Thermal/Structural Dynamic Analysis via a Transform-Method-Based Finite-Element Approach

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The paper describes a generalized transform-method-based finite-element methodology for interfacing interdisciplinary areas, with emphasis on thermal/structural dynamic applications. The purpose of the paper is to present an alternate approach for interdisciplinary analysis via a common numerical methodology for each interdisciplinary area, and therein outline the potential of the proposed formulations. Characteristic features of the methodology and fundamental concepts are highlighted for the interdisciplinary areas of heat transfer and structural dynamics. Details of a Laplace-transform-based finite-element interface methodology are described and applied to discrete-type flexural configurations subjected to rapid surface heating. Results obtained demonstrate excellent agreement in comparison with analytic solutions and/or conventional finite-element formulations. The methodology offers potential for thermostructural applications, and the concepts outlined, it is hoped, will provide avenues to interface other interdisciplinary areas as well.

Nomenclature

A = cross-sectional area
$[B_s]$ = strain-displacement function matrix
$[C_s]$ = damping matrix of structural element
$[D]$ = elasticity matrix
e = element
E = modulus of elasticity
$\{F_T\}$ = equivalent nodal thermal force vector
h = depth of structural member
I = moment of inertia
$[K_s]$ = structure stiffness matrix
$[\bar{K}_s]$ = transformed structure stiffness matrix
$[\bar{K}]$ = transformed thermal stiffness matrix
ℓ = length of structural member
m = mass per unit length
$[M_s]$ = mass matrix
$[\bar{N}]$ = transformed thermal or structural interpolation function matrix
$\{\bar{q}\}$ = transformed vector of nodal displacements and rotations
$\{\bar{Q}\}$ = transformed heat load vector
s = Laplace transform variable in transformed domain
$\{T\}$ = temperature vector
t = time
$\{u\}$ = vector of nodal displacements
w = lateral deflection of structural member
x, y, z = Cartesian coordinates
α, α_c = thermal diffusivity, thermal expansion coefficient
β = $(ms^2/4EI)^{1/4}$, see Eq. (15)
$\{\varepsilon\}$ = strain vector
θ = slope
λ = $(s/\alpha)^{1/2}$, see Eq. (12)

Subscripts
s = structure
T = temperature

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Introduction

THERMAL/STRUCTURAL modeling and analysis are of considerable practical importance to structural designers concerned with problems related to temperature-induced displacements and stresses and the associated structural dynamic response due to thermal considerations. It has been known for quite some time that when long, slender structural configurations are subjected to the rapid surface heating typical in several large space structures in orbit, thermally induced oscillations take place and may become significant. The problem of structural vibration due to thermal effects was originally introduced by Boley[1] in 1956. His studies showed that structural inertia effects in most analyses can be disregarded, thereby permitting a quasi-static thermal/structural analysis, except in uncommon cases of slender structures such as very thin beams and plates under rapid surface heating. Although complex aerospace structures have potential for thermally induced oscillations, as noted by several researchers,[2,3] there is little systematic fundamental research, particularly on thermal/structural approaches for both static and structural dynamic responses for complex structural configurations. A literature review[3-5] cites the importance of efficiently and effectively predicting the static and dynamic characteristics of large flexible structures and complex structural configurations because routine experimental and/or ground tests are highly impractical and difficult to simulate. This is especially the case when the structure's dynamic responses are due solely to thermal effects. A typical example is that of a microwave radiometer spacecraft,[3] as shown in Fig. 1. The spacecraft system is representative of complex structures characterized by lattice structures, pretensioned cables, flexural beam members, and tubular tension and compression members. The complexity of typical structural configurations influenced by the interdisciplinary nature of thermal/structural mechanics significantly influences the response characteristics and makes the analysis of such problems challenging.

The present paper describes a generalized transform-method-based finite-element methodology[6] for interfacing interdisciplinary areas, with emphasis on thermal/structural dynamic applications. The purpose of this paper is to present an alternate methodology for interdisciplinary thermal/structural dynamic analysis and therein outline the advantages of the proposed transform-method-based finite-element approach for combined thermostructural analysis. The research is aimed directly at providing avenues and concepts via a common numerical methodology for the automated solution of each of the transient heat-transfer and structural dynamic responses.