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Adaptive numerical method algorithms for nonlinear viscous and bilinear oil damper models subjected to dynamic loading

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ABSTRACT

Adaptive numerical method algorithms are presented for the numerical simulation of the hysteretic behaviour of nonlinear viscous and bilinear oil dampers within a finite element program for nonlinear dynamic analysis of frame structures under earthquake excitations. The adaptive algorithms are applicable for computing high-precision solutions for nonlinear viscous and bilinear oil dampers with valve relief that are typically represented mathematically with a nonlinear Maxwell model. The algorithms presented possess excellent convergence characteristics for viscous dampers with a wide range of velocity exponents and axial stiffness properties. The algorithms are implemented in an open source finite element software, and their applicability and computational efficiency is demonstrated through a number of validation examples with data that involve component experimentation as well as the utilization of full-scale shake table tests of a 5-story steel building equipped with nonlinear viscous and bilinear oil dampers.

1. Introduction

In the past three decades various types of supplemental damping devices have been developed and utilized in frame buildings to control seismic and wind-induced vibrations [11,14,16,6,56,57]. To this end, viscous dampers are advantageous as the forces they develop are typically out-of-phase with displacement-induced forces within a frame building under earthquake loading [13]. Recent earthquakes demonstrated the effectiveness of viscous dampers in response modification of conventional buildings to control structural and non-structural damage [26,44,7].

For the successful implementation of viscous dampers into the earthquake engineering design practice the availability of mathematical models that represent accurately the hysteretic response of such devices is necessary. Rigorous integration methods are essential for the numerical solution of these models when nonlinear response history analysis (NRHA) is conducted. Unlike in solid viscoelastic dampers [9] the temperature dependency of fluid viscous dampers is relatively low [32,57]. In contrast with the idealized assumption of purely viscous dashpot models, viscous dampers show stiffness dependency characteristics that generally undermine the effectiveness of a viscous damper [40]. Although a number of researchers, have studied the effect of axial stiffness of viscous dampers on the seismic performance of frame buildings [12,36,39,54,10], they mainly focused on linear viscous dampers. In the case of nonlinear viscous dampers, a common practice has been to neglect the damper axial stiffness [15,22,38,50,52]. This is a convenient assumption because a closed-form analytical solution of the damper force can be computed when NRHA is employed. Recent shake table experiments of a full-scale 5-story steel frame building equipped with viscous dampers that were conducted at the world's largest shake table around the world [25,48] demonstrated that the consideration of the damper axial stiffness is critical in order to accurately predict both local and global seismic demands of the test structure [25,28]. A blind analysis contest that was conducted to challenge the existing modeling capabilities for steel frame buildings equipped with various types of dampers demonstrated that when the brace and damper axial stiffness is incorporated in nonlinear viscous dampers, it improves the overall prediction accuracy by more than 20% compared to the experimental data [65]. Recent studies [16,17] have shown that the displacement-induced forces and damper force demands may be in phase within a frame building due to the axial stiffness of the respective damper. This has a profound effect on the seismic demands transferred to the steel columns and foundations and should be carefully quantified. Several researchers have

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proposed ways to account for the stiffening and frequency dependency of viscous dampers and to compute numerically their hysteretic response under harmonic and seismic excitations by employing the Maxwell model [14,40,47,53,54,59]. Typical fixed time-step integration algorithms that have been employed to obtain numerically the viscous damper hysteretic response may require considerably small integration steps to overcome convergence problems [47]. In particular, numerical convergence may still be a challenge for frame buildings equipped with nonlinear viscous dampers with high axial stiffness and small velocity exponents [47]. In such cases, a smaller integration time step for the overall analysis is necessary. This reduces the computational efficiency of the analysis of building models with nonlinear viscous dampers. This may also be a fundamental constraint for the optimal seismic design and/or retrofit of frame buildings with nonlinear viscous dampers in which the locations as well as the damper sizes should be explicitly identified as part of the optimization problem [34,35,51]. It is understood that improved integration algorithms should be utilized to reliably obtain the numerical solution of nonlinear viscous damper models.

Others have proposed ways to account for the stiffening and frequency dependency of viscous dampers to compute their hysteretic response under harmonic and seismic excitations. For instance, Terenzi [60] has employed the Kelvin-Voigt model, in which a spring is connected parallel to a dashpot. This modeling approach is commonly utilized for solid viscoelastic devices. However, a Maxwell model (i.e., spring connected in series with a dashpot), has been found to be more appropriate to account for both the stiffness and frequency dependency of fluid viscoelastic dampers [14,40,47,53,54,59]. Others [55] have utilized a mixed Lagrangian approach to conduct nonlinear response history analyses of frame structures with linear and nonlinear viscous dampers.

This paper discusses the numerical implementation of an improved adaptive algorithm for the numerical solution of the constitutive equations of nonlinear viscous and bilinear oil damper material models under dynamic loading when the axial stiffness of the dampers is considered as part of the constitutive damper formulation. The efficiency of the proposed algorithms is compared with that of traditional integration schemes that are typically used for the numerical solution of initial value problems. The proposed numerical solution techniques are implemented in an open-source finite element simulation platform and are validated with full-scale tests from nonlinear viscous and bilinear oil dampers subjected to sinusoidal excitations and various loading frequencies. Furthermore, experimental data from a 5-story steel building with the same damper types that was tested at full-scale is utilized to demonstrate the efficiency of the proposed adaptive numerical schemes in predicting global and local engineering demand parameters of frame buildings equipped with supplemental damping devices. Finally, the paper provides tools to aid the preliminary design of steel frame buildings equipped with nonlinear viscous dampers so as analysis iterations with unnecessarily too stiff or too flexible damper models can be eliminated.

2. Hysteretic behaviour of viscous dampers as pure viscous models

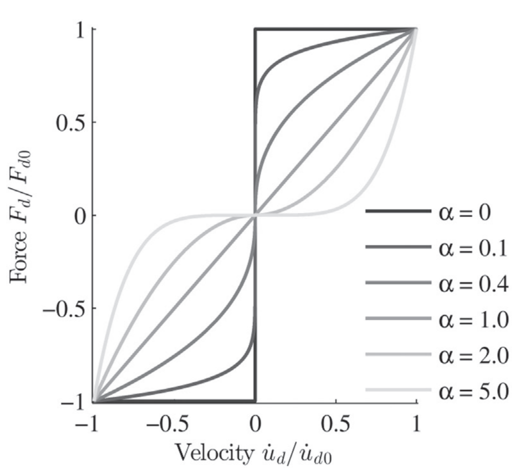
Viscous dampers contain a polymer liquid and its flow through orifices leads to pressure differential across a piston head, which produces the damper force. The design of orifice dictates the relationship between the force and velocity. Thus, the general force-velocity relationship of nonlinear viscous models can be mathematically expressed by Eq. (1) [58],

$$F_d(t) = C_d\,|\dot{u}_d(t)|^{\alpha}\,\mathrm{sgn}(\dot{u}_d(t)) \tag{1}$$

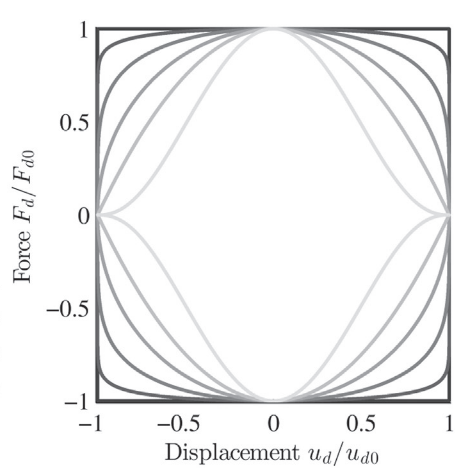
in which, C_d is the damping coefficient and α is the velocity exponent that characterizes the viscous material; u_d is the dashpot displacement; and sgn represents the signum function. Thus, the peak force F_{d0} of a viscous damper under a harmonic displacement excitation that is described as $u_d(t) = u_{d0}\sin(\omega t)$, is as follows,

$$F_{d0} = C_d(\omega u_{d0})^{\alpha} \tag{2}$$

in which, u_{d0} and ω are the peak displacement amplitude and the circular frequency of the sinusoidal excitation, respectively. Fig. 1 shows the normalized force-velocity and normalized force-displacement relations of nonlinear viscous models with different α values. A typical Bernoullian cylindrical shaped orifice produces forces, which are proportional to the square of the velocity (i.e., $\alpha = 2$). Such dampers are utilized for shock wave absorption. For $\alpha = 1$, a viscous damper becomes linear while for $\alpha = 0$ the force-displacement hysteretic relation of a viscous damper becomes rectangular, which is typical for friction models [49]. For seismic design applications of frame buildings the capability of limiting the damper force output under high velocity pulses is often desirable. Therefore for seismic applications, α is often selected such that $\alpha < 1$. Because linear viscous dampers produce forces that vary linearly with respect to the velocity demand, large damper forces may be generated under high velocity demands. This introduces uncertainties and conservatism in capacity design of non-dissipative members. In order to overcome this undesirable response, bilinear oil dampers were developed that contain a relief mechanism, which suppresses the force after a certain limit [23,27,32,61]. This creates a bilinear relation between the damper force and velocity as



(a) Force - velocity relation



(b) Force - displacement relation

Fig. 1. Hysteretic behaviour of nonlinear viscous dampers with various velocity exponents under sinusoidal motion.