AIAA JOURNAL
Vol. 48, No. 11, November 2010

Flexible Boundary Method in Dynamic Substructure Techniques Including Different Component Damping

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DOI: 10.2514/1.J050484

There are various condensation methods for substructure techniques in structural dynamics. A generalized condensation method that comprises most of the classical condensation techniques and allows for arbitrary mode shapes within a standardized approach is described here. Within the framework of this method, a flexible boundary method is introduced that allows for elastic and mass-loaded boundaries for eigenmode determination, as well as for mode shapes that reflect the influence of damping. The relationship to other approaches taken from existing literature is examined. For damped structures, the flexible boundary method provides a condensation process that takes into account the influence of the complex eigenmodes of structures with nonproportional and high damping. To couple substructures with different component damping, the equivalent structural damping approach is provided. The problems associated with diagonal system damping of substructures and the full triple matrix product are overcome.

Nomenclature

$[A]$	=	attachment modes
$[B]$	=	flexibility matrix
$[C]$	=	structural damping matrix
$[D]$	=	viscous damping matrix
$\{F\}$	=	external force vector
$[G]$	=	condensation matrix
$[G^*]$	=	matrix of Ritz vectors
$[K]$	=	stiffness matrix
$[M]$	=	mass matrix
$[P]$	=	projection matrix
$\{q\}$	=	vector of generalized degrees of freedom
$[R]$	=	residual flexibility
$[T]$	=	transformation matrix
$\{x\}$	=	vector of physical displacements
$[\theta]$	=	complex eigenmodes
$[\Phi]$	=	static modes
$[\varphi]$	=	real eigenmodes
Ω	=	frequency domain variable
ω	=	eigenfrequency

Introduction

FOR structural dynamic investigations, large structures are usually divided into several substructures. For undamped structures, condensation and coupling techniques are already well known and established. Usually, the condensation of mathematical models is performed by using structural mode shapes under certain boundary conditions of the interfaces (I/Fs). Clamped boundaries are used for the Craig–Bampton [1] approach that is in wide use. Several other approaches extend the base of the mode shapes and will be discussed within this paper. A discussion of general topics concerning computational methods may be found in [2,3]. The first description of a generalized method that allows the investigation of several approaches within a unified framework is presented in [4].

Received 5 February 2010; revision received 10 May 2010; accepted for publication 15 June 2010.

For structures with different component damping, severe problems occur, as described by Blelloch and Tengler [5]. Using the results of space shuttle analyses, they demonstrated that the combination of 1% damped modes with 2% damped modes on the substructure level yields several modes of the coupled structure with less than 1% and more than 2% damping. Moreover, the commonly used damping approach on the substructure level results in severe errors in the response analysis.

Several approaches were implemented in order to overcome these problems. The full triple matrix product (FTMP) is state of the art; several improvements (two-step method, Hruda–Benfield [5]) were investigated, but none of them is satisfying. In [6], the reasons for the problems are investigated. An approach that is based on the formulation of equivalent structural damping of substructures (ESD approach) is described.

Within this paper, a consistent formulation of the condensation, coupling, and analysis of structures with different component damping will be presented.

Ritz Approximation by Generalized Coordinates

In the frequency domain, the equation of motion of a substructure is noted as

$$-\Omega^2[M_{ff}]\{\tilde{x}_f\} + i\Omega[D_{ff}]\{\tilde{x}_f\} + ([K_{ff}] + i[C_{ff}])\{\tilde{x}_f\} = \{F_f(\Omega)\} \tag{1}$$

where $[M]$ denotes the mass matrix, $[K]$ denotes the stiffness matrix, $[D]$ denotes the viscous damping matrix, and $[C]$ denotes the damping matrix associated with structural damping. The displacement vector is $\{\tilde{x}\}$, and $\{F\}$ is the corresponding force vector. The f-set degrees of freedom (DOFs) include the I/F DOFs (i.e., at least the DOFs that will be coupled with other structures) and all the other independent DOFs of the substructure.

A condensation of the f-set DOFs to the reduced a set of the generalized coordinates $\{q_a^*\}$ is defined by the introduction of the approximation vector $\{x_f\}$:

$$\{x_f\} = [G_{fa}^*]\{q_a^*\} \tag{2}$$

where the number of the DOFs of the a set is smaller than the number of the f-set DOFs. The columns of the matrix $[G_{fa}^*]$ must be linear independent in order to avoid a rank deficiency problem. Apart from