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Detection of structural alterations in metal bodies: An approximation using Fourier transform and principal component analysis (PCA)

Detección de alteraciones estructurales en cuerpos metálicos: una aproximación mediante transformada de Fourier y análisis de componentes principales (PCA)

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Abstract— **In this theme some advances have been developed, verified in the background, where attempts have been made to determine the existence of structural alterations such as perforations, defective welding and dents in metal structures; a pattern of mechanical vibration that allows to differentiate each alteration has not yet been clearly defined. In this work, the data taking was carried out taking into account the position of the sensors, two beams were added without alteration, in order to be able to interact with the five configurations, which were adopted for the experimental design. To the tests of repeated measurements, in each configuration, analysis (ANOVA) was used for the validation of NULL hypotheses, and thus to determine the number of tests to be treated. After having the defined matrices representing each configuration, in each anomaly, it is necessary to apply the principal component Analysis (PCA), to the data obtained by the calculation of the fast Fourier transform (FFT). And thus, determine the number of components by means of three Criteria (Jollife, Kaiser and PVA), using a classification algorithm, which evaluates the percentage of classification vs lower standard deviation. In this analysis the descriptors were not calculated but the main components of each criterion were taken as a description tool. The process of extraction of characteristics was fundamental to determine the proper configuration in each alteration (fissure, welded, perforated, deformed). On the other hand, statistical parameters were calculated (average, standard deviation, variation factor, Euclidean distance) of each anomaly. Taking as descriptors. Finally, it was shown that the Jollife criterion is the one that allows to better differentiate between components associated with each alteration studied**

Index Terms— **Fast Fourier transform (FFT), Metal bodies, principal components analysis (PCA), structural alterations.**

Resumen—**En este tema se han realizado diversos trabajos buscando identificar un rasgo distintivo de las alteraciones en estructuras metálicas, que permita reconocer tipo de alteración con el fin de prevenir fallas (detección temprana). En este trabajo se ha abordado la temática desde la perspectiva del análisis vibracional empleando la transformada de Fourier y el análisis de componentes principales; incluyendo las alteraciones por perforaciones, abolladuras y soldadura defectuosa. En este trabajo, la toma de datos se realizó teniendo en cuenta la posición de los sensores, se agregaron dos piezas sin alteración, para poder interactuar con las cinco configuraciones, que se adoptaron para el diseño experimental. Para las pruebas de repetibilidad, en cada configuración, se utilizó el análisis (ANOVA) para la validación de hipótesis nula y, por lo tanto, para determinar el número de pruebas a tratar. Después de tener las matrices definidas que representan cada configuración, en cada anomalía, es necesario aplicar el análisis de componentes principales (PCA) a los datos obtenidos mediante el cálculo de la transformada rápida de Fourier (FFT). Y así determinar el número de componentes mediante tres Criterios (Jollife, Kaiser y PVA), utilizando un algoritmo de clasificación, que evalúa el porcentaje de clasificación frente a la desviación estándar más baja. En este análisis, los descriptores no se calcularon, pero los componentes principales de cada criterio se tomaron como una herramienta de descripción. El proceso de extracción de características fue fundamental para determinar la configuración adecuada en cada alteración (fisura, soldada, perforada, deformada). Por otro lado, se calcularon los parámetros estadísticos (promedio, desviación estándar, factor de variación, distancia euclidiana) de cada anomalía, tomando los mismos como descriptores. Finalmente, se demostró que el criterio de Jollife es el que permite diferenciar mejor entre componentes asociadas a cada alteración estudiada.**

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***Palabras claves*— Análisis de componentes principales, alteraciones estructurales, Cuerpos Metálicos, transformada rápida de Fourier.**

I. INTRODUCTION

A VIBRANT structure has four basic properties: mass, stiffness, damping and displacement. A mechanical vibration is the oscillation of the mass around its equilibrium point. The nature of the oscillation is determined not only by the mass but also by the rigidity and damping characteristic of the structure. In theory, the mass may be an infinitesimal particle, such as a condensed mass, and the damping may be absent. In practice, the mass of a mechanical structure has weight and spatial dimensions, and damping is always a factor to consider. Mechanical vibrations appear when the structure is disturbed from its equilibrium position by applying either a pulse or periodic excitation [1].

On the other hand, vibrations can be observed in time or frequency [2]. When measuring the vibration level, it is necessary to define what physical magnitude you want to quantify to describe the vibration. The time domain and the frequency domain are related through Fourier analysis, as well as an analysis of the spectral representation of signals, they will contribute to obtain the level of vibration for each structural anomaly, being a determining factor to develop techniques for mitigate the impact of the condition on metal structures as it is in this case. In this sense, the scientific community has developed different strategies for the health monitoring of these structures that range from the application of ultrasound techniques [3], modal analysis [4], fractal models in the detection of clearances [5], as well as the use of RFID chips for the detection of cracks in metals [6], among other studies on rotors and armor [7], [8] , [9]. In this order of ideas, initiatives have emerged to analyze the condition of the structures in order to avoid future failures. Thus, in the present work we propose to characterize structural anomalies (deformation, welding, cracking, perforations) that presents a structure under study, using the Fourier transform and the analysis of main components applied to the spectrum. In this order of ideas, the description of the structure under study, as well as the instrumentation and measurement software, the analysis of the Fourier coefficients and the main components found at these coefficients, the extraction of characteristics and descriptors of each alteration will be shown. and results evaluation between characteristics with a classification algorithm [10].

II. MATERIALS AND METHODS

A. Study structure and test cases

Steel structure with an angle of 1” x1 / 8” with a height of 1.70 meters and a base of 41x41 cm, has two diagonal supports to simulate alterations due to bad welding and fissure, and two other horizontal supports to simulate alterations due to deformation and excess of perforations in the support (figure 1 a and 1 b).

Fig 1. a. Structure. b Test Cases

B. Exciter module, control circuit and power circuit

A bell is used as an exciter module as shown in the Fig 2.a, which works with the principle of electromagnetic induction. The flow generated by the coil is concentrated in the ferromagnetic center which is mobile (Figure 2.a).

On the other hand, a circuit is used to control the vibration generator power system through the Labview program for which the maximum output signal of the USB- was taken into account.

6008 + 5V, voltage and intensity of the vibrating equipment 110V. (figure 2 b)

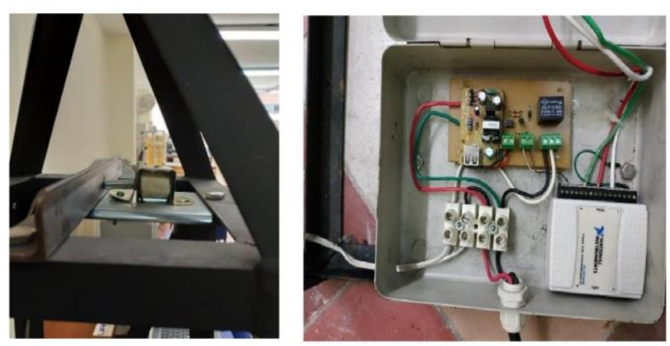

Fig. 2. a. Shutter or excitation module. b. Control circuit

C. Measuring instruments and software

3 Standar KS-64 sensors were used as shown in the figure. For the monitoring of the vibrations in the project, its easy coupling to the structure, allows maneuvering with all possible configurations in which the experimental design was worked (Fig. 3 a). An interface developed in LabVIEW is managed for data acquisition. Figure 3.b and 3.c show the block diagram and the front panel of the interface, respectively

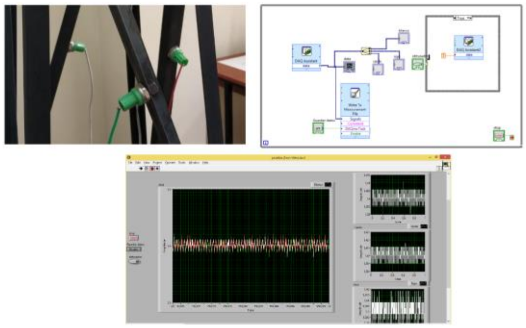

Figure 3.a. Sensors, 3.b Blocks diagram, 3.c Front Panel

D. Methods (Data collection, Fourier coefficients and obtaining the principal components)

The methodology was based on inducing a voltage of 0-5 vdc to activate the shutter, through the interface and obtain the vibration measurements with each of the configurations proposed in the design, for each alteration. The calculation of the Fourier coefficients and the obtaining of the principal components of the data sets are obtained through MATLAB and also the classification algorithm and the comparison of the alterations at the end of the method.

Data collection was carried out taking into account the position of the sensors, two additional beams were ordered to interact with the 5 configurations (figure 4) (location of the sensors: white, red and green), which were adopted for the experimental design. In each one, 5 runs of the program were made, taking 1,000 samples per second. To get 5,000 samples per configuration, for a total of 25,000 samples per anomaly.

Figure 4. Sensor configuration (left to right= one to five)

To obtain the main components, it should be noted that the objective is to reduce the size of the set of input data attempted to maintain as much information as possible in order to analyze them more easily and that in later stages, such as classifiers or regressors [11], can simplify the following criteria for decision or component selection. Jollife criteria: Only components whose variance is greater than 0.7 are retained. Kaiser criteria; Components whose variance is greater than average is retained. Accumulated Variance Criteria: Components whose Variance is greater than 20% of the total accumulated variance of all components are retained.

On the other hand, the technique used to evaluate the results of the statistical analysis and ensure that they are independent of the partition between training and test data. In each of the k iterations of this type of validation an error calculation is performed. The final result is obtained from the arithmetic mean of the K values of errors obtained, according to equation 1.

$$E = \frac{1}{k}\sum_{i=1}^{k} MSE_i \qquad (1)$$

Figure 5 shows the algorithm that allows the calculation of the Fourier coefficients and the analysis of main components.

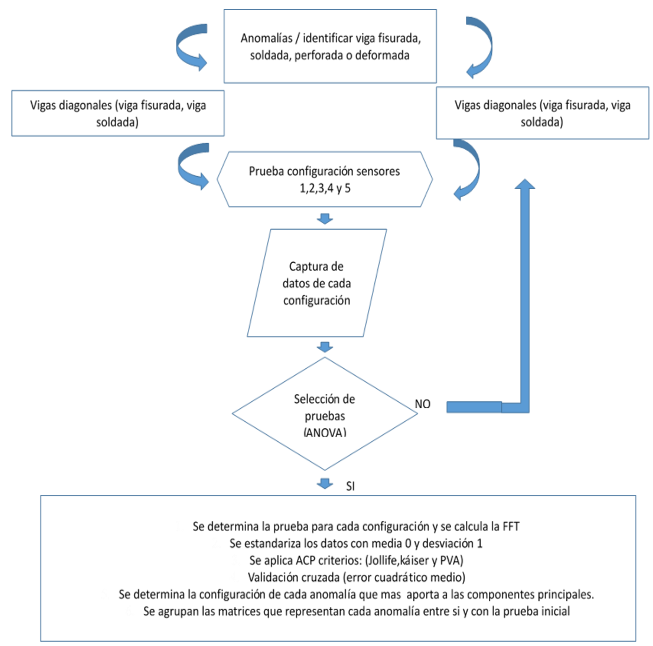

Fig.5. Algorithm for analysis

III. RESULTS

The tests consisted in the application of the 3 criteria to retain the components main alterations (cracked beam, welded, perforated and deformed) and from they select the sensor configuration that more information I provide according to the related feature in each variable. The results of the cross validation for algorithm testing. In Table I

TABLE I
TEST RESULTS

Criteria	Ranking percentage	standard deviation
FISURED BEAM		
Joliffe	93.49	1.8
Kaiser	91.88	1.34
PVA	88.87	1.09
WELDED BEAM		
Joliffe	93.19	1.32
Kaiser	91.46	1.28
PVA	89.13	0.6
DRILLED BEAM		

Joliffe	96.23	1.06
Kaiser	94.64	0.96
PVA	88.89	0.58
	DEFORMED BEAM	
Joliffe	92.95	1.65
Kaiser	93.08	1.6
PVA	88.88	1.49

In the cracked, welded and perforated anomalies, the jollife criterion and in the deformed one, the Kaiser criterion, obtain the best performance indicating a higher percentage of classification vs a lower standard deviation (data dispersion), but it is noted that the greatest decrease in variables The criterion of Percentage of accumulated variance (PVA) was obtained with an average number of 4 retained components, but its behavior against the percentage of successes was lower.

Similarly, for comparison between anomalies, the sensors are first labeled with the following initials and subscript.

Diagonal cracked beam sensors = B1, R1, V1

Welded diagonal beam sensors = B2, R2, V2

Perforated horizontal beam sensors = B3, R3, V3

Deformed horizontal beam sensors = B4, R4, V4

For each anomaly, the sensor configuration was chosen that provides more information on the main components: data matrices from Fourier.

Cracked anomaly beam (configuration # 4)
Beam welded anomaly (configuration # 3)
Perforated anomaly beam (configuration # 1)
Deformed anomaly beam (configuration # 1)

The sensors were grouped together to calculate the averages, standard deviations, variation factor, comparison of average distance between anomalies and obtain the following results(see table II).

TABLE II
STATISTICS FOR EACH SENSOR

	AVERAGES	
WHITE SENSOR	RED SENSOR	GREEN SENSOR
0.3507	0.5316	0.4203
0.6071	0.3731	0.4418
0.4553	0.4119	0.5764
0.3841	0.4890	0.3729
	STANDARD DEVIATION	
0.1770	0.2162	0.2028
0.2160	0.1865	0.1988
0.2123	0.2081	0.2139
0.1803	0.2116	0.1739
COEFFICIENT OF VARIATION % WHITE SENSOR		
50.46 ; 35,58 ; 46.83 ; 46.93		
COEFFICIENT OF VARIATION % RED SENSOR		
40.67; 49.98; 50.52; 43.26		
COEFFICIENT OF VARIATION % GREEN SENSOR		
48.24; 45.22; 37.10; 46.64		

For the comparison between anomalies, the average main components were taken and compared between each anomaly with each other and also with respect to the beam without apparent alterations (Table III).

TABLE III
DISTANCES BETWEEN DESCRIPTORS

Distance descriptor: white sensor					
B1-B2	B1-B3	B1-B4	B2-B3	B2-B4	B3-B4
0.2564	0.1026	0,0334	0,1537	0,2229	0,0692
Distance descriptor: red sensor					
R1-R2	R1-R3	R1-R4	R2-R3	R2-R4	R3-R4
0.1585	0.1198	0,0426	0,0387	0,1158	0,0771
Distance descriptor: green sensor					
V1-V2	V1-V3	V1-V4	V2-V3	V2-V4	V3-V4
0.00215	0.1198	0,0474	0,1347	0,0689	0,2036

The experimental design aimed to analyze two different scenarios; one without damage (initial conditions without alterations) and another with an established damage that is represented by each anomaly in the structure, a method was used alternating the position of the sensors to obtain the greatest possible information of each test and to be able to determine the differences against at each alteration vs without alteration.

In Table IV, both the beam averages without anomalies and the distances with respect to the other characteristics evaluated are subtracted.

TABLE IV
DISTANCES WITHOUT ALTERATION VS WITH EACH ANOMALY

Results averages: without alterations			
White Sensor	Red Sensor	Green Sensor	
0,5739	0,6214	0,3795	
Distance descriptor: white sensor			
B0-B1	B0-B2	B0-B3	B0-B4
02.232	0.0332	0.1206	0.1897
Distance descriptor: red sensor			
R0-R1	R0-R2	R0-R3	R0-R4
0.0898	0.2482	0.2095	0.1324
Distance descriptor: green sensor			
V0-V1	V0-V2	V0-V3	V0-V4
0.0408	0.0623	0.197	0.0066

IV. Conclusions

During the tests carried out, it is concluded that: The analysis of the cracked anomaly, the jollife criterion retained 6 characteristics or CP, which determined two parameters: one determined by the red sensor that provides more information and is located in the anomaly beam and the other by the green sensor, which has a participation in characteristic number 5 and number 6. On the other hand, component number 3 weighs; that is, the variable (R4) with a value of 0.786 has a large absolute value and in component number 6 the variable (V4) with a value of 0.643, according to this result, configuration number 4 is chosen, as the location of sensors that contribute more to this analysis of main components.

The analysis of the welded anomaly, also the Jollife criterion retains 6 characteristics or CP, which determined two parameters: one determined by the red sensor that provides more information and is located on the beam of the anomaly and the other the green sensor, which has a participation in the CP number 6. Component number 3 weighs; that is, it has a large absolute value, the variable (R3) with a value of 0.760 and in component number 6 the variable (V3) with a value of 0.80, according to this result, configuration number 3 was chosen.

The analysis of the perforated anomaly, the Jollife criterion retains 9 characteristics or CP, which determined me three parameters: determined by the red sensor, the green sensor (located in the anomaly) and the white sensor. Component number 5 weighs; that is, the variable (R1) with a value of 0.80 has a large absolute value, in component number 8 the variable (V1) with a value of 0.565 and in component number 6 the variables (B1) with a value of 0.597, according To this result, configuration number 1 was chosen.

The analysis of the deformed anomaly, the Kaiser criterion behaves as the best classification criterion, retains 6 characteristics or CP, which determined two parameters: determined by the red sensor and the other by the white sensor, component number 4 weighs; that is, the variable (R1) with a value of 0.76 has a large absolute value and in component number 6 the variable (B1) with a value of 0.90, in this configuration the green sensor (located in the anomaly) has no weight or relation with the other two variables. . According to this result, configuration number 1 was chosen.

On the other hand, according to the results obtained from the calculations of averages, standard deviation, variation factor and distance between observations, it is determined that the method is adequate in the detection of damage, distinguishes the results between beams with anomaly and results of the structure in a healthy state (without alterations) with those of each beam in an altered state.

Finally, a study has been carried out to identify characteristics that are differentiable from each other. In this first approach the analysis of main components was used, managing to find some components that could be characteristic. However, to determine a pattern associated with some alteration is still an open topic.

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