Journal of Sound and Vibration 359 (2015) 179–194

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Formulation of an experimental substructure model using a Craig–Bampton based transmission simulator

Daniel C. Kammer [a,*], Mathew S. Allen [a], Randy L. Mayes [b]

[a] Department of Engineering Physics, University of Wisconsin, 1500 Engineering Dr., Madison, WI 53706, USA
[b] Structural Dynamics, Sandia National Laboratories[1], Albuquerque, NM, USA

ARTICLE INFO

Article history:
Received 23 October 2014
Received in revised form
20 July 2015
Accepted 2 September 2015
Handling Editor: S. Ilanko
Available online 26 September 2015

ABSTRACT

Experimental–analytical substructuring is attractive when there is motivation to replace one or more system subcomponents with an experimental model. This experimentally derived substructure can then be coupled to finite element models of the rest of the structure to predict the system response. The transmission simulator method couples a fixture to the component of interest during a vibration test in order to improve the experimental model for the component. The transmission simulator is then subtracted from the tested system to produce the experimental component. The method reduces ill-conditioning by imposing a least squares fit of constraints between substructure modal coordinates to connect substructures, instead of directly connecting physical interface degrees of freedom. This paper presents an alternative means of deriving the experimental substructure model, in which a Craig–Bampton representation of the transmission simulator is created and subtracted from the experimental measurements. The corresponding modal basis of the transmission simulator is described by the fixed-interface modes, rather than free modes that were used in the original approach. These modes do a better job of representing the shape of the transmission simulator as it responds within the experimental system, leading to more accurate results using fewer modes. The new approach is demonstrated using a simple finite element model based example with a redundant interface.

1. Introduction

Component mode synthesis (CMS) has been a fundamental tool for the structural analysis of large complex systems for years. Instead of the system being modeled as a whole, it is broken up into components or substructures that are modeled using finite elements, and then reduced to a smaller number of degrees of freedom. The substructure approach is often a necessity due to sheer model size. In addition, individual system components are often constructed by different entities leading to separate substructure models. This is especially true in the aerospace community. Substructuring can be used to couple physical or modal models of subcomponents to create a model for the assembly. Refs. [1,2] provide an excellent review of competing methods and their relations. For linear systems, one can also operate on the frequency responses

[1] Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract: DE-AC04-94AL85000.

* Corresponding author. Tel.: +1 608 262 5724.
E-mail addresses: kammer@engr.wisc.edu (D.C. Kammer), msallen@engr.wisc.edu (M.S. Allen), rlmayes@sandia.gov (R.L. Mayes).

http://dx.doi.org/10.1016/j.jsv.2015.09.002
0022-460X/

Nomenclature

dof	degrees of freedom
$\mathbf{I}$	identity matrix
$\mathbf{k}^B$	exact component B stiffness matrix
$\mathbf{K}$	stiffness matrix
$\mathbf{m}^B$	exact component B mass matrix
$\mathbf{M}$	mass matrix
$\mathbf{P}$	orthogonal projector
$\mathbf{q}$	fixed interface modal displacement vector
$\mathbf{T}$	transformation matrix
TS	transmission simulator
$\mathbf{u}$	displacement vector
$\boldsymbol{\phi}$	fixed interface modes of transmission simulator
$\boldsymbol{\Phi}$	free interface modes of transmission simulator
$\boldsymbol{\psi}$	interior partition of constraint modes

superscripts

A	component A
B	component B
C	component i
D	component D
E	system E
T	matrix transpose

subscripts

c	interface dof
C	constrained interface
CB	Craig–Bampton
F	Frobenius norm
G	uncoupled system
IP	interface preserving method
m	measurement dof
m_B	measurement locations on component B
m/c	m relative to c
o	interior dof
q	modal dof
S	static reduction to interface dof

directly to predict the response of the assembled system. The latter approach is called frequency based substructuring, or impedance coupling [1].

In recent years, there has been a renewed interest in combining analytical and experimental based substructure models using CMS. Experimental–analytical substructuring is attractive in many applications where there is motivation to replace one subcomponent with an experimental model. For example, a component may be difficult to model if it contains materials with unknown properties, intricate geometry that would require many elements to approximate, or joints or interfaces with unknown stiffness and damping properties. In these scenarios, one can perform a careful dynamic test of the substructure and extract an experimental-based model. This experimental model can then be coupled to finite element models (FEM) of the rest of the structure to predict the system response.

Over the years, a relatively large number of researchers have studied the feasibility of combining analytical and experimental substructures. For example, Martinez et al. investigated the coupling of an experimental beam like structure and a shell-payload structure [3]. Urgueira [4] considered the need for the inclusion of residual compliances when free interface substructure modes are used, and the difficulty associated with measuring rotations. Morgan et al. [5,6] developed a modified residual flexibility approach based on frequency response measured at the substructure interface. A Craig–Bampton [7] substructure representation was then recovered from the measured experimental results. Researchers have attempted to eliminate the need for interface residuals by mass loading the substructure interface during a free–free vibration test. Karpel and Newman [8] developed the fictitious mass method for mass loading the interface of analytical models of substructures. The experimental version, called the boundary mass method [9], required the attachment of large rigid masses to the substructure interface during the experimental vibration test. Ind [10] considered the problem of testing a delicate substructure by attaching a fixture, testing the combined system, and then removing the effects of the fixture from the measured responses using a variety of techniques. The direct approach to substructure coupling would be to then enforce compatibility in the physical connection, or interface, degrees of freedom between substructures. Note that "interface" and "connection" are used interchangeably in this paper. Work in this area has resulted in a measured amount of success, but in most cases, significant difficulties were encountered due to lack of sufficient precision in the measurements, uncertainties, numerical ill-conditioning, inability to measure rotations, nonphysical results, etc. Large errors in system response can result from small errors in subcomponent models [11].

Recently, a new approach was introduced by Allen et al. [12], known as the Transmission Simulator (TS) method. In this approach, the component of interest is tested with a fixture, called a transmission simulator, attached at the interface in order to improve the experimental model for the component. This method reduces ill-conditioning by imposing a least squares fit of a constraint connecting two substructures through a set of generalized coordinates corresponding to deformations of the transmission simulator, rather than connecting the substructures directly through the actual physical interface degrees of freedom. The transmission simulator method captures the compliance and damping of the bolted joints at the interface, provides a means for dealing with continuous, compliant interfaces that cannot easily be reduced to a few connection points, and improves the modal basis of the experimental component by exercising the interface. The disadvantage of this approach is that the transmission simulator must be modeled accurately and its model representation