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An interface force measurements-based substructure identification and an analysis of the uncertainty propagation

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ABSTRACT

Substructure-decoupling techniques are used to identify a substructure as a stand-alone system while it is coupled to a complex structure. These techniques can be used for various applications, *e.g.*, when the substructure cannot be measured separately from the complex structure, when modal testing methods are not appropriate due to the limits of the measurement equipment and for vibration-control techniques. The complex structure consists of the unknown substructure and the remaining structure. A drawback of the available substructure-decoupling techniques is that they require a model of the remaining substructure. However, when the model cannot be calculated or (experimentally) identified, the substructure-decoupling techniques cannot be used. In this paper a new approach is presented that does not require a model of the remaining substructure, but is based on an experimental identification of the interface forces. The sensitivity of the approach to experimental errors was researched. Numerical and experimental test cases are researched.

1. Introduction

Substructure techniques were developed to characterize complex structures that are assembled from several substructures (parts) [1–3]. In the field of substructure-coupling techniques each of the substructures can first be analyzed independently of the others. Then, the obtained results are used to calculate the dynamical behavior of the complete complex structure [1,2]. Substructure-coupling techniques can be used, *e.g.*, to reduce the computational time in the field of finite-element methods (FEMs) or to combine theoretically and experimentally derived models [1]. In this research the inverse problem is considered, where a substructure is identified as a stand-alone system while it is coupled to a complex structure. These recently introduced methods are termed substructure-decoupling techniques [4–7] and can be used to identify the substructure's model when it cannot be disassembled or it cannot be measured independently of the complex structure, *e.g.*, a fixture is needed for the testing [6]. Further, substructure techniques can be used in structural monitoring and vibration-control [6].

In the field of substructure-decoupling techniques the complex structure is usually divided into the unknown and the remaining substructures. The result of the substructure-decoupling technique is a model of the unknown substructure, which is identified from the complex structure. The substructure-decoupling techniques can be classified

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as the inverse and the direct decoupling techniques [8]. The inverse techniques are based on coupling equations, that are rearranged in such a way that the model of the unknown substructure is isolated [8]. Examples of the inverse techniques are the impedance [9,7,10] and the mobility [4,7,10] substructure-decoupling techniques. The direct decoupling techniques are based on the adding of a fictitious subsystem to the model of the complex structure, that is the negative of the residual substructure [6,8,11].

It is a common feature of all the available decoupling techniques that they require a dynamical model of the complex and the remaining substructures. The model of the complex structure is identified experimentally and the model of the remaining substructure is calculated or experimentally identified. A drawback of the substructure-decoupling techniques is that the calculation or identification of the remaining substructure's model requires an additional effort. When the remaining substructure is too complicated to be calculated or experimentally identified, the substructure-decoupling techniques cannot be used.

In this research a new approach to linear substructure decoupling is introduced that does not require a model of the remaining substructure. This approach is based on measuring the interface forces [1]. The interface forces of the complex structures usually cannot be measured directly; therefore, an identification is made. In this paper two types of dynamical systems are analyzed. As an illustration, the proposed approach is considered on a mass-spring-damper system. To show the application possibilities of the proposed approach for real structures, this research considers complex structures with beam-like coupling elements, *i.e.*, structures where there is a beam in the region of the coupling degrees of freedom (many real structures contain beam-like components in their assembly). The research includes an uncertainty propagation analysis of the proposed approach. This approach was also validated by numerical simulations and experimental tests.

The paper is organized as follows: Section 2 introduces the responses of the complex structure and substructures. Section 3 describes the approach to substructure decoupling. This is followed by the theory of error analysis in Section 4. The case studies are presented in Sections 5 and 6. The conclusion follows in Section 7.

2. The responses of the complex structure and the coupled substructures

The substructure decoupling will be considered for the complex structure AB (Fig. 1a) that is assembled from the substructures A and B. It is assumed that the considered systems are linear and time invariant. In this paper all the quantities are functions of frequency, except for the constants and integers. The subscripts a, b and c correspond to the substructures A, B and the coupling degrees of freedom (DOF), respectively. The structure AB is excited with the external excitation forces $\mathbf{f}_\mathrm{a}$ and $\mathbf{f}_\mathrm{b}$ (Fig. 1a). The response for the structure AB is defined as [1,5,12]

$$\begin{bmatrix} \mathbf{u}_\mathrm{a} \\ \mathbf{u}_\mathrm{c} \\ \mathbf{u}_\mathrm{b} \end{bmatrix} = \underbrace{\begin{bmatrix} \mathbf{H}^{\mathrm{AB}}_{\mathrm{aa}} & \mathbf{H}^{\mathrm{AB}}_{\mathrm{ab}} \\ \mathbf{H}^{\mathrm{AB}}_{\mathrm{ca}} & \mathbf{H}^{\mathrm{AB}}_{\mathrm{cb}} \\ \mathbf{H}^{\mathrm{AB}}_{\mathrm{ba}} & \mathbf{H}^{\mathrm{AB}}_{\mathrm{bb}} \end{bmatrix}}_{\mathbf{H}^{\mathrm{AB}}} \begin{bmatrix} \mathbf{f}_\mathrm{a} \\ \mathbf{f}_\mathrm{b} \end{bmatrix} \tag{1}$$

where $\mathbf{u}_\mathrm{a}$ and $\mathbf{u}_\mathrm{b}$ are the responses that correspond to the internal DOF of the substructures A and B, respectively. $\mathbf{u}_\mathrm{c}$ is the response of the coupling DOF. $\mathbf{H}^{\mathrm{AB}}$ is the frequency-response-function (FRF) matrix of the complex structure AB (without the elements that correspond to the coupling DOF). Using the interface forces $\mathbf{f}^{\mathrm{A}}_{\mathrm{c}}$ (Fig. 1b) the response of the coupled substructure A (Fig. 1b) can be written as [5]

$$\begin{bmatrix} \mathbf{u}_\mathrm{a} \\ \mathbf{u}^{\mathrm{A}}_\mathrm{c} \end{bmatrix} = \underbrace{\begin{bmatrix} \mathbf{H}^{\mathrm{A}}_{\mathrm{aa}} & \mathbf{H}^{\mathrm{A}}_{\mathrm{ac}} \\ \mathbf{H}^{\mathrm{A}}_{\mathrm{ca}} & \mathbf{H}^{\mathrm{A}}_{\mathrm{cc}} \end{bmatrix}}_{\mathbf{H}^{\mathrm{A}}} \begin{bmatrix} \mathbf{f}_\mathrm{a} \\ \mathbf{f}^{\mathrm{A}}_\mathrm{c} \end{bmatrix} \tag{2}$$

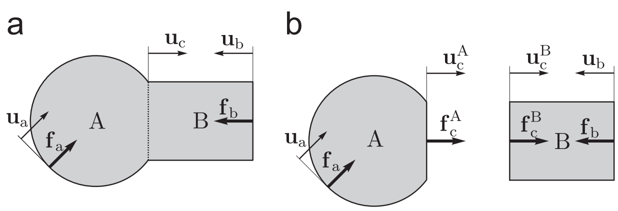

Fig. 1. (a) The complex structure AB. (b) The coupled substructures A and B.