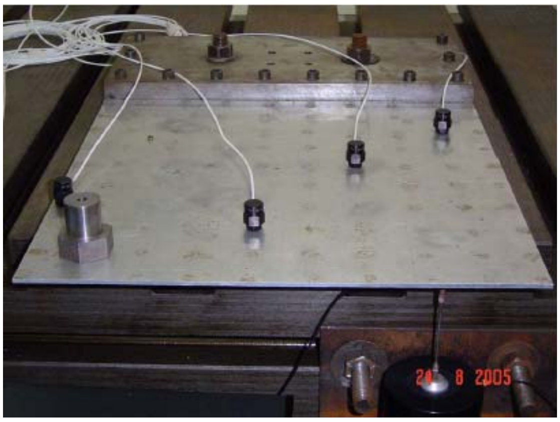


Figure 7. - Modified position of the accelerometers and the mass.

Table 3 – Values of the identified natural frequencies using FRFs when the positions of the accelerometers and the mass were changed on the aluminium plate according to Fig. 7.

Natural frequencies obtained using FRFs (Hz)
15.63
37.50
152.50
132.82
158.44

This variation can also be observed in Fig 8.

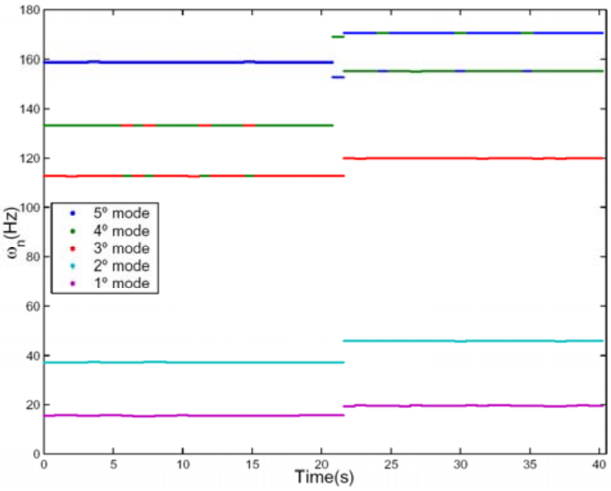


Figure 8. - Identified natural frequencies in real time.

CONCLUSIONS

The experimental tests in the aluminum plate were carried out to verify the efficiency of the EERA in identifying, in real time, the modal parameters of this structure. The EERA was implemented in the dSPACE® system and the input and output experimental data have been obtained directly in the time domain, being the process of identification carried out in real time. The results obtained with the identification, using the EERA, revealed to be satisfactory and coherent confirming the efficiency of the considered method. During the identification process tests with extraction and addition of mass, it could be observed that the algorithm identified the changes in terms of natural frequencies when the structure suffered the alterations. This can be observed through the presented graphs and occurred in all the cases considered in this work.

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