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PREFACE

Preface for the special issue on advances on inerter-based seismic protection of structures

Agathoklis Giaralis[1] · **Alexandros A Taflanidis**[2]

The emergence of the inerter, both as an idealized mechanical element and as a device, contributed a new dimension to the field of structural vibrations control over the past 20 years, by enabling the provision of readily scalable inertia to structures and to dynamic vibration absorbers without adding any significant gravitational mass. Theoretically, this is based on the default definition of the ideal inerter to be a zero-weight linear two-terminal mechanical element resisting relative acceleration by a force proportional to a constant termed inertance and measured in mass units (kg). Technologically, a plethora of inerter devices have been prototyped and experimentally verified, achieving inertance several orders of magnitude higher from the device physical mass by relying on different technologies including flywheels with gearing mechanisms, hydraulic pumps, fluid mechanics principles, and electromagnetic emulation.

Historically, the first inerter-like device were developed as early as 1970s in Japan, motivated by earthquake engineering applications, with some device embodiments patented in late 1990s and underpinned by some early theoretical studies in 2000s. However, it was the seminal paper by Prof. Malcolm Smith (Smith 2002) to rigorously define the inerter mechanical element and to conceptualize possible mechanisms to materialize devices with scalable inertance. In early 2010s, it was theoretically established that efficient seismic response mitigation in building structures can be achieved by using inerters, either as standalone elements (Takewaki et al. 2012), or in judicial combinations with damping and stiffness elements to form inerter-based vibration absorbers (IVAs), such as the tuned viscous mass damper (TVMD) in Ikago et al. (2012), the tuned inerter damper (TID) in Lazar et al. (2014) and the tuned mass damper inerter (TMDI) in Marian and Giaralis (2014). Further, by 2017, a handful of high-rise buildings were completed in Japan featuring TVMD

✉ Agathoklis Giaralis Associate Professor
agathoklis@city.ac.uk

Alexandros A Taflanidis Professor
a.taflanidis@nd.edu

[1] Department of Engineering, University of London, London, UK

[2] Department of Civil and Environmental Engineering and Earth Sciences, University of Notre Dame, Notre Dame, IN, USA

devices for earthquake resistance. Building on the above developments, the use of inerters and IVAs in earthquake engineering applications attracted immense attention of researchers worldwide in the past 5 years.

In this regard, the timeliness, proliferation, and promise of inerter-based vibration control solutions for structural seismic response mitigation created the premise for organizing this special issue, the first to be focusing explicitly on this niche area. We received more than 20 full papers, from which 13 have been included in this special issue following a rigorous reviewing process to ensure that the current state-of-art in this rapidly expanding field is reflected, and that novel and potentially impactful developments are communicated. Contributions are coming from several different groups with long-standing research activity in the area and with a wide geographical distribution to include North America, Europe, Asia, Africa, and Australia.

More specifically, this special issue includes several contributions addressing the novel application of inerter-based seismic vibration control to a wide range of special structures. In this context, Labaf et al (2022) propose the use of base isolation in combination with the TMDI for mitigating the seismic response of cylindrical liquid storage tanks. The design of the resulting passive hybrid vibration control system is underpinned by solving a multi-objective optimization problem for a simplified linear model of a typical liquid storage tank resting on isolators and fitted with a TMDI, while accounting for liquid-structure interaction. The potential of the proposed hybrid vibration control system is numerically assessed through linear response history analysis for a suite of recorded ground accelerations, demonstrating the key role of the TMDI in mitigating both the impulsive and the convective response displacements. Additionally, Xu et al (2022) studies the potential of TID for response mitigation of offshore steel jacket platforms, widely used by the oil and gas as well as by the wind renewable energy sectors, under combined wave and earthquake loadings. Linear structural response is assumed for which an analytical design method is put forth to determine optimal TID installation location and tuning. The reported numerical data evidence that the platform deck is the optimal TID installation location for both wave and seismic loads. Further, the tower-top displacement mitigation in seismically excited land-based wind turbines is addressed in Chen et al (2021) using a wide range of different linear optimally tuned IVA configurations attached to turbine nacelle. The performance of IVA configurations are numerically assessed by considering comprehensive numerical results pertaining to a linear model of a well-studied benchmark wind turbine with 5 MW capacity exposed to different recorded ground accelerations. It is shown that IVAs perform better than the conventional tuned mass damper absorber currently considered by wind turbine developers in practical applications.

Turning the attention to base isolated buildings, Ye and Nyangi (2021) consider the incorporation of inerter elements within dual-layered seismic isolation systems to control the lateral seismic deformation demands at the isolators, without compromising the effectiveness of the dual isolation system in reducing inter-storey drifts and floor acceleration in the superstructure (building). Optimal design of the inerter-equipped dual isolation system is considered assuming linear response in the isolators and the superstructure, while response history analysis for a suite of recorded ground motions is undertaken to demonstrate a favorable numerical assessment of the proposed system. Moreover, Wang et al (2021) studies numerically the potential of an IVA featuring an electromagnetic damping element for enhancing the seismic performance of base isolated structures under earthquake excitations representative to different site soil conditions. To this aim, the authors adopt a linear simplified IVA model together with linear structural and isolation layer behavior and pursue optimal IVA design and assessment using a phenomenological nonstationary stochastic seismic model which account for different site soil properties to define the seismic action. Comprehensive numerical data derived from non-stationary random vibration analyses as well as from response history analyses using artificial and recorded ground motions are provided, demonstrating good efficacy of the IVA with electromagnetic element for the task at hand.

From a theoretical viewpoint, the inerter can be seen as a frequency-dependent negative stiffness element. In this respect, the inerter element and associated devices complement the frequency-independent negative stiffness (NS) device configurations, oftentimes materialized technologically through pre-tensioned springs, which have also attracted significant recent interest for seismic response mitigation of buildings. In this regard, Kalogerakou et al (2022) proposes a novel vibration absorber for mitigating structural response due to the vertical ground motion component combining NS elements, tuned mass damper and inerter devices. An efficient optimal design approach of the absorber is put forth ensuring good acceleration isolation without compromising the gravitational load-bearing capacity of structures, while numerical assessment is undertaken using a large suite of vertical components of recorded accelerograms. Further, Islam and Jangid (2022) contribute a theoretical study on the optimal design and assessment of various novel vibration absorber configurations combining NS and inerter elements with damping and stiffness elements for the seismic protection of base-isolated structures.

The optimal tuning of IVAs is very important to fully exploit the presence of inerter devices and becomes challenging when multiple IVAs are used and/or in the presence of nonlinearities. In this regard, Zhang et al (2022) develops a semi-analytical method for optimal design of multiple TVMDs in multi-storey buildings to achieve a pre-specified (targeted) displacement performance. Further, Rajana et al (2022) develops a practicable method for optimal TMDI design with nonlinear viscous dampers in multi-storey buildings and numerically assesses the influence of such a nonlinearity vis-à-vis the linear TMDI using a benchmark 9-storey steel moment resisting frame. Moreover, Patsialis et al (2021) contributes a numerical bi-objective IVA design framework for multi-storey hysteretic buildings whereby the peak IVA force assuming linear device behavior and the consequence of critical engineering demands parameters (such as storey-drifts and floor accelerations) exceeding predefined design thresholds are taken as the objectives of the optimization problem. The framework uses spectrum compatible recorded ground motions to model the earthquake hazard and is numerically illustrated for TMDI and TID devices using the previous 9-storey steel benchmark structure which exhibits nonlinear (yielding) behaviour.

Additionally, Talley et al (2022) and Zhang et al (2022) shed new light to the potential of the energy dissipative clutching inerter damper (CID) for seismic response mitigation of hysteretic structures and of rocking structures, respectively, both modelled as nonlinear single degree of freedom systems. The CID is nonlinear and dissipates kinetic energy by combining two flywheels driven by rack and pinion mechanisms with mechanical clutching which engages/disengages each flywheel depending on the direction of the structural displacement. In this regard, Talley et al (2022) undertake incremental dynamic analysis to demonstrate the positive impact of CID for delaying the onset of structural yielding and collapse, while Zhang et al (2022) examined thoroughly the effects of different CID parameters using a detailed mechanical model of the absorber to nonlinear seismic rocking response.

Finally, Deastra et al (2022) study experimentally the potential of TID/TMDI with hysteretic frequency-independent damping, instead of the commonly considered frequency-dependent viscous damping, for a more accurate representation of real-life devices and their implication to the seismic response mitigation of multi-storey buildings. This is achieved by fitting different parametric device models to experimental data from a shaking table testing campaign for a scaled three-storey frame structure equipped with TID/TMDI with hysteretic gel dampers as well as with viscous eddy current dampers.

Overall, this collection of papers represents well the breadth of inerter applications in earthquake engineering, while further contributes important theoretical and technological developments in this field. We hope that it will serve as a solid starting point for researchers who foresee to embark on research in this rapidly growing field, as well as a focal point to researchers already working in diverse aspects and applications of inerter-based seismic protection of structures. Lastly, we aspire that this special issue will contribute in increasing the awareness of practising engineers on the potential of inerters to reduce the seismic vulnerability of different existing and new structures.

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