Optimal Sensor Placement for Laminated Composite and Steel Cantilever Beams by the Effective Independence Method

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Abstract

In modal testing, the quality of vibration signals and clarity of peak points to extract the natural frequencies, corresponding mode shapes and damping ratio depend on the number and location of the sensors. High measurement costs are required for structural identification and long-term structural health monitoring in large structures, which require a high number of sensors. Therefore, the minimum number of sensors should be placed at appropriate locations on the system during experimental measurements to ensure both information of sufficient quality and cost reductions. The aim of this study is to perform cost-efficient non-destructive modal tests for a laminated composite and steel cantilever beams using an optimal sensor placement approach. Finite element models of the sample beams are constituted in ANSYS® software to determine the initial candidate set of sensor locations. Then, ambient vibration tests are conducted. Based on the experimental modal amplitudes and mode shapes, optimal sensor locations are determined using the effective independence method, and measurements are repeated. The study shows that there is good agreement between the natural frequencies and mode shapes obtained from the initial measurements and those obtained using the limited number of sensors.

Keywords: laminated composite beam; dynamic characteristics; effective independence method; modal testing; optimal sensor placement; steel beam

Introduction

The structural behavior of engineering structures can be identified according to dynamic characteristics such as mode shapes, natural frequencies and damping ratios. These can be obtained by finite element analyses in the design stage, before construction. However, the existing dynamic characteristics generally do not match the finite element results after construction for reasons such as faulty workmanship, material degradation, changing of boundary conditions, corrosion, damage and fatigue. Therefore, numerical dynamic characteristics should be verified by non-destructive experimental measurements reflecting the in-situ existing state of the structure.[1]

Two different methods are used to identify dynamic characteristics experimentally: experimental modal analysis and operational modal analysis.[2] In experimental modal analysis, the response of the structure is measured using known input forces such as impulse hammers and shakers, while in operational modal analysis, the response of the structure is measured using unknown input forces due to environmental effects such as traffic load, wind and waves.

During the experimental measurements, sensors should be placed on nodal points of the structure, which are decided according to the initial finite element analysis results. The quality of vibration signals and clarity of peak points to extract the natural frequencies, mode shape and damping ratio depend on the number and location of sensors.[3–6] In addition, high measurement costs are required for structural identification and long-term structural health monitoring, especially in large structures, because of the need to use a high number of sensors. Thus, optimal sensor locations should be taken into account to ensure that all important dynamic characteristics are obtained with sufficient accuracy, and that measurement costs are effectively reduced during the tests for structural identification, structural health monitoring and damage detection.

The optimal sensor placement (OSP) problem is a common and well-known issue in all areas of engineering. It was first used by NASA for system identification and correlation of large space structures.[7] Nowadays, this method is widely applied to aerospace, civil and mechanical structures. There are many methods in the literature on OSP, such as the effective independence (EI) method,[7] optimal and non-optimal driving point methods,[8] EI driving point residue method[9] and sensor set expansion technique.[10]

In the literature, the OSP problem has been investigated in bridges,[11–15] towers,[16–20] historical masonry structures,[21] stadiums,[22] dams,[23–26] timber structures,[27] buildings, etc.[28–31] In these studies, many aspects of the subject have been examined experimentally and numerically.

It can be seen from the literature review that many studies have been performed to propose a novel sensor placement technique and to determine the OSP of structures made up of composite materials using finite element models. Many aspects of the subject have been studied using composite structures.[32–47] However, studies in which the capabilities of OSP techniques have been experimentally determined are limited. Therefore, the aims of this study are to investigate the OSP problem for a laminated composite cantilever beam and hollow-sectional steel cantilever beams, and to determine the effects of sensor locations on the dynamic characteristics. Experimental measurements are performed on three sample beams, namely a laminated composite beam, a hollow-circular cross-sectional steel