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A modified precise integration method for transient dynamic analysis in structural systems with multiple damping models

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ABSTRACT

Sophisticated engineering systems are usually assembled by subcomponents with significantly different levels of energy dissipation. Therefore, these damping systems often contain multiple damping models and lead to great difficulties in analyzing. This paper aims at developing a time integration method for structural systems with multiple damping models. The dynamical system is first represented by a generally damped model. Based on this, a new extended state-space method for the damped system is derived. A modified precise integration method with Gauss-Legendre quadrature is then proposed. The numerical stability and accuracy of the proposed integration method are discussed in detail. It is verified that the method is conditionally stable and has inherent algorithmic damping, period error and amplitude decay. Numerical examples are provided to assess the performance of the proposed method compared with other methods. It is demonstrated that the method is more accurate than other methods with rather good efficiency and the stable condition is easy to be satisfied in practice.

1. Introduction

The increasing use of composite materials and complicated engineering systems in aerospace, ship and automotive industries demands sophisticated components of dissipative forces. Furthermore, the structural components used in nanoelectromechanical and microelectromechanical systems (NEMS and MEMS) enhance the importance of modeling structural systems using multiple damping models, due to the fact that various dissipative mechanisms (including thermoelastic loss, quantum dissipation, surface loss) are involved in a small-scaled structures [1–3]. The damping model that depends on the past history of motion via convolution integrals over some kernel functions has been considered to be the most general damping model in linear system [4]. Theoretically, any quantity other than the instantaneous generalized velocities determines the dissipative forces can be called non-viscous (viscoelastic) damping model. As a consequence, the traditional dynamic methods for linear viscous damping model cannot be employed directly to deal with the non-viscous (viscoelastic) damping model problems and new methods are urgent to be studied.

In recent years, a lot of researchers have considered the dynamics of viscoelastic damping systems [5–14]. Since the solving process of eigensolutions for viscoelastic damping system is usually time-consuming, some researchers devoted to effi-

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ciently calculate the eigensolutions [15–29] and the corresponding derivatives [30–37] with different damping models. These methods can be mainly classified into tow groups. One is called state-space method [38] based on introducing internal variables. The other group is called approximate method [22–25,27–29] based on iterative algorithms.

While the above methods often attempt at solving the eigensolutions of the system, only a few studies are available towards the calculation of the dynamic response in time-domain. Muravyov [39,40] and Muravyov and Hutton [41] studied free and forced vibrations of nonviscous damping system in time-domain. Then, Adhikari and Wagner [42] proposed a direct time-domain approach for exponentially damped linear systems which largely improved the computational efficiency built on the extended state-space scheme developed by Wagner and Adhikari [21]. Later, Cortés et al. [43] presented a high-efficient direct integration formulation which did not employ any internal variables enlarging the size of original system. But the method can be only applied to exponentially damped models which the order is no higher than two. Shen and Duan [44] proposed a Gauss integration method to approximate the dynamic loadings based on the extended state-space scheme [21]. Pan and Wang [45] investigated the dynamic responses of exponentially damped systems in frequency-domain using the discrete Fourier transform as well as the fast Fourier transform method.

However, the majority of the studies mentioned above proposed methods for systems in which the damping kernel function adopted an exponential model. In practice, a wide range of damping kernel functions are possible. Liu [46] and Puthanpurayil et al. [47] proposed some implicit integration methods applicable to all possible damping kernel functions. These methods are based on Newmark integration method but suffered from high computation cost. Recently, Liu [48] presented an explicit integration method of dynamic response for non-viscous damping systems. This method performs better than the implicit methods [46,47] in efficiency, but is restricted by the scope of application for kernel functions as well as the unclear stable conditions. In addition, some studies [49–51] are also conducted for linear systems with other specific viscoelastic damping models.

Modern engineering systems often involve various subcomponents with significantly different energy dissipation levels due to their complex and large structures. Hence, two or more different damping models are usually encountered in one system. However, to best knowledge of the authors, there are few reports about the solutions of dynamic responses considering such system and the existing methods may have some limitations to deal with the problem. Recently, Ding et al. [52] proposed a time integration method for structural systems with multiple damping models. However, the linear approximation of the displacements, the velocities and the internal variables may lead to badly computational errors in some cases.

The precise integration method (PIM) [53] has been successfully used to compute the dynamic responses of structural systems for its high accuracy and efficiency [54–56]. Zhong [57] developed a linear interpolation scheme to approximate the dynamic loadings within a time step. Lin et al. [58] proposed solutions of integral term for sinusoidal and Fourier series loadings. Wang and Au [59,60] investigated the stability condition of the PIM and found it to be conditionally stable for undamped and viscously damped systems. However, the accuracy and efficiency are limited by the inherent errors in matrix inversion and the approximation of the applied loadings when considering forced vibrations. Therefore, a modified PIM method introducing a Guass-Legendre quadrature to approximate the integral term will be adopted in this paper.

The aim of this work is to present a new time integration method for multiple damping models with high accuracy. Firstly, we introduce a generally damped model to express the multiple damping properties. Then, an extended state-space method for structural systems with multiple damping models is derived. Based on the first order state-space formulation, the dynamic responses for the multiple damping models are calculated by a modified precise integration method with Gauss-Legendre quadrature. The numerical properties including stability and accuracy analyses are studied for both undamped and damped systems. The integration method turns out to be of high accuracy and conditionally stable, but the stable condition is easy to be satisfied in practice.

This paper is organized as follows: in Section 2, some theoretical backgrounds, including the preliminary concepts and basic definitions are presented. In Section 3, we propose a unified expression of damping model and its corresponding extended state-space scheme. Then, the framework of the precise time integration method for structural systems with multiple damping models is developed and summarized. In Section 4, the stability and the accuracy analyses of the proposed method are conducted. Some numerical examples and discussions are presented in Section 5 to assess the performances of different methods. The paper ends with some conclusions in Section 6.

2. Theoretical backgrounds

The equation of motion of forced vibration of an N degrees-of-freedom (DOF) linear system with viscoelastic damping models, which depend on the past history of motion via convolution integrals over suitable kernel functions other than the instantaneous generalized velocities, can be expressed in time domain as [61,22,19]

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \int_0^t \mathbf{g}(t-\tau)\dot{\mathbf{x}}(\tau)d\tau + \mathbf{K}\mathbf{x}(t) = \mathbf{f}(t) \tag{1}$$

with initial conditions

$$\mathbf{x}(t=0) = \mathbf{x}_0 \in \mathbb{R}^N, \dot{\mathbf{x}}(t=0) = \dot{\mathbf{x}}_0 \in \mathbb{R}^N \tag{2}$$