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Advancements in hybrid dynamic models combining experimental and finite element substructures

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ABSTRACT

This paper presents very practical enhancements to the transmission simulator method (TSM); also known as the Modal Constraints for Fixtures and Subsystems (MCFS). The enhancements allow this method to be implemented directly in finite element software, instead of having to extract the reduced finite element model from its software and implement the substructure coupling in another code. The transmission simulator method is useful for coupling substructures where one substructure is derived experimentally and the other is generated from a finite element model. This approach uses a flexible fixture in the experimental substructure to improve the modal basis of the substructure; thus, providing a higher quality substructure. The flexible fixture substructure needs to be removed (decoupled) from the experimental substructure to obtain the true system characteristics. A modified method for this removal and coupling of the experimental and analytical substructures is provided. An additional improvement guarantees that the experimental substructure matrices are positive definite, a requirement for many finite element codes. Guidelines for designing robust transmission simulator hardware are provided. The concepts are applied to two sample cases. The first case consists of a cylinder connected by eight bolts to a plate with a beam. The second example is an outer shell structure that is connected through a bolted flange to a complex internal payload structure.

1. Introduction

A complex full system model can be a synthesis of individual components (substructures). Typically, these components are designed and analyzed by different groups of engineers, and often they are in different organizations if not companies. However, the development of one component requires knowledge of the characteristics of the other components to predict the response of the full system. The engineering team of one component would prefer not to model or expend additional computational resources on other substructures. Several analytical component mode synthesis (CMS) techniques have been developed to address these issues [1–8], but these methods are difficult to implement in experimental substructures. Possibly, an experimental substructure may provide a more accurate model as well as a more economical one.

This paper enhances the current body of knowledge on the CMS techniques for coupling experimental and analytical models. It employees a technique developed by Allen, Mayes and Bergman termed Modal Constraints for Fixtures and

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Subsystems (MCFS) with the use of a flexible fixture named the transmission simulator (TS) [9]. Hereinafter, this will be called the Transmission Simulator method (TSM). The basic premise of their concept is to use an additional substructure (transmission simulator) at the interface of two components. This additional substructure allows for the joining of two components with multiple connection points. It is connected to the experimental substructure to improve the modal basis and reduce the required number of measurement points. In addition to the experimental TS, an analytical model of the TS was attached to the finite element (FE) substructure model. The two substructures were coupled and then both transmission simulators were subtracted. The modified TSM addressed here does not require the analytical TS be attached to the FE substructure model. The experimental TS is first subtracted from the experimental substructure. Then, a constraint equation is used to couple the resulting experimental substructure to the FE substructure model. With this enhancement, the coupling can be performed within the FE code instead of extracting the FE substructure and combining it with the experimental substructure in a separate code.

The TSM removes the difficult issues commonly found with experimental substructures: measuring connection rotational responses and moments, and measuring constraint modes or residual attachment modes with both translations and rotations at multiple connection points. It is important that the modes of the experimental substructure system form an adequate basis for the motion of the coupled system, as is the case with any modal substructuring technique. The TSM method also provides additional advantages when combining analytical and experimental substructures. The TSM captures the damping and stiffness of not only the experimental substructure, but also the joint between the experimental and FE substructure models. In addition, the TSM provides relief from experimental errors in the mode shape measurements.

A number of researches have investigated the combining of analytical and experimental substructures. The classical approach of Craig-Bampton that uses fixed interface and constraint modes [2] is difficult to implement experimentally, because the perfectly fixed boundary condition cannot be achieved. Another popular set of basis vectors addressed in the literature [4,6] is a set of modes comprised of the rigid body modes, kept free interface modes and residual flexibility attachment and/or inertia relief modes. The free interface modes are easy to measure and the rigid body modes can be either measured or calculated. Often these are not accurate enough without the residual flexibilities, because they do not capture the strain near the joint. Martinez et al. used free modes with residual flexibility [10]. Yet, the residual flexibilities between all the attachment degrees of freedom (DOF) are not easily measured, especially the rotational/moment terms. This is significantly more difficult for many attachment DOF. An attractive approach to improve the modal basis vectors experimentally is to attach masses at the coupling interface of the experimental substructure [11]. Unfortunately, if there are several connection points, this can become infeasible, for there will be a need for six sensors per connection point to determine all the displacements and rotations.

Corus et al. [12] provided a method for structural dynamic modification with similarities to the TS method. They generated a coarse finite element model of a local portion of a structure to be modified and added to it a model of the conceived modification. Then an experimental modal model of the original structure was measured and extracted. Translation measurement points on the structure that coincided with DOF on the coarse model were thus expanded to the translations and rotations connected to the new modification model using the mode shapes of the coarse finite element model.

The transmission simulator method can be viewed as an extension to the approach where rigid masses are attached to the experimental substructure [13]. However, it does not require as many sensors as physical connection DOF. This paper adds to Allen et al. modal constraint method [9] with the following: it provides a computationally efficient implementation appropriate for use in FE codes, design recommendations for the transmission simulator are offered, and a new diagnostic is addressed to eliminate indefinite matrices. The computationally efficient implementation uses multi-point constraints (MPCs) to connect the experimental substructure into the finite element substructure. This is more convenient for the finite element analyst. Previously, substructure models of the finite element substructure and experimental substructure had to use an additional computational code to perform the coupling as well as the fixture subtraction. This may not be convenient if the forces are widely distributed over thousands of DOF in the FE model. The calculation of the right hand side moving phi transpose times the force vector to another code can be tedious or even prohibitive. For these cases, it would be easier to bring the relatively small modal model of the experiment into the FE analysis code and connect it with constraints to the finite element model. Finally, the TSM also allows one to analyze the finite element model with different types of solutions (transient, non-linear transient, modal, etc.).

The paper is organized as follows. Section 2 provides the theory for the new MPC approach. This section also discusses a methodology to avoid indefinite matrices that can happen with the TSM. Section 3 provides verification examples of the new MPC approach. Section 4 elaborates on the transmission simulator design and desired characteristics. The appendix provides the original formulation for the Modal Constraint method so that the paper can stand alone for completeness.

2. Theory

This paper presents a very practical enhancement to the transmission simulator method (TSM); also known as the Modal Constraints for Fixtures and Subsystems (MCFS). The original theory is presented in Appendix A. The derivation begins with the coupling of a finite element substructure to an experimental substructure. The derivation assumes that the Transmission Simulator has already been removed from the experimental substructure in a previous step. The removal of the Transmission Simulator from the experimental substructure will be discussed after the coupling of the finite element substructure to the experimental substructure. It is important to note that many nodes of the analytical Transmission