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Title: Response Modification of Structures with Supplemental Rotational Inertia

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Motivation

Tall, multistory, buildings are becoming increasingly popular in large cities as a result of growing urbanization trends. As cities continue to grow, many of them along the coasts of continents which are prone to natural hazards, the performance of tall, flexible buildings when subjected to natural hazards is a pressing issue with engineering relevance. The performance of structures when subjected to dynamic loads can be enhanced with various response modification strategies which have been traditionally achieved with added stiffness, flexibility, damping and strength. Together with the elastic spring that produces a force proportional to the relative displacement of its end-nodes and the viscous dashpot that produces a force proportional to the relative velocity of its end-nodes; the inerter produces a force proportional to the relative acceleration of its end-nodes and emerges as the third elementary mechanical element (in addition to the spring and dashpot) capable for modifying structural response. Accordingly, in this report we examine the seismic performance of multistory and seismic isolated structures when equipped with inerters.

Objectives

The main objective of this report is to develop response analysis techniques and offer insights on the dynamics of multistory and seismic isolated structures when equipped with inerters. The extensive elastic and inelastic response analysis offered in this report addresses issues such as the effect of the compliance of the support of the inerters and the potential advantages of employing a pair of clutching inerters.

Methodology

The response analysis presented in this study employs standard techniques known in structural dynamics. Whenever the equations of motion are coupled, the response is computed in the time-domain by following a state-space formulation.

Conclusions

The basic response-functions of the inerter and other simple inertoelastic and inertoviscous networks derived in chapter 2 in association with the mathematical operations outlined, extends the well-established theory of linear viscoelasticity to the inertoelastic and inertoviscoelastic behavior (combination of inerters, dashpots and springs) and introduces the subject of inertoviscoelasticity.

Chapter 3 shows that the supplemental rotational inertia (inerter) controls effectively the displacements of the first story of a two-degree-of-freedom (2DOF) elastic structure along a wide range of the response spectrum. The proposed seismic protection strategy can accommodate large relative displacements without suffering from the issue of viscous heating and potential leaking that challenges the implementation of fluid dampers under prolonged cyclic loading. When the frame that supports the rotational inertia system is stiff, the use of two parallel rotational inertia systems offers improved results for the response of the 2DOF structure. However, as the compliance of the chevron frame that supports the inerters increases, the use of a single rotational inertia system offers more favorable response other than increasing the forces transferred to the chevron frame.

Chapter 4 shows that while a small amount of supplemental rotational inertia is needed to eliminate the participation of the second mode of the 2DOF linear isolated structure; the effect of this elimination is marginal on the structure response, since the participation of the second mode is invariably small even when isolation systems without inerters are used. The nonlinear response analysis of the same 2DOF isolated structure is examined by adopting a bilinear behavior for the isolation system in association with a formulation that accounts for the compliance of the support of the inerter. Our study shows that supplemental rotational inertia aggravates superstructure displacements and accelerations at larger isolation periods ($T_b > 2.5sec$). In view of these findings in association with the small gains in reducing displacements above isolators, the use of inerters in isolation systems is not recommended.

The response analysis of a SDOF elastoplastic and bilinear structure in chapter 5 reveals that when the yielding structure is equipped with supplemental rotational inertia (inerters), the equal displacement rule is valid starting from lower values of the preyielding period given that the presence of inerters lengthens the apparent preyielding period. Furthermore, inerters suppress effectively the inelastic displacements of SDOF and 2DOF yielding structures; while the resulting base shears are systematically lower than when large values of supplemental damping ($\xi_d = 25\%$) are used. The forces transferred at the mounting of the inerters are appreciably lower than the corresponding forces originating from an elastic structure analyzed in chapter 3. Consequently, the implementation of inerters emerges as an attractive response modification strategy for elastoplastic and bilinear SDOF structures with larger preyielding periods. The use of a pair of clutching inerters does not offer any additional benefits compared to the case where a single inerter is used. Pair of clutching inerters are found to be attractive when suppressing the response of elastic structures. The effectiveness of inerters to suppress the inelastic response of the 2DOF yielding structure outperforms appreciably the effectiveness of large values of supplemental damping ($\xi_d = 25\%$) when the support frame of the response modification device is compliant. For larger pre-yielding periods (say $T_1 > 2.0sec$), the effectiveness of inerters to suppress the inelastic response of 2DOF yielding structures reduces; and for very flexible first stories; as in the case of isolated structures examined in chapter 4, the use of inerters at the first level (isolation system) is not recommended.

Motivated by the known distinct property of inerters when installed without being interrupted, starting from the first level, to suppress the ground induced excitation; in association with a growing number of publications that examine the response of tall buildings when equipped at a higher level with a solitary mechanical network that involves ineters. In chapter 6, we examine whether inerters have indeed a unique role when placed at floor-levels other than the first level. Our study shows that in spite of the reduced role of inerters when placed at floor levels other than the first level, they still manifest a unique role since it is not possible to replace a structure with solitary inerters at higher levels with an equivalent tradional structure without inerters. Our proof contributes to support the merit of past investigations that examine the use of solitary inerters installed at higher floor-levels as alternative tuned mass dampers.

Keywords: Supplemental rotational inertia, Response modification, Inerter, Nonlinear analysis, Seismic protection, Earthquake Engineering.