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OPTIMAL SENSOR PLACEMENT METHODOLOGY FOR OPERATIONAL MODAL SYSTEM IDENTIFICATION OF A HYPERBOLIC PARABOLOIDAL FABRIC

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ABSTRACT

This paper presents a numerical pre-test that considers finite element modelling and optimal sensor placement study for a singular spatial truss structure field vibration test. The singularity and importance of such structure require easier, quicker and cheaper monitoring methods. Vibration-based health monitoring methods determine the modal characteristics of the structure via a limited number of sensors. These characteristics are intrinsic properties, so that a variation in them may be induced by structural damage. Only a limited number of degrees-of-freedom can be measured for the system identification process. By developing a finite element model for the spatial truss structure, these degrees-of-freedom can be identified. Based on these results, Effective Independence Method (EFI) method is employed to determine the optimal sensor number and locations. This methodology is formulated with the use of the modal properties of the structure, where the independence of the target modal shape matrix is maximised in an iterative process, and those degrees-of-freedom that do not contribute to the independence of the target modes are eliminated. It is concluded that utilising just a few number of sensors the result of placement location is improved for structural health monitoring purposes.

KEYWORDS : *Optimal Sensor Placement, System Identification, Modal Analysis.*

INTRODUCTION

Sensor placement in a host structure is an important initial step in the field of experimental modal analysis (EMA) and in particular in operational modal analysis (OMA) [1, 2]. Applications with wired and wireless methodologies necessarily need a planned methodology to locate the sensors. This sensor location can either be permanent for permanent monitoring, or can be temporary in the case of roving sensor monitoring. Furthermore, Structural Health Monitoring (SHM) techniques require an optimal number of sensors for system identification, structural damage identification, and finite element model updating.

An optimal sensor placement methodology for system identification of a Hyperbolic Paraboloidal (hypar) fabric structure is presented. The structure under consideration is a roof for a multifunctional sport court whose construction took place in 2010 in Seville, Spain. The covering of this surface of 46.00 x 24.00 m. is solved with a pre-stressed textile surface consisting of four hypar frames in a metal tubular structure. The structural behaviour is assessed by ambient vibration testing (also called operational modal analysis (OMA)). In OMA, the measurement locations and the number of measurements are of vital importance for data accuracy. The number of measurement points is limited to the number of accelerometers employed, therefore ambient vibration testing of big structures such as this requires several set ups, with each one including several fixed reference

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points. Using a robust finite element model of the present structure, optimal sensor placement algorithms are run to identify the ideal measurement points to improve the quality of the measured data. PolyMax system identification algorithm [3] is employed to extract the modal parameters from the ambient data. The modal parameters are compared between optimal sensor placement and an extensively setup. This methodology has previously been tested numerically but in this paper the results confirm the application experimentally on a full scale structure.

1 DESCRIPTION OF THE STRUCTURE

The structure under consideration is the roof for a multifunctional sport court whose construction took place in the year 2010 in Seville, Spain [4]. The structural layout plan can be seen in Fig. 1.

The covering of this surface is solved with a pre-stressed fabric consisting of four Hyperbolic Paraboloids framed in a metal tubular structure. The tubular structure is composed of four supports which are arranged at the midpoints of each side rather than the corners, so as to constitute four cantilevers whose spans are 23 m in the larger direction and 12 m in the shorter direction. There are two main trusses connecting these supports to provide stiffness to the whole set. The edge beam assembly is constituted by a steel frame stabilized with cables. Finally, it was necessary to introduce three struts in each of the four insets to avoid the lateral bending of the trusses edges and also at 45º at the corners.

Regarding the textile surface, it has structural function since it has to resist itself and all the overloads for transmission to the central trusses and edges. Finally, the assembly is also endowed with important additional elements to operate, as a perimeter textile enclosure sliding on guides, so that it can easily be withdrawn or extended. The view of the structure can be seen in Fig. 2.

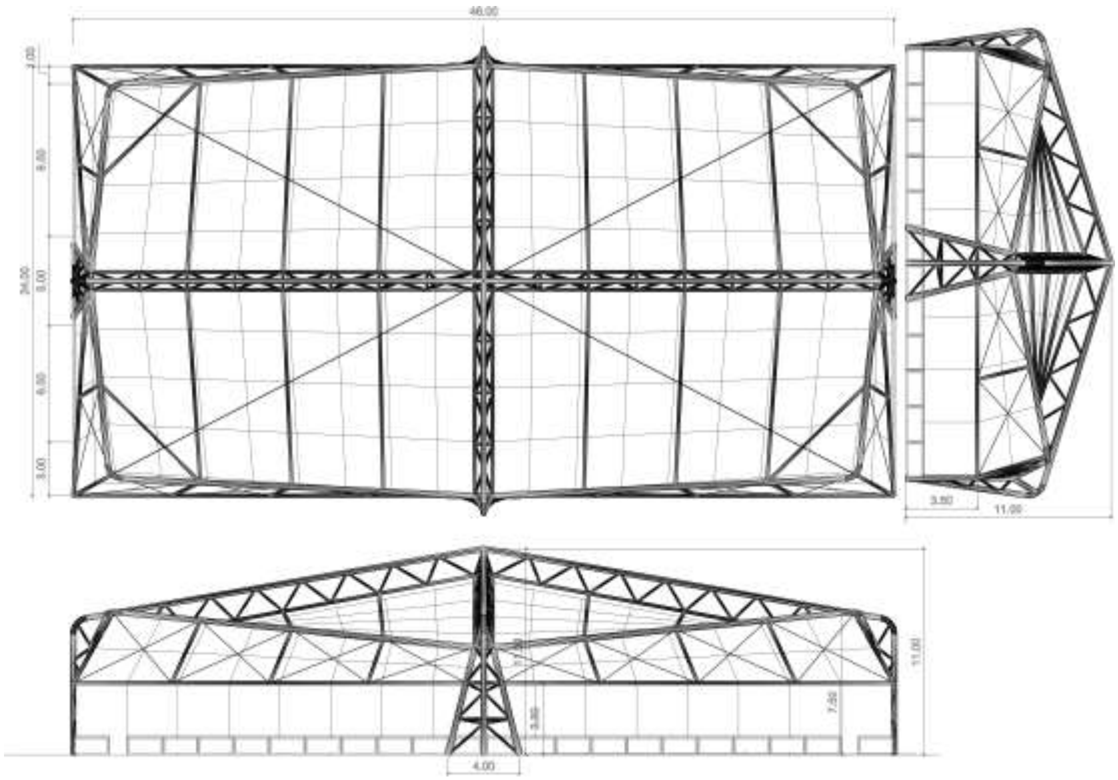

Figure 1: Structural layout plan of the roof for the multifunctional sports court (units: m)

Figure 2: Aerial view of the roof with partially open side

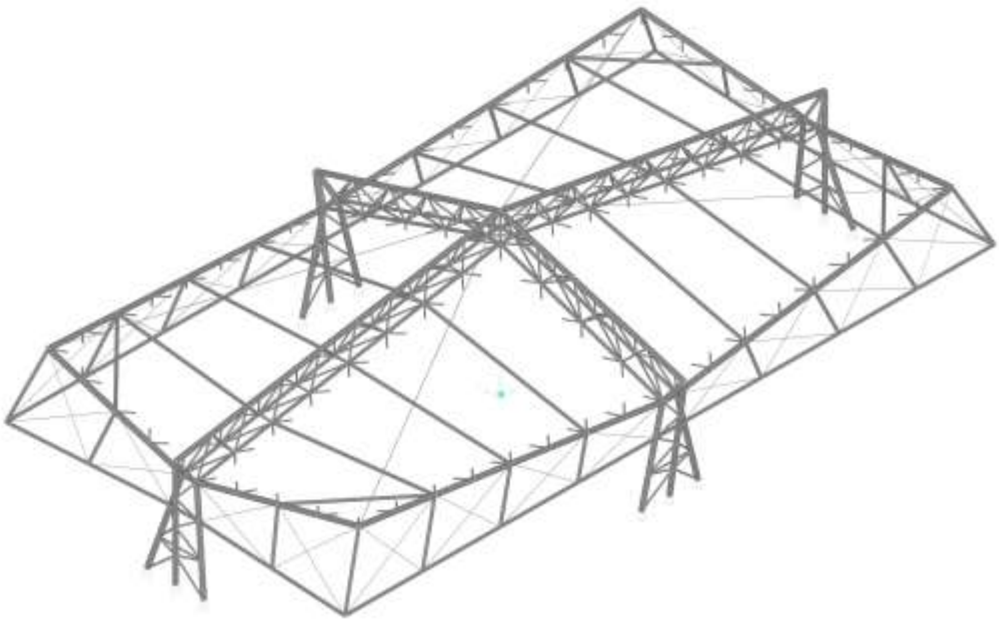

Figure 3: Finite element model of the whole structure

The nominal values of the design loads are listed as follows:

- Permanent load includes self-weight for the tubular and the textile structure.
- The tubular structure is considered automatically by the software, while the textile self-weight (1300 g/m^2) is applied at the connection points of the textile to the tubular structure.
- Pre-stress load for the textile surface was determined from the equations of membrane of a hypar (60 kN·m).
- Finally, reference wind pressure is 0.45 kN/m^2.

The material of the steel truss is taken as S355JR. The section dimensions of the tubular elements are determined in the design process. In detail, the section dimension (OD x WT (outside diameter x wall thickness) (mm)) of the main elements in trusses are Ø323x8 and Ø120x5 for the rest of elements. The section dimensions of struts and the edge truss are Ø200x6. The section dimensions of the cables that stabilize these frames are Ø25. All elements sections are described in Fig. 3, where the finite element model of the whole structure established by the finite element analysis software SAP2000 is shown.

2 MODAL ANALYSIS BY FEM

The finite element model of the whole structure is shown in figure 3 and, as mentioned above, was developed in the finite element software SAP2000v15.1.0. All the elements were modelled by 3D elastic steel frames. The main structure is defined by three tubular hollow sections as well as the cables with circular sections, whose dimensions are the same as the drawing. The tensioned fabric is not explicitly modelled but the connections to the main structure by short massless tubular frames where the resultant membrane stresses on fabric as well as its self-weight are applied. The material properties are taken from S355JR steel whose Young's modulus is 2 x 1011 N/m2 and the density is 7850 kg/m3. Two important issues in modal analysis which must be carefully considered are mass definition and the boundary conditions. On one hand, in relation to mass definition, SAP2000 only has implemented lumped masses concentrated at nodes. On the other hand, the boundary conditions are constraints of translational degrees of freedom in the three legs of each support.

Then the vibration properties were calculated by performing modal analysis based on iterative eigenvector determination. The structural dynamic characteristics including the eight modes of vibration were obtained, the frequencies are shown in Table 1 and the first six mode shapes are shown in Fig 4. Observing the mode shapes, mode shape 1 can be defined as the first lateral bending deflection of the whole roof in the transverse direction coupled with the second vertical bending deflection, mode shape 2 has the same behaviour as the prior mode but in the longitudinal direction, mode shape 3 and 4 are close in terms of frequency and both correspond to second bending lateral deflection with torsional behaviour of the triangular trusses and different vertical contributions of the short porch, modes 5 and 6 are again close in terms of frequency and correspond to first anti-symmetric vertical bending deflection respect to both directions and the first anti-symmetric vertical bending deflection of the perimeter truss respect to the longitudinal direction respectively, mode 7 is the first anti-symmetric vertical bending deflection of the perimeter truss respect to the transverse direction and, finally, mode 8 corresponds to the local first vertical bending of the parameter truss. It is clear that the structure has a narrow band of low natural frequencies and highly coupled, what makes the dynamic features of the structure quite complex.

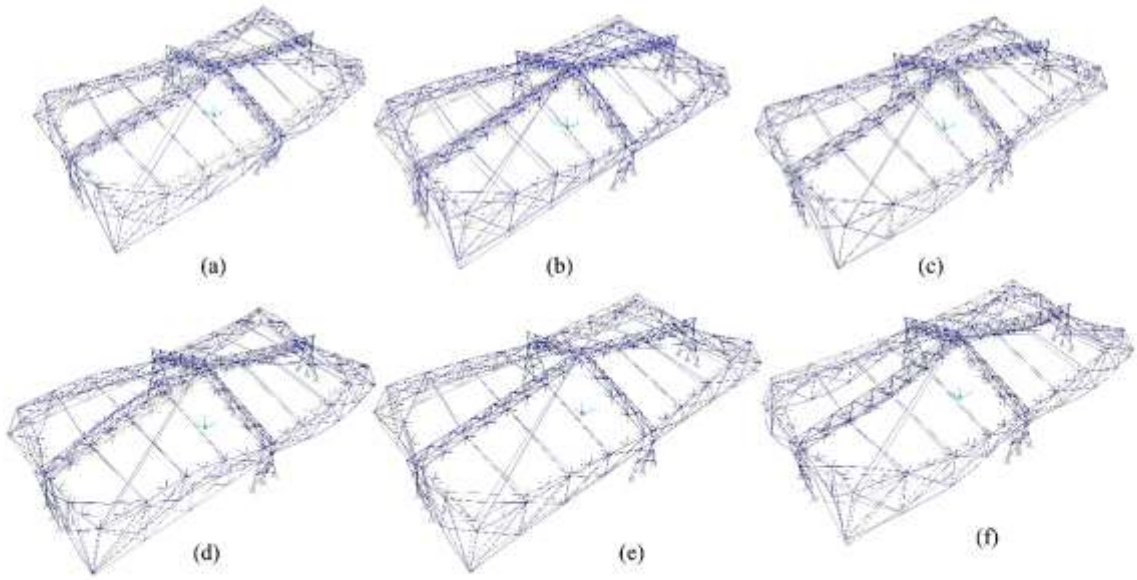

Figure 4: First six modes of vibration.

Table 1: List of modes and natural frequencies considered in the OSP.

	FEM
No.	Frequency (Hz)
1	1.724
2	2.298
3	2.609
4	2.619
5	3.209
6	3.223
7	3.472
8	3.732

3 OPTIMAL SENSOR PLACEMENT

An optimal sensor methodology which is commonly used in OSP is considered in this study and it is based on the Fisher information matrix (EFI).

Kammer [5] introduced the EFI optimal sensor placement algorithm which aims to search the best set of DOFs locations from all the candidate locations in the structure such that the linear independence of the mode shapes is maintained. The starting point of this method is the full modal matrix (F) from a finite element model. All the DOFs used in the FE model cannot be measured in the real structure due to physical limitations. Therefore, the DOFs corresponding to rotations and coordinates which cannot be measured are eliminated from the full modal matrix. Similarly, not all of the mode shapes can be experimentally measured, hence some target modes are selected to be optimally detected. Hence, the rows corresponding to DOFs that can be measured are kept and the columns corresponding to target modes are retained in the full modal matrix. The Fisher information matrix (FIM) is defined as

$$FIM = \Phi^T * \Phi \quad (1)$$

If the determinant of the FIM is zero, the columns of the modal matrix (i.e. the target modes) are linearly dependent. Therefore, the purpose of the EFI method is to select the best DOFs (to place the sensors) which maximizes the determinant of the FIM.

4 FIELD VIBRATION TEST

Dynamic test on the Hypar fabric structure can provide an accurate and reliable prediction of its global modal parameters including natural frequencies. First, the locations of the acceleration sensors were optimized according a general and intensive measurement. Five setup ups were considered with three reference sensors and five rowing sensors. High sensitive seismic sensors (PCB393B31) and a LMS Scada were employed for this purpose (see Fig. 5). The frequency band of interest was 102.4 Hz and the Nyquist frequency was exactly the double in order to avoid aliasing problems. The data were simultaneously recorded for 300 s at all channels.

In a second approach, EFI algorithm was employed to test eight positions at once in order to compare results with the intensive set ups. The optimal sensor configuration is shown in Fig 6.

Figure 5: Sensors in field vibration test

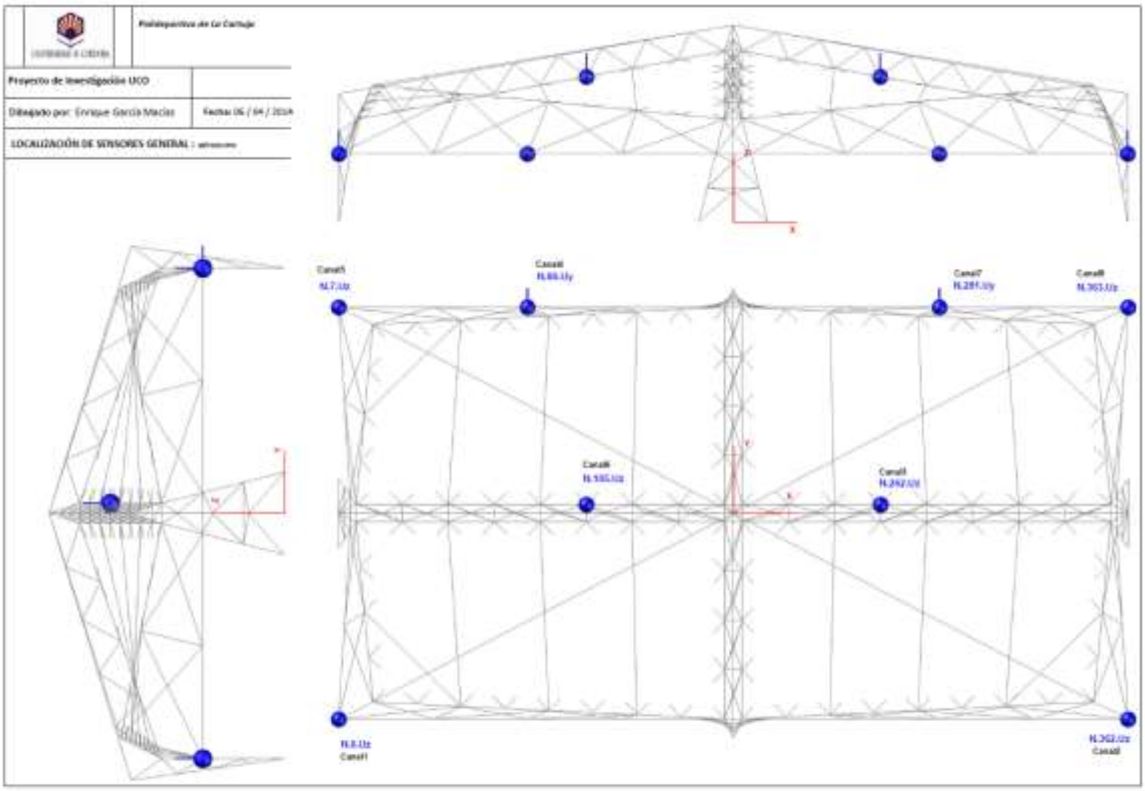

Figure 6: Optimal sensor configuration by EFI algorithm

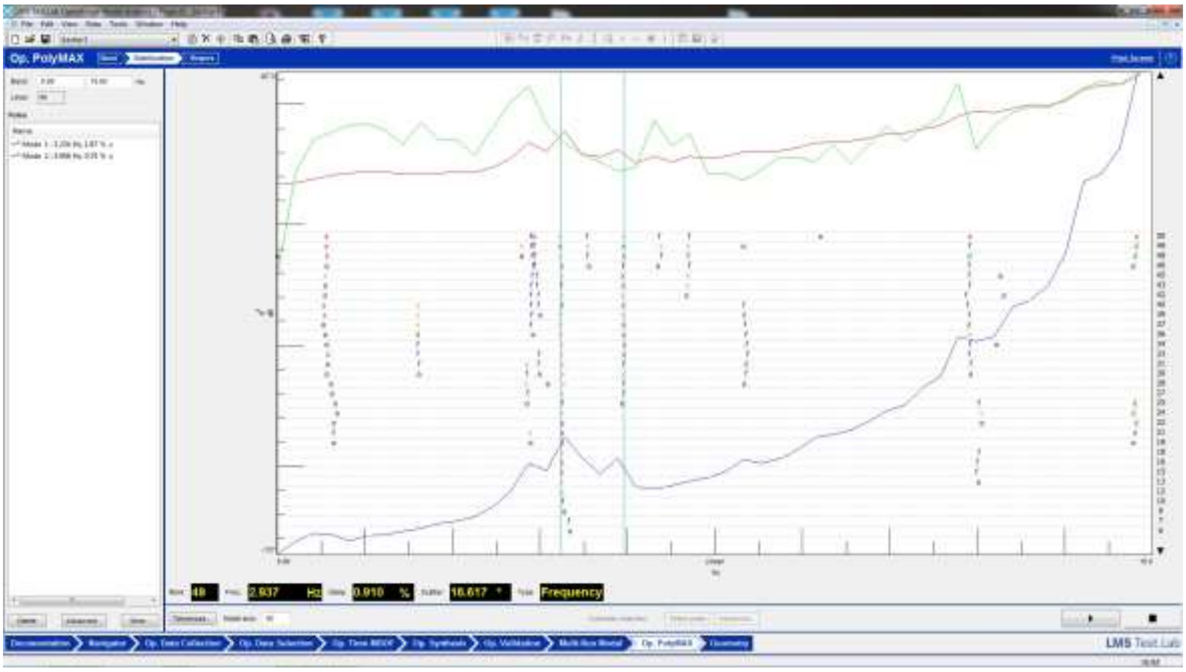

Figure 7: PolyMax stabilization diagram for the case of EFI location sensors

5 DISCUSSION ON MODAL RESULTS

PolyMax system identification algorithm was employed to analyse both the intensive and optimal configuration set ups. Several difficulties occurred during the process of system identification due to the low level of excitation of the structure. Only a few of natural frequencies were identified during the analysis of the time data. However, it could be proved that an optimal sensor configuration can be applied successfully with system identification purposes. In the case of EFI algorithm natural frequencies of 3.2 Hz and 3.9 Hz were found (see Fig 7) that they are in good correlation with the numerical frequencies.

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Project credits:

Project name: Cubierta sobre una pista multifuncional en el Centro de Alto Rendimiento de la Cartuja de Sevilla.
Location: Cartuja de Sevilla.
Client: Consejería de Turismo y Deportes de la Junta de Andalucía.
Project function: Eventual cover.
Construction year: 2010.
Architects: Félix Escrig and José Sánchez.
Engineering: Performance Ideas y Aplicaciones S.L. performance@arquired.es.
Prime contractor: SANROCON S.A. sanrocon@sanrocon.com.
Fabric contractor: ARQUITECTURA TEXTIL S.L. info@arquitecturatextil.com.
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