VARIATION OF THE PARAMETERS INVOLVED IN THE PROCESS OF IDENTIFICATION IN REAL TIME IN EXPERIMENTAL TESTS

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Abstract. *In the Aeronautical Industry, the project and the development of adequate structures are of extreme importance, being the dynamic behavior of these structures one of its most important aspects. The aerospace structures must be submitted to some form of verification before flight, to assure that the aircraft is free of any aeroelastic instability phenomenon, which, when occurring, will provoke structural fatigue problems or failure, such as flutter. The accurate and fast identification of the modal parameters allows determining, with antecedence and security, the flight conditions where the flutter phenomenon will occur. In this work an experimental test, in real time, with an aluminum plate, was carried out to identify natural frequencies and damping factors. The results obtained in the process of identification in real time, considering the variation of the involved parameters, the dimension of the block Hankel matrix and the order of the estimated system, are presented. The method of identification used for this study is the EERA - Extended Eigensystem Realization Algorithm, a time domain method of identification, considered efficient and powerful, since it is capable to identify complex dynamic behavior in structures. The method EERA calculates the modal parameters using input and output time histories data.*

Keywords*: Identification, Real Time, EERA.*

1. INTRODUCTION

In the Aeronautical Industry, it is of extreme importance the quality and the performance of its products, which directly are related to the project and the development of the adjusted structures. Therefore, beyond their functional character, their integrity in the most diverse operation conditions must also be guaranteed. Their dynamic behaviour is one of their main aspects, mainly due to continuous demand for lighter and consequently more flexible structures. Traditionally, 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, wich can occur provoking structural problems of fatigue or failure. One of the more important instability phenomena is called flutter.

Flutter is a phenomenon of aeroelastic instability where the interaction between the aerodynamic, elastic and inertial forces leads to divergent oscillatory movements and in some cases to destructive ones (Bisplinghoff et al., 1996). The techniques of flight tests for flutter identification are of extreme importance for the knowledge of the limits of safe flight. However these tests are dangerous due to the divergent oscillatory and destructive movements associated to the phenomenon. One of the essential elements for the accomplishment of flutter tests in flight is the process of identification of the structural modal parameters 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, in real time, the identification of the modal parameters associated to flutter.

The methods of identification in real time can be considered a particular case of the traditional methods of identification. Modal parameters estimation of mechanical systems is a special case of system identification (Ljung, 1987). To identify the modal parameters of mechanical systems, many algorithms for identification of linear systems in state space have been developed. Among this group one can distinguish the algorithms in the time domain called Subspace Identification Methods (Van Overschee, 1996). The development of these subspace identification methods is motivated by difficulties in estimating modal parameters of 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 systems 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. Examples of such methods in the structural dynamics community are the Eigensystem Realization Algorithm – ERA (Juang and Pappa, 1985), the Polyreference Time Domain Algorithm (Deblauwe, Brown and Allemang, 1987) and the Extended Eigensystem Realization Algorithm (EERA) (Tasker, Bosse and Fisher, 1998).

The EERA method is a modified form of the ERA one that calculates the modal parameters by manipulating both input and output time histories. 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. 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 air speed in the wind tunnel. The method EERA successfully identified the parameters involved in flutter.

In this work an experimental test, in real time, with an aluminum plate, was carried out to identify natural frequencies and damping factors using the EERA method. The obtained results considering the variation of the parameters involved in the process of identification in real time, i.e. the dimension of the block Hankel matrix and the order of the estimated system, are presented.

2. 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:

$$\begin{aligned} \{x(k+1)\} &= \lfloor A_d \rfloor \{x(k)\} + \lfloor B_d \rfloor \{u(k)\} \\ \{y(k)\} &= \lfloor C_d \rfloor \{x(k)\} + \lfloor D_d \rfloor \{u(k)\} \end{aligned} \tag{1}$$

where $\{x(k)\}$ is the $2n$ dimensional state vector at the kth 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 the system responses, $\lfloor A_d \rfloor$ is the $2n \times 2n$ system matrix, $\lfloor B_d \rfloor$ is the $2n \times r$ input matrix, $\lfloor C_d \rfloor$ is the $m \times 2n$ output matrix, and $\lfloor D_d \rfloor$ is the $m \times r$ direct transmission matrix.

Basically, the identification procedure using the EERA consists on the determination of the system matrix $\lfloor A_d \rfloor$ from the time history data of inputs and outputs. The identification of the system matrix $\lfloor A_d \rfloor$ 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, M, time history 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.,

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

$$[X] = [\{x(1)\} \quad \{x(2)\} \quad \cdots \quad \{x(N)\}]_{2n \times N} \tag{4}$$

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 to $[Y][U]^{\perp}$,

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

where $[R]$ $(mM \times mM)$ is the matrix of the left singular vectors, $[\Sigma]$ $(mM \times N)$ 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 process.

Considering that the number of singular values is determined as *2n* the matrix of singular values can be represented as:

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

So, the matrices can be written as:

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

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,

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

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 outputs, or responses, can be introduced as in Eq. (12). The dimensions of this new matrix are connected to the length of the output time history vector (i.e. the number of samples in a time window) that will be used during the identification process. This window is advanced one or more steps in time, as can be compared with the original block Hankel matrix of the outputs (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 outputs 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) where the term on the right side is easily obtained comparing the original and the shifted versions of the observability matrices, that is, $[\Gamma]_S = [\Gamma][Ad]$.

$$[Y]_S[U]^{\perp} = [\Gamma]_S[X][U]^{\perp} = [\Gamma][A][X][U]^{\perp} \tag{15}$$

The block Hankel matrix of the outputs 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 rewritten as:

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

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:

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

The system matrix $[Ad]$ is a minimum realization of the system. The dimension of this matrix is *2nx2n* and it also determines the dimension of the identified system. This realization can be transformed to state space equations in modal coordinates, and, natural frequencies and damping 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, this expression is identical to the expressions observed in ERA.

3. IDENTIFICATION OF MODAL PARAMETERS IN REAL TIME USING EERA

The experimental model used in this work is a square aluminium 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.

For the accomplishment of the tests, the plate was marked with the localization of the single excitation point and four acceleration measurement points. For the output, due to little 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, respectively. Moreover, for the accomplishment of the tests, an extra mass of 212,42 gr was added with the objective of identifying the modal parameters with and without this extra mass.

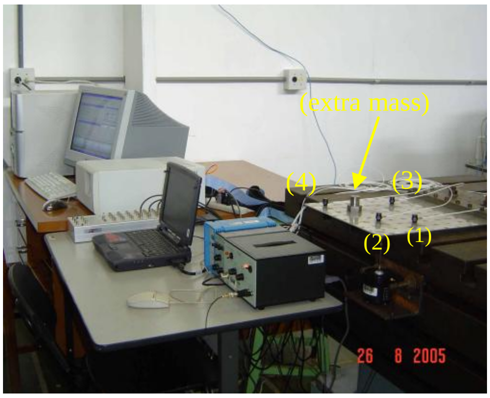

Figure 1 – Test environment.

3.1. Acquisition of the Experimental Data Section

The plate was excited using a 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 considered for analysis 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 dSPACE® acquisition and signals processing system. This dSPACE DS1005 processor board is equipped with a PowerPC processor of 400 Mz and 128 Mbytes of RAM. This system possesses two processing boards, the DS2003 that possesses two A/D converters of 16 bits resolution, 32 I/O multiplexed channels and the DS2102 with 6 output D/A channels of 16 bits resolution.

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 the 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 to 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.

3.2. Experimental Verification of the EERA Method - Results

The experimental tests had as objective the identification, in real time, of 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 was 0,8s, what means that at every 0,8s the signals proceeding from the identification process were updated. Initially, to do the real time identification with EERA, the dimension determined for 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 $2n$ = 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 them. 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 the mass was modified. So, in this work, the results of the natural frequencies identification process will be the only to be presented.

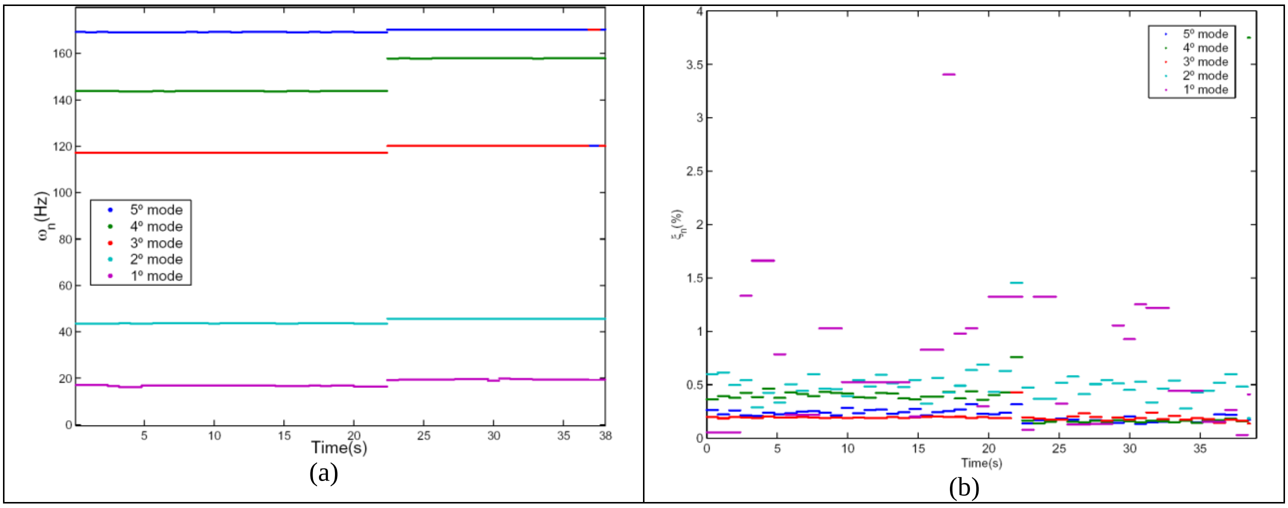

Figure 2- Identified modal parameters in real time when mass was subtracted: (a) natural frequencies; (b) damping factors.

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 when considering off-line and on-line identification. The off-line results had been obtained in an experimental test carried out initially to validate the algorithm and can be seen in Rebolho (2006).

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

With added mass		**Without added mass**	
off-line	*on-line*	*off-line*	*on-line*
16.78	16.78	20.71	19.46
42.92	43.62	45.82	45.60
116.04	117.21	119.60	120.14
142.86	143.70	156.14	157.86
167.88	169.20	170.20	170.20

After experimental tests had been carried through to verify the efficiency of the method during the variation of the parameters necessary to realize through the identification process, the parameters are the dimensions of the block Hankel matrices and the order of the estimated system.

These tests carried through during 60s, had been divided in agreement with Tab. 2, where in each interval of time it got excited dimension of the matrices of Hankel and the order of the system. In the accomplishment of the tests, first it is considered the mass added to the structure and then without the addition of this mass. Fig. 3 (a) and (b) present these results.

Table 2 - Variation of the parameters involved in the identification process.

Time(s)	Dimension of the block Hankel matrices - M	Order of the estimated system – 2n
0 - 10	100	25
10 - 20	95	25
20 - 30	95	22
30 - 40	91	22
40 - 60	91	18

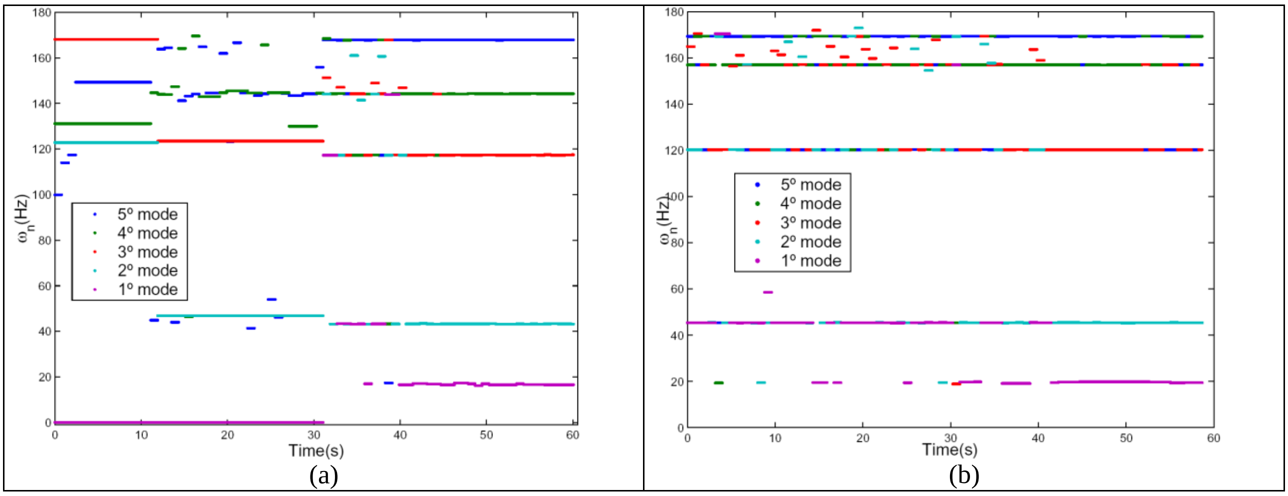

Figure 3- Natural frequencies identified in real time: (a) with extra mass; (b) without extra mass.

The identified modes shown in Fig. 3 (a) and (b) can be compared with the modes presented in Table 1. In the case when the structure is considered with the added extra mass, Figure 3 (a), one can observe that until 40s there is much variation in the identification and only some desired modes are identified. The second mode is identified after the 10 first seconds and the first mode only after 40s. However, without the extra mass added the structure, Figure 3 (b) , an improvement in the identification process has happened, but only after 40s it stabilizes.

Finally, another test was carried out to try to diminish the values of the dimensions of the Hankel matrices and of the order of the system, to verify how the system would react during the identification process. The tests had been carried out with and without the mass added on the plate. The acquisition time was of 60s divided in lesser intervals, as Tab. 3, for some parameters of *M* and *2n*. Figures 4 (a) and (b) present these results.

Table 3 - Variation of the parameters involved in the identification process.

Time(s)	**Dimension of the block Hankel matrices - *M***	**Order of the estimated system – *2n***
0 - 10	91	18
10 - 20	85	25
20 - 30	85	15
30 - 40	70	15
40 - 50	50	15
50 - 60	50	10

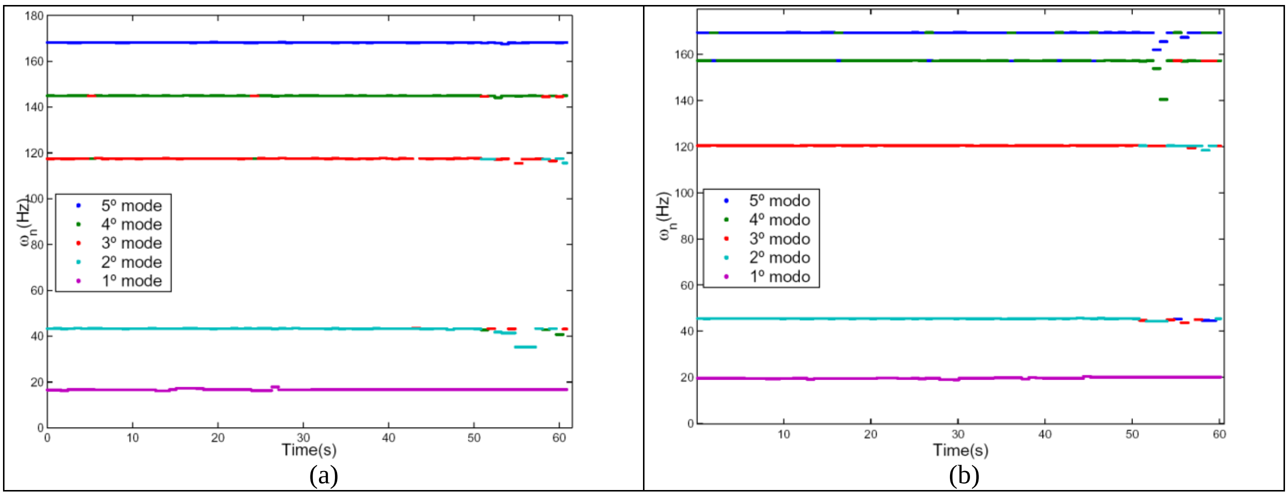

Figure 4- Natural frequencies identified in real time: (a) with extra mass; (b) without extra mass.

Looking at Table 1 it is possible to observe and to compare the identified modes presented in Fig. 4 (a) and (b). It is possible to observe that until 50s the identification of the five modes analyzed in this work is good, and after this time there is a small deterioration in the identification, however the modes continue to be identified. This must be due to the fact that the dimensions of the Hankel matrices and the order of system, *2n*, are not adequate to perform the identification in a satisfactory way.

4. CONCLUSIONS

In this work, in order to verify the effectiveness of the EERA method to identify, in real time, the natural frequencies when there is variation of the involved parameters, i.e., the dimension of the block Hankel matrix and the order of the estimated system, experimental tests were carried out, using for that an aluminum plate. In the experimental tests, in real time, the dSPACE® system was used and the input and output experimental data had been obtained directly in the time domain, being the process of identification carried out also in real time. During the identification process tests with subtraction and addition of mass, it could be observed that the algorithm identified the changes in terms of natural frequencies and damping at the precise moment when the structure suffered the alterations. 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 them. In relation to the variation of the involved parameters in the identification process, one could observe that it was not possible to identify all the modes simultaneously depending on the variation of these parameters. This occurred mainly with the increase of the value of these parameters and in the case where they diminished much. The results, obtained with the identification, using the EERA, revealed to be satisfactory and coherent confirming the efficiency of the considered method, and showed that the algorithm presented good performance when applied to experimental data.

4. ACKNOWLEDGEMENTS

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