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Strain sensors optimal placement for vibration-based structural health monitoring. The effect of damage on the initially optimal configuration

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ABSTRACT

We revisit the optimal sensor placement of engineering structures problem with an emphasis on in-plane dynamic strain measurements and to the direction of modal identification as well as vibration-based damage detection for structural health monitoring purposes. The approach utilized is based on the maximization of a norm of the Fisher Information Matrix built with numerically obtained mode shapes of the structure and at the same time prohibit the sensorization of neighbor degrees of freedom as well as those carrying similar information, in order to obtain a satisfactory coverage. A new convergence criterion of the Fisher Information Matrix (FIM) norm is proposed in order to deal with the issue of choosing an appropriate sensor redundancy threshold, a concept recently introduced but not further investigated concerning its choice. The sensor configurations obtained via a forward sequential placement algorithm are sub-optimal in terms of FIM norm values but the selected sensors are not allowed to be placed in neighbor degrees of freedom providing thus a better coverage of the structure and a subsequent better identification of the experimental mode shapes. The issue of how service induced damage affects the initially nominated as optimal sensor configuration is also investigated and reported. The numerical model of a composite sandwich panel serves as a representative aerospace structure upon which our investigations are based.

1. Introduction

A great deal of effort has been devoted the last two decades to the optimal sensorization of engineering structures with a predefined (or not) number of sensors. The practical interest is huge and the relevant literature has flourished giving a number of very interesting contributions that address the optimal sensor placement (OSP) problem. Among the many sensor types and relevant tests, we focus on vibration testing which can be utilized towards either system identification, finite element model updating and/or quality control and damage detection. OSP is formally an optimization problem having been described by various objective functions. One of the first and most well established approaches was the maximization of a norm of the Fisher Information Matrix (FIM). Fisher information is a concept from mathematical statistics which measures the

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amount of information that an observable random variable X entails about an unknown parameter vector $\boldsymbol{\theta}$ which defines the probability density function of X conditional on $\boldsymbol{\theta}$.

In a non-exhaustive literature review, Kammer [1] was among the first researchers to utilize the maximization of the trace and determinant of a FIM built with mode shapes obtained from Finite Element Modeling. He called his method the Effective Independence method for modal identification and showed its superiority over the Kinetic Energy approach. Udwadia in Ref. [2], focused on OSP for parameter identification and gave a more general framework relying on the maximization of the trace of the FIM of any of the targeted parameter(s). Li et al. [3] discussed and compared the modal kinetic energy (MKE) and effective independence (EI) methods, whilst Meo and Zumpano [4] investigated six different OSP techniques for the sensorization of a bridge and utilized the mean square error (MSE) between experimental and numerical mode shapes as a criterion for the efficiency of each OSP approach. They concluded that the EI method and its variation EI-DPR coupled with the driving point residue (DPR) coefficient give the least total MSE for the three first mode shapes of the bridge.

Papadimitriou et al. [5] and Papadimitriou [6] presented a rigorous probabilistic formulation of the optimal sensor placement problem for structural identification. They utilized the information entropy as the objective function of the OSP task searching for the sensor configuration that minimizes it. They adopt a Bayesian framework and rationale, conditioning all the associated variables on measured data which are most probably non-existent in the design stage prior to the sensorization of a structure. They tackle this problem by making an assumption of a large number of measured data and an asymptotic approximation of information entropy. Papadimitriou and Lombaert in Ref. [7], categorize OSP problems in two categories: a) OSP for parameter identification and model updating and b) OSP for modal identification. Not surprisingly, the OSP problems of the second category end up to an information entropy proportional to the determinant of the Fisher information matrix, resulting in an identical OSP as in the EI method, if equal variances of the prediction error are assumed for each measured DOF. This happens because what starts as a Bayesian approach which calculates conditional (on data) probabilities, becomes a classic maximum likelihood estimate approach since the conditioning is relaxed as data hardly ever exist before the sensorization of a structure. Thus, a genuinely Bayesian approach cannot be applied without any available experimental data. Yuen et al. [8], discuss scenarios where changes due to damage induce larger uncertainties in the parameters to be identified, demonstrating that the locations of the candidate sensors do not actually change. This only partially agrees with our findings reported in Section 4, where sensor re-positioning does not arise only for quite small induced damage (e.g. 5×5 mm^2 disbonding).

Li and Der Kiureghian in a recent study [9], develop a novel probabilistic framework for the OSP problem having as objective the maximization of the expected utility function from information theory. It is generic enough to accommodate any utility function, the authors though admit that there is no way to say which proposed configuration is the best unless specific evaluation criteria are introduced and posterior experimental evidence under various sensor configurations is obtained. Li et al. [10], propose a load-dependent OSP strategy developing the respective framework theoretically and testing their approach experimentally. Their approach though, relies on structural responses/measurements which are usually not available in the design phase of an OSP of an engineering structure problem. Moreover, it can only provide with OSP configurations under a priori known load histories which may or may not be available for a given structure. Stephan in Ref. [11], following the work of Kammer [1], also builds his FIM with mode shapes obtained from Finite Element models and introduces for the first time a redundancy criterion to avoid the unnecessary placement of sensors in neighborhood degrees of freedom (DOF) and thus obtain a wider coverage of the structure. He ends up with more expanded sensor configurations compared to the EI method which is desirable for subsequent experimental mode shape determination and damage detection. Papadimitriou and Lombaert in Ref. [7] also discuss a similar issue on spatial correlation of candidate sensors and introduce an exponential correlation function to account for it. Regarding OSP for damage detection, most of the limited works published deal with this issue as a parameter identification task. In Schulte et al. [12], a sensor placement strategy is proposed which maximizes the determinant of a Fisher information matrix based on the eigenvector sensitivities of a numerical model. Damage is considered as an element thickness decrease in a typical aeronautical stiffened panel. Similar approach is followed in Refs. [13,14].

In the present work, we develop an OSP framework for in-plane dynamic strain sensors with a view on Fiber Bragg Grating (FBG) sensors utilization. A lot of focus has been given the last 15 years [15–19] to the utilization of FBG sensors for static as well as dynamic strain measurements for SHM purposes in various industries (aeronautics, space, wind energy, etc.). Our focus is on the pre-service planning of FBG strain sensor placement having no prior experimental data other than the numerical model of the structure. To this direction, we extend the framework set by Stephan in Ref. [11], utilizing strain mode shapes from two directions simultaneously -instead of accelerations or displacements- and proposing a simple convergence criterion to decide on the redundancy threshold he introduced. Moreover, we discuss the effect of damage on the initially nominated optimal sensor placement, an issue marginally investigated in the relevant literature. Through numerical simulations with Finite Element Analysis (FEA) on a honeycomb sandwich composite panel, it can be shown that even very minor damage in the form of skin to core debonding can change locally the mode shapes and shift the sensors from their initially assigned locations.

2. Methodology - sensor placement algorithm

The governing differential equation of motion for a linear time-invariant dynamic system under external excitation $\boldsymbol{F}(t)$ is expressed as: