MULTI-OBJECTIVE SENSOR PLACEMENT OPTIMIZATION IN HELICOPTER MAIN ROTOR BLADE CONSIDERING THE NUMBER OF SENSORS AND MODE SHAPE INTERPOLATION

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Abstract: Sensor location optimization plays a key role in the application and development of structural integrity monitoring methodologies, especially in large mechanical structures. Given the existence of an effective damage detection and identification procedure, the question of how many and where to place the acquisition points (sensors) so that the monitoring system operates at peak efficiency arises. In this study, an innovative methodology is proposed in order to maximize the quality of modal information and minimize the number of sensors in the SHM system. To maximize the quality of modal information, it considered the reconstruction of mode shapes using Kriging interpolation. The study was carried out on a main rotor blade of the AS-350 helicopter. The initial modal information (modal deformation) was obtained through the finite element method, and the multi-objective Lichtenberg algorithm was used in the optimization process. The proposed method presented in this work allows for the best possible distribution of a minimum and sufficient number of acquisition points in a structure in order to obtain more modal information for a better modal reconstruction from kriging interpolation of these minimum points. Numerical examples and test results show that the proposed method is robust and effective for distributing a reduced number of sensors in a structure and at the same time guaranteeing the quality of the information obtained. Numerical results considering show that the proposed combined FS-kriging method is effective in distributing a finite number of sensors on the structures and at the same time guaranteeing the quality of the modal information obtained. The results also indicate that the layout of sensors obtained by multi-objective optimization does not become trivial and symmetrical when a set of modes is considered in the objective function formulation. The proposed strategy is an advantage in modal testing, as it is only necessary to acquire signals at a limited number of points, saving time and operating costs in vibration-based processes.

Keywords: Sensor Placement Optimization; Multi-objective; Mode shapes; Lichtenberg Algorithm

INTRODUCTION

Structural health monitoring (SHM) is a multidisciplinary field that involves the automatic detection of structural loads and responses through a large number of sensors and instruments, followed by a structural health diagnosis based on the data collected. Because an SHM system implemented in a structure automatically detects, assesses, and alerts on structural conditions in real time, massive data is a significant feature of SHM. Techniques related to massive data are called "data science" and include acquisition techniques, transition techniques, management techniques, and processing and mining algorithms for data analysis ([1]).

One of the most used and efficient methods in SHM concerns techniques based on vibrations (modal data). For this, the experimental modal analysis is an efficient experimental methodology to estimate the dynamic characteristics of a structure. The identification process consists of estimating the modal parameters from a set of frequency response functions (FRF). Sensor Placement Optimization (SPO) is a common problem encountered in many engineering applications, which has led to the development of several techniques, being applied to various mechanical, aerospace, and structural systems to identify the best detection locations, which are used to estimate modal parameters based on vibration responses ([2]).

Furthermore, vibration testing on large structures such as aircraft is an expensive and time-consuming job. Typically in aircraft design, this involves a set of 500 accelerometers, which, in addition to the difficulty of placing them where appropriate, also add mass and can significantly modify the actual dynamic characteristics of the structure. In particular, the position of these vibration sensors influences the modal identification quality of structures, which for a given number of sensors is usually estimated in terms of correlation between natural modes using the modal assurance criterion (MAC) ([3]).

The sensor is a crucial object in an SHM system. A sensor (in the SHM philosophy) must meet some basic specifications: (1) it must monitor only the actual damage condition of the host structure and be independent of changes in the environment; (2) it must transmit the acquired signals reliably; (3) it must produce the least possible compromise in the host structure; (4) it must survive the surrounding working environment for at least the life of the host structure; and (5) it must be easy to handle, attach, integrate, and operate. Furthermore, within the scope of aerospace mechanics, sensors for SHM of aerospace structures require additional resources, such as small dimensions and lightweight construction ([4]). In this sense, SPO techniques that reduce the number of sensors are essential.

The main objective of the present study is to optimize the number of sensors and their respective locations in complex mechanical structures. The major contributions of this study are: to perform a multi-objective optimization of sensors using the Lichtenberg algorithm (MOLA) and consider the sensor number variable; to apply the proposed methodology in a real AS-350 helicopter blade. The methodology proposed in this work is extremely important in modal testing, reducing signal acquisition time and costs, especially for large structures.

NUMERICAL METHODOLOGY

Direct Problem Modelling

Kriging is an interpolation method used to estimate correlated values in space from a sample set and can be applied in the reconstruction of the structural mode shapes ([2, 5]). In this way, the kriging method will be used as the interpolating algorithm responsible for the reconstruction of the mode shapes, in addition to feeding the optimization algorithm with the objective function.

Starting from the experimental analysis of the main rotor blade, the numerical model was created by inverse modelling, in which the blade geometry is created from a single material. The mechanical properties of the model are obtained by a search algorithm in such a way that the numerical model behaves like the real one.

The blade is 4665 mm long, of which 3880 mm corresponds to the aerodynamic section whose profile is NACA0012. The numerical model of the blade was also developed in ANSYS APDL from two symmetrical shells in the aerodynamic region using SHELL281-type elements (Figure 1). The material to be investigated by the search algorithm is a laminated composite of 12 layers having a thickness of 1.08 mm each.

Lichtenberg's algorithm is responsible for determining the properties of the laminate. The parameters elasticity modulus, Poisson's ratio, and density are the variables of the problem. The optimizer aims to minimize the difference between the values of natural frequencies obtained experimentally and those numerically calculated by LA ([6]). The final numerical model presented 746 elements and 2266 nodes. As a boundary condition in the problem, the real operating situation was considered, that is, fixed at the root and free at the end.

Having determined the blade geometry and its mechanical properties, the modal analysis was performed numerically in order to obtain the first six mode shapes. The difference between the natural frequency calculated by the numerical model and the experimental model, in all modes evaluated, was less than 1%, except for the second mode, where the natural frequency varied 5% ([6]), which is also considered a substantially small difference.

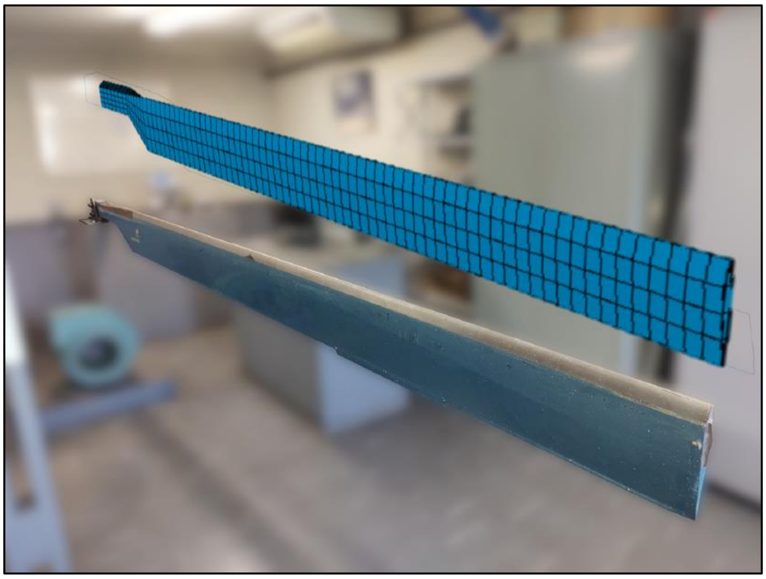


Figure 1: Detail on the real model of the AS HB-350 blade and numerical model discretized in 2266 nodes and 746 elements.

Inverse Optimization Problem

An SPO problem aims to determine the best arrangement of sensors on the evaluated structure. This type of optimization considers the positioning and quantity required to achieve a good signal intensity in each of the sensors during the operation. Therefore, the positioning of the sensors must be done in order to guarantee the best possible reconstruction for each of the mode shapes.

Spatial interpolators, such as kriging and thin-plate, make use of known data in space, samples, to estimate the values of unknown points in the region of interest. The difference between each interpolator is in the way each estimate is made. In the case of Kriging, the concept of covariance is used through a variogram model, while the thin plate considers the integral of the square of the second derivative—this forms its smoothness measure.

The sensors were considered samples for the interpolators since the displacement information obtained by the sensors is the knowledge data of the evaluation zone. From the results of the modal analysis, each node that composes the numerical model is a candidate point for sensors in the optimization, structuring the optimizer's search space. However, for complex geometries, such as the rotor blade of an aircraft, for example, the search space can be reduced in order to minimize the computational cost.

The optimization of the positioning of the sensors occurs by minimizing the objective function (*F*), which has, in essence, to calculate the interpolation error defined by Equation 1.

$$F = \left\|\Phi_n^{true} - \Phi_n^{interpolated}\right\|_F \tag{1}$$

where Φ_n^{true} is the result obtained by finite element analysis and $\Phi_n^{interplatede}$ is the interpolation response. The index n represents the mode shape evaluated, for example, if $n = 7$ it refers to the interpolation error of the seventh mode shape. Therefore, the interpolation error was defined by the difference of the Frobenius norm ([7]).

RESULTS AND DISCUSSION

This section addresses the main rotor blade of the AS-350 aircraft, considering the real operating conditions (clamped-free). Due to the complexity of the blade geometry, some simplifications were adopted to evaluate the proposed problem.

The approach with the kriging algorithm proved to be quite effective for the reconstruction of mode shapes for a plate. Modelling under the helicopter rotor blade seeks to apply this methodology to a practical problem in the SHM process.

Starting with the curvature of the wing profile, being neglected. In this way, the extrados surface behaves as a flat surface, so the problem can be studied as a rectangular plate with dimensions of length and width being the span and chord of the profile, respectively.

The second simplification is related to the design space for the optimization problem. The mesh generated by the numerical model presents nodes dispersed throughout the blade surface, including the clamped section with the helicopter rotor. To make the analysis feasible, the clamped nodes were not included in the search space, which considered only the region of the blade's aerodynamic profile. Furthermore, the search space includes only the nodes contained in the upper surface of the wing profile, totalling 891 sensor candidates.

The setting promoted by the fixation was assigned as one of the boundary conditions of the problem, where the nodal displacement is null. Thus, the nodes in the crimp region fed the interpolator with their respective nodal displacements, which is a constraint. Attributing such simplifications, the parameters assigned to MOLA in this analysis were: Population: 1000 ($pop = 1000$); $N_{iter} = 300$; liveable points in the Pareto front: 100 ($N_T = 100$).

The optimization was performed according to the objective functions described by Equation 2. In this way, the SPO considered variable sensors with the FS approach and evaluated five mode shapes simultaneously.

$$\begin{cases} \text{minimize } N_{sensors} \\ \text{minimize } F = \displaystyle\sum_{n=1,3,4,5,6} \left\|\Phi_n^{true} - \Phi_n^{interpolated}\right\|_F \end{cases} \tag{2}$$

As the side constraints (lower and upper bounds), as shown in Equation 3.

$$\begin{Bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{Bmatrix}_{891\times 1} \leq \begin{Bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{891} \end{Bmatrix}_{891\times 1} \leq \begin{Bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{Bmatrix}_{891\times 1} \tag{3}$$

RESULTS AND DISCUSSION

In this case, the ability of the proposed methodology to solve SPO problems in more complex geometries was evaluated. The AS-350 blade was modelled, and the mode shapes were obtained numerically, as shown in Figure 2. As described in previous paragraphs, the SPO process was developed in order to evaluate the first six rotor blade modes by varying the number of sensors through the FS. The second mode shape was not considered, as the nodal displacements of the upper surface of the profile in z-direction were all very close to zero. So the SPO problem was run for modes 1, 3, 4, 5 and 6.

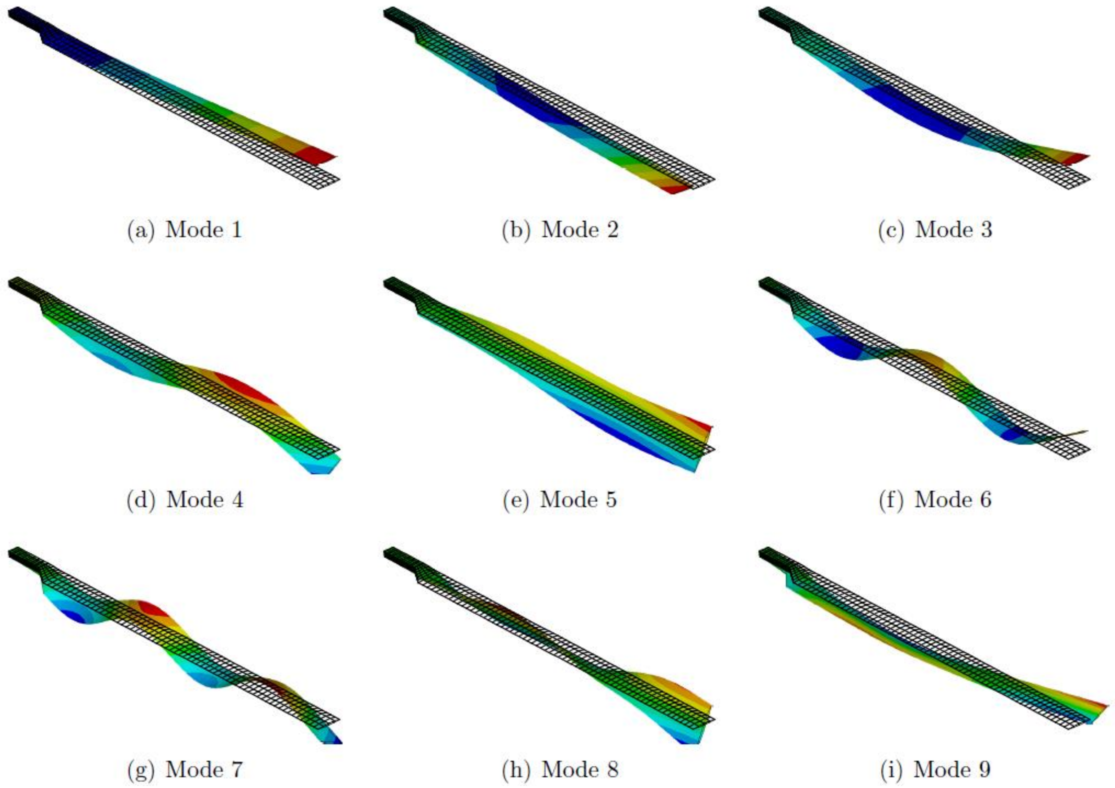

(a) Mode 1 (b) Mode 2 (c) Mode 3
(d) Mode 4 (e) Mode 5 (f) Mode 6
(g) Mode 7 (h) Mode 8 (i) Mode 9

Figure 2: Nine first mode shapes of the main rotor blade of the AS-350 helicopter.

The approach with the kriging algorithm proved to be quite effective for the reconstruction of the mode shapes for a plate. Modelling under the helicopter rotor blade seeks to apply this methodology to a practical problem in the SHM process.

Due to the complexity of the blade geometry, some simplifications were adopted to evaluate the problem. The nodes in the clamped region fed the interpolator with their respective nodal displacements ($U_z = 0$), that is, a constraint. These nodes are not sensor candidates; therefore, they are not part of the MOLA search space.

The responses of the multi-objective analysis can be seen in Figure 3. The behaviour is similar to the analysis performed for the square plate, where the increase in the number of sensors tends to reduce the response error, reaching a saturation point at which the increase in sensors has an irrelevant contribution to the response. This occurs from 48 sensors. In a direct example, starting with 48 sensors, the reconstruction error is 0.77 while, with 202 sensors, the error is 0.55, that is, by quadrupling the number of sensors, the error was only approximately 28%.

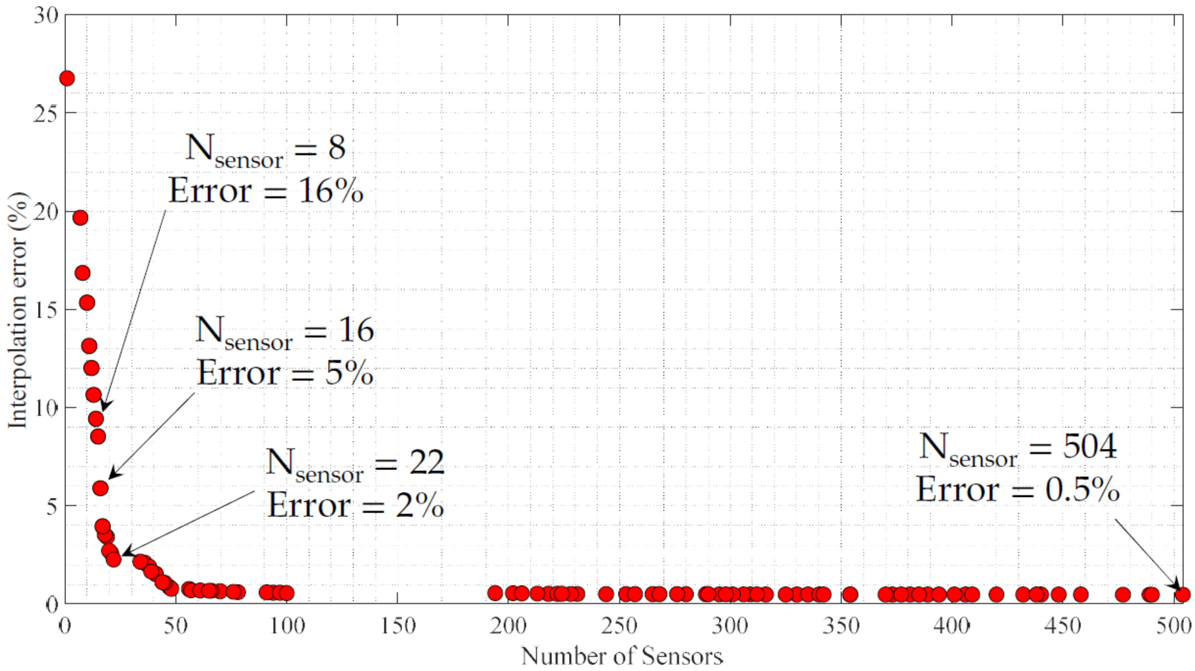
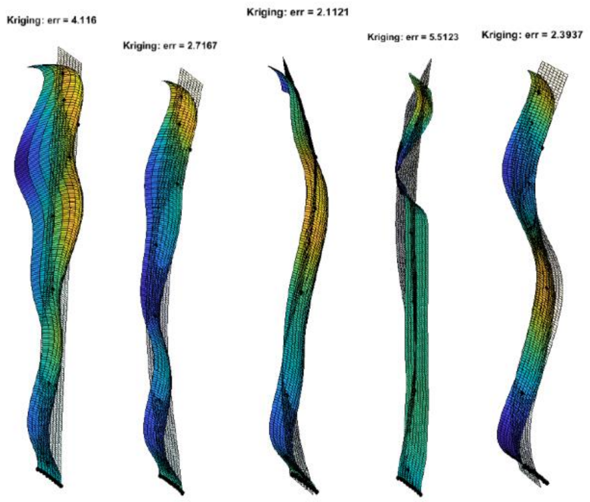


Figure 3: Pareto front correlating the number of sensors (ordinate) with the sum of the errors obtained by the interpolation (abscissa).

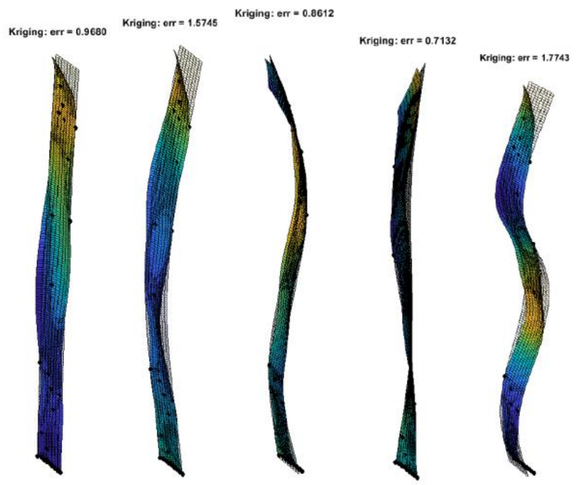
It is important to note that even with all the simplifications, the optimization process proved to be quite complex, requiring a considerable computational cost due to the high number of modes evaluated simultaneously (five in total) and the large search space considered (891 sensor candidate nodes). For this reason, the elapsed time for optimization was 19 hours. The 2nd mode was not included due to its redundancy (symmetry to the first mode).

Finally, the reconstruction of the mode shapes can be seen in Figures 4 to 7 and the positioning of the sensors resulting from this simulation is shown in Figure 8. It is clearly observed that with the increase in the number of sensors, the interpolation by kriging in order to obtain the continuous mode is significantly improved. With the use of only eight sensors, as long as they are placed in optimal positions, it is already possible to obtain slightly adjusted modes. Taking into account the TOPSIS decision-making solution (22 sensors), the interpolated modes were able to faithfully represent the reality of the modes.



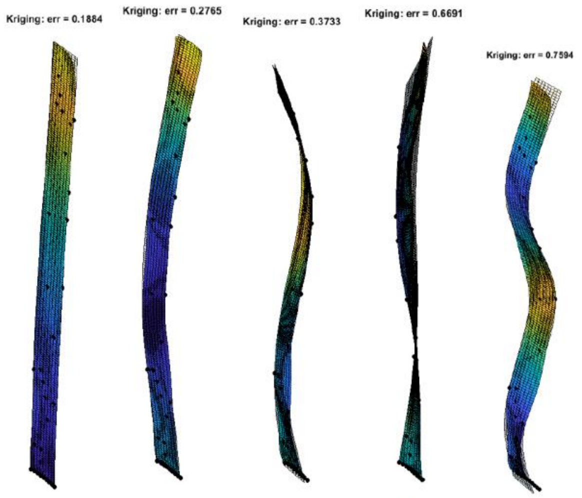
(a) Mode 1 (b) Mode 3 (c) Mode 4 (d) Mode 5 (e) Mode 6

Figure 4: Reconstruction of the five blade mode shapes with 8 sensors.



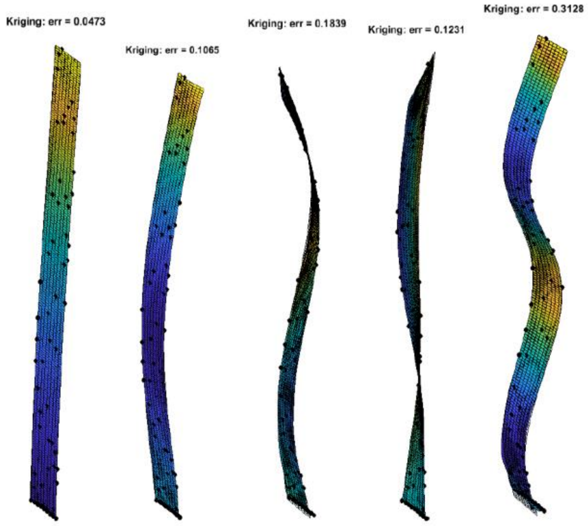
(a) Mode 1 (b) Mode 3 (c) Mode 4 (d) Mode 5 (e) Mode 6

Figure 5: Reconstruction of the five blade mode shapes with 16 sensors.



(a) Mode 1 (b) Mode 3 (c) Mode 4 (d) Mode 5 (e) Mode 6

Figure 6: Reconstruction of the five blade mode shapes with 22 sensors.



(a) Mode 1 (b) Mode 3 (c) Mode 4 (d) Mode 5 (e) Mode 6

Figure 7: Reconstruction of the five blade mode shapes with 48 sensors.

(a) 8 sensors

(b) 16 sensors

(c) 22 sensors

(d) 48 sensors

Figure 8: Positioning sensors after optimization.

CONCLUSIONS

In this work, a complete and detailed study on the multi-objective optimization of sensors in the field of structural integrity monitoring is carried out. It was considered as objectives in the formulation i) the number of sensors and ii) the optimal position of these sensors in order to interpolate a reduced mode shape.

In the multi-objective optimization of mode shape interpolation *vs*. number of sensors, all Pareto fronts obtained were convex with evidence of the knee-point.

In the decision-making considering TOPSIS, 8 sensors were enough for a simpler structure and 22 for a more complex structure.

In future studies, the authors recommend the evaluation of other algorithms capable of reducing the computational cost, in addition to the inclusion of noise in the sensors' responses. The evaluation of traditional SPO (e.g., MAC, EI, KE, etc.) techniques is also recommended at the discretion of comparison.

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