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Passive, semi-active, active and hybrid mass dampers: A literature review with associated applications on building-like structures

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ABSTRACT

In this paper, a state-of-the-art literature review is presented emphasising on the development of control variants for mass damper schemes on building-like structures. Additionally, a systematic literature review is conducted addressing three relevant questions: What type of mass damper is preferable by the associated industry? How are mass dampers distributed around the world? Is industry following research? Through the systematic literature review, updated lists of mass damper implementations and control algorithm applications in real-life structures were compiled. 208 case-studies are discussed in total. It is found that, 63% of them refer to passive tuned mass dampers, 31% to hybrid mass dampers, 4.0% to active mass dampers and only 2% to semi-active mass dampers. Regarding control algorithms, controllers of 24 structures driving semi-active, active or hybrid mass dampers are presented. It is concluded that the industry considerably lags behind latest structural control research both regarding implementations and overall management.

1. Introduction

Over the recent years, there has been an increasing trend of building high-rise structures around the world (CTBUH (2020)). This trend came along with the modern way of designing and constructing buildings, aiming to keep them sustainable and aesthetically pleasing. Ultimately, this evoked their slender and lightweight design. Sustainable building design is arguably an effective design approach since, less material is required for the construction of a project. However, such structures may be vulnerable to excessive vibrations caused by dynamic loadings, i.e. wind (Simiu and Yeo (2019); Solari (2017); Nikitas et al. (2011)), earthquake (Jangid and Datta (1995); Xie et al. (2020)), human action (Sachse et al. (2003); Živanović et al. (2005); Jones et al. (2011)) and traffic (Avci et al. (2020)). The need for vibration control due to dynamic loadings, forced the structural control research community to develop smart systems that will allow vibration mitigation in civil structures. The evolution of the smart control systems that are studied today, arise mainly from passive solutions. Amongst many, one technology that received a great attention is the tuned mass damper (TMD). A passive TMD (PTMD) was firstly proposed by Frahm (1911) for decreasing the rocking motion of ships. Since then, serious efforts have been made by the structural control community to enhance the performance of the PTMDs which lead to the development of semi-active, active and hybrid mass dampers.

A PTMD consists of a constant mass, spring (stiffness element), and dashpot (viscous damping element), as shown in Fig. 1 (a). This control appendix is attached to a vibrating system (structure) to reduce any undesirable vibrations. When referring to buildings, it is usually located at the top floor and tuned to the fundamental frequency of the global uncontrolled structure, dissipating in this way considerable amounts of external energy input. The PTMD is characterised by its mechanical simplicity, cost-effectiveness and reliable operation Yang et al. (2021).

The semi-active technology can be deemed as the directly evolved energy dissipating technology from passive since, it integrates adaptive, rather than constant, elements to improve performance and effectiveness, as shown in Fig. 1 (b). The semi-active TMD (SATMD) capitalises on its adaptiveness by gathering information about the structural response and adjusting damping and/or stiffness parameters in real-time using a performance optimisation strategy. The SATMDs consist of sensor(s), a control system (controller), a stiffness and a damping device with either or both allowing adjustment of their base values. Bhaiya et al. (2019) state that the semi-active systems can be thought as being the most efficient control strategy of any alternative however, this depends on inherent limitations of SATMDs e.g. those utilising

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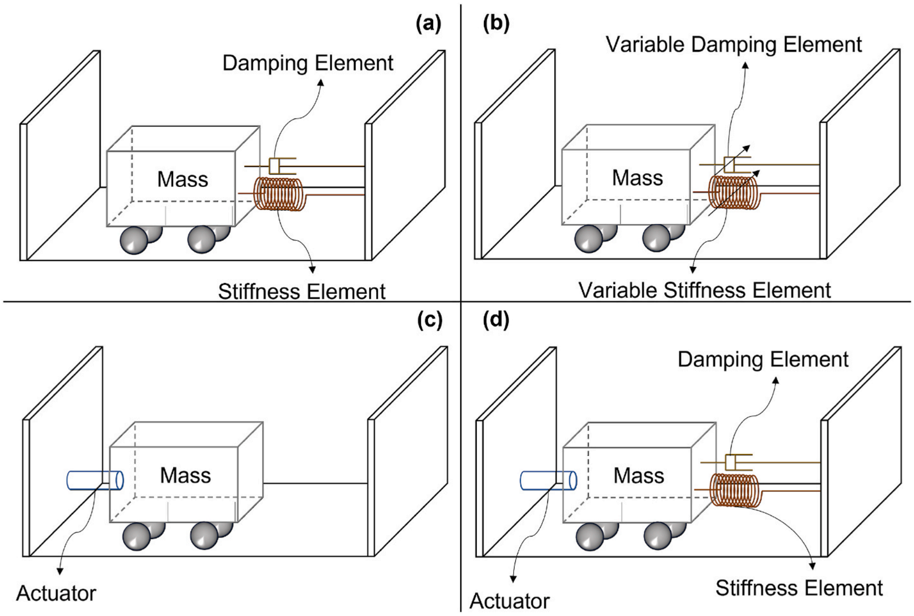

Fig. 1. Illustration of mass damper options: a) PTMD, b) SATMD with variable stiffness and variable damping, c) AMD, d) typical HMD, combining passive and active parts, ATMD.

magnetorheological (MR) dampers have bounds in the control force capability. Spencer and Nagarajaiah (2003) mentioned that, appropriately installed semi-active systems have a significantly enhanced performance when compared to the passive equivalents and have the potential to achieve, or surpass the performance of even fully active systems. Nagarajaiah (2009) mentions that, in semi-active control, the variation of stiffness is considered to be more efficient since, the stiffness adjustment can directly track the instantaneous tuning frequency. In the case of the damping variation, it is stated that, the damping ratio needs to change extensively, defeating in this way the main purpose of the TMD; the tuning. Thus, the damping becomes the dominant characteristic and not the tuning. The author concludes that, it is generally more desirable to use the stiffness parameter as the variable property rather than the damping unless, there are major constraints that need to be encountered, such as stroke length.

Active control systems consist of sensor(s), controller(s) (with a predetermined algorithm as in Wani et al. (2022)), and actuator(s) (seen in Fig. 1) (c). An active control system requires a relatively large power in order to allow the actuators to provide large control forces in real-time. Active control systems are mainly designed to increase the effective structural damping, without any major impact in the effective structural stiffness. Their sensors can be located at different positions of the structure to measure the external excitation in terms of distributed system response variables i.e. velocities, displacements, accelerations and the control forces, mass damper position. The controller receives the data from the sensors, and after analysing it, it generates a control signal to drive the actuator(s). Therefore, the controller uses a feedback function of the lagged measured data provided by the sensors and produces actuation signals. The actuators produce appropriate forces that could naturally deviate from these controller signals. Such a so-called active mass damper (AMD) was installed on a real high-rise building for the first time ever in 1989 on the Kyobashi Seiwa Building in Japan (Kobori et al. (1991)).

Elias and Matsagar (2017) state that a hybrid control system can be a combination of passive to passive, passive to active and alike control techniques. This type of systems started becoming very famous structural control options since, they aim to minimise negative characteristics that each system has when acting independently yielding a more efficient structural control system overall. Soong and Spencer (2002) mention that, the term “hybrid” generally denotes a configuration that combines passive and active control systems. Additionally, they state that the passive part controls a portion of the control objective and thus, less active control effort is needed, which leads to lowering the power consumed by the active part. It is noticed that in the literature, there is an inconsistency in the terminology of mass damper systems. More specifically, researchers tend to describe their proposed systems as hybrid when referring to active tuned mass dampers (ATMD) since, the aforementioned system combines by default a passive and an active control system (as seen in Fig. 1 (d)). Ikeda (2009) states that in Japan, it is common to refer to an ATMD as a hybrid mass damper (HMD) because, the ATMD is considered to be a derivation from either active control or passive control. Specifically, Kobori (1996) mentions that the ATMD is referred to as hybrid control since, it is the alteration of a passive TMD into an active one. Moreover, they add that another form of a hybrid control system is the mounting of an AMD on a TMD. Sakamoto and Kobori (1995) report that this type of hybrid systems is popularly called DUOX.

Previous reviews in the structural control field include the works of Housner et al. (1997) who included passive, semi-active, active and hybrid systems and Spencer and Sain (1997) who reviewed the research development of structural control systems including 24 full-scale building and 15 bridge implementations, actuator types and characteristics, and new technological and algorithmic trends. Kareem et al. (1999) presented an overview of the state-of-the-art control systems for the response reduction of civil structures, and included a list of 27 full-scale mass damper applications. Symans and Constantinou (1999) presented a state-of-the-art review of semi-active control systems for the protection of structures under earthquake loading. Buckle (2000) presented a review of the control performance passive systems under seismic excitations. Nishitani and Inoue (2001) presented an overview of 29 buildings equipped with active and hybrid control systems in Japan. Soong and Spencer (2002) reviewed the development and assessment of passive, semi-active, active and hybrid control and included a list of 40 full-scale implementations of mass damper control systems. Spencer and Nagarajaiah (2003) reviewed the structural control schemes and presented a list of 46 building and 15 bridge mass damper applications. Datta (2003) reported an updated review of the active control systems applied on earthquake excited structures. Jung et al. (2004b) reviewed the dynamic models used for semi-active mass dampers with MR fluid dampers. Ikeda (2009) presented a a list of 52 real practical applications of active and semi-active control schemes on buildings in Japan. Fisco and Adeli (2011a) presented a state-of-the-art review of active and semi-active control systems and a companion paper (Fisco and Adeli (2011b)) where the same authors reviewed the hybrid control systems and control strategies within the civil engineering field. Casciati et al. (2012) reviewed the theory and applications of active and semi-active control of civil structures. Gutierrez Soto and Adeli (2013) reviewed the PTMD research efforts and demonstrated a list of 93 real full-scale applications of PTMDs on civil structures. Basu et al. (2014) attempted to give a common frame by demonstrating the recent research and applications of structural control systems across Europe. Nagarajaiah and Jung (2014) reviewed the advances in smart TMDs which included active and semi-active mass dampers. Saaed et al. (2015) reported a review of passive, semi-active, active and hybrid control systems used for the response control of civil engineering structures. Elias and Matsagar (2017) presented a state-of-the-art review of civil structures using passive TMDs. Yang et al. (2021) reported a critical review of structural control vibration dissipation using TMDs where they focused on TMD modifications, mathematical modelling, and optimisation procedures to obtain the TMD optimal parameters. They also included active and semi-active dampers, and TMD practical realisations.

2. Paper contributions

This work aims to provide firstly, an exhaustive literature review including advances in the area of structural control using mass damper technology. Secondly, it aims to systematically gather a list of real mass damper applications of building-like structures around the world and draw conclusions through the application trends.

The explicit contributions of this work are:

1. Review the efforts that have been made by the structural control community in order to:
    - Include an up-to-date detailed review of studies which consider passive, semi-active, active, and hybrid mass damper control of civil structures
    - Present the state-of-the-art control algorithms that proved efficient for the control of civil structures
    - Identify the control system limitations, as these are reported in the literature
2. Carry out a systematic literature review to:
    - Report an updated list of real-life applications of mass dampers systems on building-like structures
    - List the control algorithms utilised on real buildings for the first time ever
    - Draw conclusions on the installation trends of passive, semi-active, active and hybrid mass dampers through the years
    - Understand whether the research carried out in the literature was applied in real-life applications
    - Identify potential gaps between the research trends and the needs of the associated engineering sector

3. Paper structure

This work is structured as follows: Section 4 presents a review of studies found in the literature including the advances of passive, semi-active, active and hybrid mass dampers, while Section 5 reports their limitations (categorised as hardware or software-related) as these were reported previously. Section 6 includes the explanation of the systematic literature review approach to be pursued and emphasises on its importance. Section 7 discusses the findings of the systematic literature search regarding the real-life implementations of mass damper systems along with the associated control algorithms. Finally, Section 8 includes the conclusions of this study and puts forward suggestions for guiding future research focus.

4. Mass damper control systems

This section includes the collection of research advances for passive, semi-active, active and hybrid mass dampers. In each subsection, the studies are organised in a chronological order.

4.1. *Passive tuned mass dampers*

One amongst the first methods for the parameter determination of PTMDs was attempted by Den Hartog (1956) where, expressions for the optimum damping ratio and frequency ratio of the undamped mass subjected to harmonic excitation were derived. It is worth mentioning that, the Den Hartog equations are based on the assumption that the structures are modelled as single degree of freedom (DOF) systems. To account for the damping in the main system, Falcon et al. (1967) developed a graphical method which was suitable for different types of structural vibration. Randall et al. (1981) and Ayorinde and Warburton (1980) developed various design charts in order to obtain the optimum parameters with known mass ratios and different primary system damping. Furthermore, the optimal parameters for tuned mass dampers under random excitations idealised by white noise were then proposed by Warburton (1982).

Clark (1988), studied how the use of multiple tuned mass dampers (MTMDs) on tall structures manage a significant response reduction under a seismic action. In contrast, it was stated that a single tuned mass damper is not recommended for reducing the seismic response of tall buildings. For many buildings, many of their modes of vibration are closely packed in the seismic excitation range. The first design rule is to place the TMDs at the antinode locations of the individual mode shapes. To decide on how many modes to consider, one must examine the mode shape matrix, the participation factors, the earthquake design response spectrum and the natural frequencies of the structure.

Xu et al. (1992) conducted wind-tunnel tests and theoretical analyses to investigate the vibration mitigation performance of passive TMDs on tall buildings under wind excitation. They used a scaled building model (1:400) of the CAARC Standard Tall Building. They tested this model with TMDs with different parameters in a wind tunnel to investigate the dissipation performance of the TMDs. They concluded that, the TMDs were effective in suppressing the wind-induced dynamic response of the building however, its performance could be enhanced with the implementation of an active control system.

Lin et al. (1994) examined the effectiveness of a passive tuned mass damper in reducing the primary structural responses under stochastic environmental loadings. It was found that the passive TMD was useful and it is more appropriate to a structure that its fundamental frequency is less than that of the input excitation. It was stated that an optimum passive TMD can reduce both earthquake and wind induced structural responses. Finally, it was shown that the passive TMD was more effective on reducing the wind induced vibrations rather than those induced by an earthquake and are useful for lightly-damped structures. Based on their numerical simulations, the authors concluded that, the passive TMD was effective on reducing the seismic responses by 60% and it was even more efficient on reducing the acceleration responses than the corresponding displacements.

Kwok and Samali (1995) demonstrated the effectiveness of TMDs in the dynamic response control of tall buildings under wind excitations. The authors concluded that the passive TMD can achieve an additional 3–4% critical damping and 40–50% response reduction.

Tsai (1995) studied the performance of a TMD on base isolated structures. The authors used a 5-storey base-isolated building equipped with a TMD under seismic loading. Their results showed that, during the first seconds of the simulation, the TMD had a very little effect on the response of the building, however, it can add damping to the structure achieving in this way a reduced structural response. Finally, it was shown that, the TMD can be more efficient when the damping of the base-isolation system has lower damping values.

Sadek et al. (1997) proposed a method for estimating the parameters for a TMD in the case of seismic excitation. The results show that the proposed method reduces significantly the displacement and acceleration of the buildings. The authors used their proposed method for the control of single and multi-DOF structures under seismic excitations. It was found that the TMDs achieved a response reduction of the order of 50%. Concluding, the authors stated that this method can be applied in the vibration control of tall buildings.

Lin et al. (2000) considered the effectiveness of TMDs on the vibration control of irregular buildings. The authors designed multi-DOF torsionally coupled shear buildings which were excited by bi-directional seismic loading. Two TMDs were introduced at the building models and, to determine the optimum location installation and the moving direction of the TMDs, the authors used the controlled mode shape values. The TMDs were used to control both the translational responses of the building models. Their simulations showed that the PTMDs were effective on reducing the responses of the a long and a square five-storey torsionally coupled buildings under five different seismic excitations.

Singh et al. (2002) presented an approach for the optimal parameter selection for the design of TMDs for the control of torsional buildings under bi-directional earthquake loading. A genetic algorithm was used to find the optimum parameters of four TMDs with fourteen design parameters. The TMDs were installed in pairs in orthogonal directions. Their results demonstrated the effectiveness of the optimal parameter selection on the dynamic response control of torsional systems.

Pinkaew et al. (2003) investigated the effectiveness of the TMD on the damage reduction of buildings under earthquake loading. The authors stated that, the effectiveness of the TMD on decreasing the displacement of the structure after the yielding point is found to be insufficient thus, they considered the damage reduction of the structure. For their simulations, they developed a single-DOF equivalent system of a 20-storey reinforced concrete building under harmonic and the 1985 Mexico City earthquake excitations. The authors added different degrees of damage protection and collapse prevention for the assessment of their model where, it was found that the TMD can be effective on preventing the structure from collapse and increase its yield resistance.

Wang et al. (2003) studied the application of TMDs for the control of train-induced vibrations on bridges. For their simulations, the authors modelled the railway bridge as an Euler–Bernouli beam, and the train forces were modelled as moving forces, moving masses, and moving suspension masses in order to simulate various vehicles on the bridge. By using the simply supported bridges of Taiwan High-Speed Railway (THSR) under German I.C.E., Japanese S.K.S. and French T.G.V. trains, the authors demonstrated the effectiveness of the TMD on decreasing the vertical displacements, absolute accelerations, end rotations, and train accelerations during resonant speeds.

Lee et al. (2006a) proposed a design approach for structures with TMDs by taking into account the states of the full dynamic system of multi-DOF structures, multiple TMDs located on different building floors and the power spectral density function of the environmental excitations. To demonstrate the effectiveness of their method, the authors used a single-DOF and a ten-DOF model equipped with a single TMD and a five-DOF model equipped with two TMDs. In all scenarios the feasibility of the method was shown.

Avila and Gonçalves (2009) investigated the influence of the masses of MTMDs on the main system dynamic performance using four different arrangements of double mass dampers. By using a minimax procedure, the authors showed that small variations on MTMD parameters and the way that the masses are connected have an influence on the response of the main structure.

Lackner and Mario (2010) considered the structural control of offshore wind turbines using TMDs. Two TMDs were installed in the nacelle of the wind turbine, acting in two different directions. After carrying out a parametric study to obtain optimal parameters of the TMDs, the authors demonstrated the effectiveness of the TMDs on response control of the offshore wind turbines. Finally, it was stated that the results show the potential for active control approaches.

Bekdaş and Nigdeli (2011) studied the optimal parameter determination of TMDs using the harmony search metaheuristic optimisation method. The authors used the peak values of first storey displacement and acceleration transfer function as the optimisation criteria. To demonstrate the effectiveness of their methodology, a ten-DOF structure was used under the El Centro (1940) NS excitation. Moreover, a second example was considered with different floor properties. The authors compared their scheme to other methodologies such as Den Hartog (1956), Warburton (1982), Sadek et al. (1997), and Hadi and Arfiadi (1998) and demonstrated the effectiveness of their scheme.

Chakraborty and Roy (2011) contacted a reliability based optimisation of TMD parameters for the vibration control of a structure subjected to seismic accelerations considering UBB (uncertain but bound) type system parameters. It was found that the optimum TMD parameters and associate probability of failure of the primary system have no unique values, and rather provides bounds. However, when considering the system parameter uncertainties, a change in the optimum parameters of the TMD and the probability of failure of the primary structure was observed. Finally, the authors mentioned that, if the uncertainty which affects the parameters of the system is not considered, the TMD performance is overestimated. Moreover, the upper bound of response may be used in such cases for a conservative estimate of the optimum TMD parameters.

Mohebbi and Joghataie (2012) studied the performance of TMDs for the response control of nonlinear frame structures subjected to seismic excitations. For the optimal parameter determination of the TMD, the authors implemented a distributed genetic algorithm. For the performance index to be minimized, the authors derived a function of the response of the nonlinear structure to be controlled. It was concluded that the proposed method was efficient on determining the optimum parameters of a TMD capable of reducing the structural responses. The authors noted that, the simplicity and the desirable convergence behaviour of their scheme were also very important outcomes of their methodology.

Yu et al. (2013) report a reliability based robust design optimisation methodology for TMDs. The authors mention that, in contrast to conventional stochastic design optimisation, their methodology is applicable for deterministic and or uncertain structures and it can take into account safety and quality simultaneously. A single-DOF system was used to test the performance of the TMD designed using the proposed methodology. When compared to a conventional stochastic design optimisation procedure, the effectiveness of the proposed optimisation methodology was presented.

Stewart and Lackner (2014) considered the control of offshore wind turbines subjected to external excitation, particularly considering the effect of wind–wave misalignment on the tower loads. The authors implemented TMDs and showed that, they managed to decrease the side-side loads caused by the wind–wave misalignment by over 40%. Moreover, they showed that the increase in the TMD mass from 10,000 kg to 20,000 kg had little benefit on the TMD performance. Concluding, the authors mentioned that the TMD is a cheap and robust solution for suppressing the tower vibrations in the offshore environment.

Yang et al. (2015) proposed an innovative approach for the optimal design of distributed TMDs. The authors compared their methodology to conventional ways for the design of distributed TMDs. It was found that the proposed design approach demonstrates superior performance and robustness compared to the conventional methodologies, and provides a simple and straightforward way to determine the optimum parameters of the distributed TMD system.

Marian and Giaralis (2015) proposed a control system which is a generalisation of the classical TMD. More specifically, the authors designed a TMD inerter to suppress the oscillatory motion of a structure. It was mentioned that this system uses the so-called ”mass amplification effect” of the inerter to enhance its performance compared to a conventional TMD. It was found that, an optimally designed TMD inerter outperforms the conventional TMD when tested in the suppression of the displacements of an undamped single-DOF structure excited by white-noise. When tested in multi-DOF structures for vibration suppression, it was seen that again, the TMD inerter was more effective on suppressing the fundamental mode of vibration compared to the classical TMD. It was concluded that, the TMD inerter configuration can either replace part of the TMD vibrating mass to achieve lightweight passive vibration control solutions, or improve the performance of the classical TMD for a given TMD mass.

More recent studies investigate TMD parameter optimisation by using various computational and mathematical methods. Amongst others, Elias and Matsagar (2017), developed a distributed genetic optimisation algorithm based on the minimisation of a performance index to find a set of TMD optimal parameters, including its stiffness and damping. Khatibinia et al. (2018) proposed an optimal design procedure of a TMD under continuous stationary critical excitation representing the most severe earthquake. The authors mentioned that optimal parameters are obtained by minimising the sum root of the mean square of story drifts defined in the frequency domain. Thus, the performance of the Improved Gravitational Search Algorithm (IGSA) using a ten story shear building with a TMD was investigated. The results showed that the IGSA converges to better solutions when compared to other algorithms. Moreover, Kang and Peng (2019) studied the optimal parameters of large mass ratio TMD and used numerical optimisation methods and a revised formula based on a fitting technique to achieve an enhanced version of previously existing formulas.

Yucel et al. (2019) used machine learning to achieve optimum TMD parameters and concluded that, their equations and graphs can be easily and effectively used as a tuning tool for the TMD parameter determination. In this paper, an Artificial Neural Network (ANN) model was proposed aiming to generate the tuning parameters of a passive TMD. For the training of the ANN, the optimum parameters of several single-DOF structures were used. The optimum values were determined using a flower pollination algorithm (FPA) (i.e. optimisation method). Moreover, the ANN model was used to generate three basic tuning formulations which were tested on single-DOF and multi-DOF structures. Lastly, when the structures were tested under seismic excitation by considering the stroke of the TMD, the parameters that occurred from the proposed model were found to be more effective than the optimum parameters that were determined from the existing formulations.

Colherinhas et al. (2019) studied the optimal parameter determination of a pendulum TMD for the control of a slender tower under random excitation. The tower was modelled as a single-DOF system. The authors used a genetic algorithm to determine the parameters (flexural stiffness/damping, mass ratio and pendulum length) of the pendulum TMD. For their fitting function, the authors chose the minimisation of the maximum frequency peaks.

Stanikzai et al. (2019) studied the control of base-isolated structures with TMD under seismic loading. For their simulations, the authors used two-dimensional reinforced concrete multi-DOF buildings. The TMD were located on different floors of the building in order to investigate its response control performance. It was concluded that, when the time period of the isolators was increased, the performance of the TMD reduced. Moreover, the placement of the TMD in low-rise buildings has no significant effect while in the case of larger structures, the placement of the TMD has a noticeable role in the overall vibration dissipation performance.

Zucca et al. (2021) proposed a methodology for the optimisation of the TMD design for the control of a historical masonry chimney located in northern Italy. The authors derived a two-phase optimisation procedure where, in the first phase, the TMD parameters were defined by starting from the dynamic behaviour of the chimney by finite element modelling. In the second phase, the authors considered the nonlinear behaviour of the masonry by using a fiber model of the chimney. The results showed the effectiveness of the proposed methodology for the control of slender masonry structures.

4.2. Semi-active mass dampers

Researchers have been investigating the performance of various algorithms and optimisation methods in order to achieve more efficient SATMDs.

Hrovat et al. (1983) were the first to study the performance of a SATMD in the field of structural control (Spencer and Nagarajaiah (2003); Yalla et al. (2001)). The authors proposed a SATMD for the control of wind excited tall buildings and compared its performance to a fully active system and to a traditional PTMD. It was found that the proposed SATMD had a better performance than the PTMD and similar dissipative performance to the active system. Actually, in some aspects, i.e. mass stroke requirements, it was superior to the active system without requiring high power to operate as the active system did.

ABÉ (1996) investigated the performance of a SATMD whose initial displacement varies based on the feedback. Their control algorithm was developed in a simple closed form using the perturbation solutions of vibration modes. Their proposed scheme was investigated using a single-DOF model equipped with the mass damper. The performance of the proposed SATMD was compared to a traditional PTMD under impulse and earthquake loadings. It was found that, in both cases the SATMD outperformed the PTMD showcasing its capabilities.

Ricciardelli et al. (2000) proposed an empirical algorithm for the optimisation of the SATMD performance based on the measured response. The authors mention that the proposed procedure allows for the properties of the SATMD to be updated in order to improve its vibration dissipation performance. The benefit of the proposed algorithm is the fact that the exact knowledge of the properties of the main structure is not needed neither it is bound to a particular form of excitation. The proposed algorithm requires only an estimate of the first frequency of the main structure and the smoothness of the excitation spectrum.

Setareh (2002) proposed a new class of SATMDs called the ground-hook tuned mass dampers (GHTMDs) for the control of the floor vibrations due to human movement. To obtain the optimum parameters of the GHTMD, the author used the minimisation of the acceleration response of the floor, the mass ratios, and the damping ratios of the floors. When compared to a classical PTMD, it was found that the GHTMD had a better performance of about (14%). Lastly, when tested in off-tuning conditions, the author concluded that the GHTMD demonstrated robustness compared to its passive counterpart.

Xu et al. (2003) considered the semi-active control of structures using MR dampers. The authors proposed an on-line real-time neural network (NN) algorithm which was trained on-line with the Levenberg-Marquardt algorithm. Their algorithm was designed to account for the time-delay problem that may occur in semi-active control schemes. Using a three-DOF reinforced concrete model the authors demonstrated the effectiveness of their algorithm on the response reduction of the structure under seismic loading.

Nagarajaiah et al. (2004) studied the effectiveness of a SATMD with variable stiffness. The proposed system was tested on a 76-storey building and its performance was compared to a passive TMD. The tuning frequency of the proposed SATMD was determined based on an empirical mode decomposition and Hilbert transform instantaneous frequency algorithm developed by the authors. It was found that the SATMD had an enhanced performance on reducing the dynamic response of the structure when compared to the uncontrolled case and the case with the conventional TMD.

Nagarajaiah and Varadarajan (2005) proposed a new semi-active variable stiffness SATMD which aimed to continuously varying its stiffness and returning its frequency in real-time. The proposed scheme implemented a short-time Fourier transform to identify the dominant frequency of response and track its variation as a function of time to retune the SATMD. The study investigated the control performance of the proposed semi-active scheme in the case of a tall building subjected to wind excitations and compared it to a passive TMD and to the uncontrolled scenario. It was found that the proposed system is effective in controlling the response of the structure when it was subjected to stiffness alternations. The authors mentioned that the proposed SATMD can achieve the performance of an ATMD while, using considerably less power.

Yan et al. (2007) developed a model predictive control (MPC) algorithm for semi-active control schemes with MR dampers in order to reduce the non-linear earthquake response of high-rise buildings. The authors demonstrated the performance of their scheme on a twenty-storey benchmark building and compared it to other semi-active control schemes on the same buildings such as linear quadratic Gaussian (LQG) by Ohtori et al. (2004), and clipped LQG by Yoshida and Dyke (2004).

Lee et al. (2010) experimentally investigated the performance of four semi-active control schemes on a full-scale five storey steel frame building structure, subjected to four historical earthquakes. The algorithms that were investigated within this study were; the clipped-optimal control algorithm (CO) proposed by Dyke et al. (1996) for controlling MR dampers; Lyapunov stability theory-based control algorithm (LYAP) where the Lyapunov function was based on Leitmann (1994), the maximum energy dissipation algorithm (MEDA) by McClamroch and Gavin (1995); and Cost Function-based Semiactive Neuro-control (CFNC) by Jung et al. (2004a) and Lee et al. (2006b). Their results showed that the LYAP and CFNC were more efficient on reducing the accelerations of the structural system where, the passive counterpart and MEDA had a good performance on decreasing the first floor displacements.

Kang et al. (2011) studied the effectiveness of a SATMD equipped with MR dampers in the response of a high-rise benchmark building under wind excitation. The authors derived a ground-hook (GH) controller for the control of their proposed scheme. Their SATMD was compared to the performance of a PTMD, a ATMD, and a SATMD with variable stiffness. Their results showed that their SATMD had a similar performance to the ATMD but with significantly lower power consumption.

Laflamme et al. (2011) developed a neurocontroller which was able to self-adapt and self-organise, and it was used in the semi-active control of uncertain systems. The authors used NNs to build the controller. Using Lyapunov stability, the adaptive rules of the controller were determined and thus, the robustness of the controller was achieved. The neurocontroller was assessed through various numerical simulations for harmonic, earthquake and wind excitations. In the case of wind excitation, it was found that the proposed controller outperformed a linear quadratic regulator (LQR) controller.

Elhaddad and Johnson (2013) studied the implementation of a hybrid MPC algorithm on semi-active control applications. The authors stated that the hybrid MPC is more suitable for semi-active control since, it can accurately model the passivity constraints by using auxiliary variables into the system model. After experimenting the proposed algorithm on a typical structure under seismic excitation, and comparing the results to the clipped LQR algorithm, it was found that the hybrid MPC was more consistent in the reduction of the objective function. However, it is mentioned that the hybrid MPC required more computational power.

Chung et al. (2013) proposed an innovative phase control methodology for the control of a SATMD applied on a simplified Taipei 101 structure model under sinusoidal and design level wind excitations. The main aim of the work was to minimise the off-tuned problems that are associated with the conventional TMDs. The results showed that, the SATMD that operated with the proposed methodology demonstrated better vibration dissipation performance and robustness compared to the passive TMD, particularly in the off-tune scenario.

Aiming to enhance the proposed work in (Nagarajaiah and Varadarajan (2005)), Sun and Nagarajaiah (2014) studied the performance of a semi-active control scheme, implementing variable stiffness and damping, under seismic excitation. The damping ratio of the proposed scheme was designed to vary based on the measured SATMD displacement. Moreover, by using a short-time Fourier transform-based algorithm to analyse the tracked displacement of the structure, the stiffness of the SATMD was tuned. The authors compared the proposed scheme with an optimal PTMD to investigate its performance. It was concluded that the variable stiffness and damping SATMD outperformed the PTMD with optimal parameters. Moreover, the effect of structural damage was studied to investigate the performance of the SATMD. It was found that, the proposed scheme was able to capture the variation in the structure and thus, it remained tuned in contrast to the PTMD which remained detuned.

Demetriou et al. (2015) investigated the performance of a SATMD equipped with a Proportional Derivative Integral (PID) controller applied on a multi-storey structure subjected to earthquake excitation. The numerical results showed that, the semi-active control system presented a better performance when compared with a TMD with optimum parameters.

Miah et al. (2015) investigated the application of the LQR algorithm equipped with an unscented Kalman filter (UKF) observer for the real-time mitigation of structural vibration on a SATMD. When they compered the LQR-UKF performance with the LQG algorithm and then validated it on a joint state-parameter estimation problem where the system model was assumed uncertain and updated in real-time; it was concluded that this method is highly promising.

Demetriou et al. (2016) studied the performance of a SATMD with different control strategies for the control of a high-rise structure under wind-loading. More specifically, the authors investigated the performance of five algorithms namely; the GH (displacement and velocity-based), clipped optimal, BANG and PID. It was found that, the algorithms that proved to be more efficient (clipped optimal, displacement-based GH and PID) sacrificed the minimisation of the damper strokes in contrast to the velocity-based GH and the BANG controllers.

In their paper, Bathaei et al. (2018) investigated the performance of a semi-active system which consisted of a TMD and an adaptive MR damper. For the control of the MR damper, type-1 and type-2 fuzzy controllers were used. The design of the fuzzy controllers was done by using the accelerating and decelerating movements of the 11-DOF test model. From the analysis, it was concluded that, the type-2 controller which considered the uncertainties related to the input variables had a better performance than the type-1 controller. Lastly, the authors stated that the type-2 controller reduced the maximum displacement, acceleration and base shear of the structure by 11.7%, 14% and 11.2% compared to the type-1 controller.

Liu et al. (2018) numerically applied a multi-SATMD device configuration on the multi-span Poyang Lake railway steel bridge aiming to increase its fatigue life for which there were major concerns. Each SATMD device consisted of an MR damper attached to a TMD, while the baseline PTMD scenario was also considered for comparison purposes. The control strategy employed a simplest possible fixed incremental control algorithm, while for the PTMD scenario the extreme cases of the MR devices providing constantly their minimum (voltage off) and maximum (voltage on) damping capability were examined. As reported, the multi-SATMD over doubles the considered nominal lifespan and achieves more than 15% better performance than the higher damping (MR damper voltage on) PTMD control solution.

Zelleke and Matsagar (2019) developed an energy-based predictive (EBP) algorithm for semi-active control systems. Their results showed that the SATMD equipped with the EBP algorithm can reduce the vibration response and the energy imparted on a structure as compared to a PTMD, especially with excitations with distinct frequencies.

Park et al. (2019) investigated the performance of a SATMD on the vibration mitigation of offshore wind turbines. More specifically, this study focused on the availability of a MR damper model on a TMD and its effectiveness on the control of offshore wind turbines. The proposed scheme utilised different GH control based logics, and their performance was studied based on the frequency response. The semi-active control scheme was compared with a PTMD for the vibration control of both fixed-bottom and floating offshore wind turbines under fatigue and ultimate limit states. It was found that, the semi-active control scheme outperformed the PTMD. More specifically, the SATMD equipped with a displacement-based GH controller had the best performance by reducing the fore-aft and side-to-side damage equivalent loads by around 12% and 64% respectively.

Weber et al. (2020) investigated the performance of a tuned mass damper equipped with an inerter (TMDI). The authors mentioned that the floor on which the inerter is grounded is directly related to the performance of the TMDI. Thus, the total performance of the TMDI was assessed based on a function of the floor on which the inerter was grounded. The TMDI was tested in the response reduction of a 20-story building model. To provide a better representation of the performance of the TMDI, the authors used the classical TMD as a benchmark for their study. When they simulated for broadband and harmonic excitations of the first three bending modes, it was found that the TMDI performed better when the inerter was grounded to the earth since, the inerter force was proportional to the absolute acceleration of the TMD rather than the relative acceleration of the two inerter terminals. They also mentioned that, in order for the TMDI to outperform the TMD, while having the inerter anywhere below the TMDs' floor, the inerter should be installed within approximately the first third of the building's height. Lastly, when investigating the most realistic case were the inerter is installed on the same floor as the TMD, the TMDI had worse performance than the classical TMD.

Shih and Sung (2021) developed an impulsive semi-active mass damper (ISAMD) for the control of a high-rise building. The authors proposed a directional active joint as the breaker to lock and unlock contact between the structure and damper in order to overcome the detuning effect that a PTMD may suffer from. When the proposed scheme was tested under seismic loading it was found that, when compared to a PTMD, the ISAMD had enhanced reduction performance on the maximum and root-mean-square (RMS) displacement. Moreover the ISAMD did not experience detuning, and has a stable control effect.

Dai et al. (2021) considered the vortex-induced vibration (VIV) control on long span bridges. They mention that, even though the passive TMDs are efficient on controlling the VIV, they present robustness issues especially the TMDs with small mass ratios. The authors proposed a SATMD with MR dampers for the mitigation of VIV with slowly time-varying frequency. The authors proposed a real-time tuning and mass stroke limitation methodology for the SATMD. For the control command determination, a feedforward control named the piece-wise linear interpolation (Weber (2013)) was adopted with a kinematic Kalman filter (Jeon and Tomizuka (2007)). For the modal identification of the long-span bridge the authors used the analytical mode decomposition method which was proposed by Chen and Wang (2012) in order to improve the modal identification accuracy. From the simulations it was concluded that, the proposed SATMD demonstrated robustness and superior performance against the resonant frequency uncertainty compared to the PTMD.

Wang et al. (2021) considered the control of human-induced vibrations on footbridges using a semi-active-type mass damper. The authors mention that, the traditional PTMDs are very sensitive to frequency deviation and suffer from detuning effects. Human-induced vibrations cover a wide range of frequencies and are considered to be of stochastic nature. Moreover, they add that the human-structure interaction can change the structural characteristics of the bridge. Thus, the authors state that, the PTMD may not be efficient on controlling the human-induced vibrations on bridges and thus, they proposed a semi-active mass damper with variable mass. The proposed system operates by using a Wavelet-transform based controller which identifies the instantaneous frequency of the bridge in real time and adjusts the mass of the control scheme appropriately. The authors used a simply-supported pedestrian bridge as a case study. The effectiveness of the proposed scheme was investigated under single pedestrian periodic and stochastic walking-induced excitations, and under crowd-induced stochastic excitation. Moreover, the effect of the human-structure interaction was investigated in their schemes. It was found that, the proposed semi-active control scheme had an excellent vibration control performance and outperformed the PTMD in all cases. Moreover, they found that, the human-structure interaction may amplify or reduce the structural responses and this depends on the type of the input loads and the pedestrian body frequencies.

4.3. *Active/hybrid control*

Maebayashi et al. (1992) proposed a prototype HMD for the response control of tall buildings against strong winds and moderate seismic loads. The prototype HMD consists of an auxiliary mass, multi-stage rubber bearings which support the mass, and actuators driven by AC servo motors. The control algorithm was designed using the optimal control theory. The HMD was installed on a real 7-storey building (30 m tall) built in 1991 at the Institute of technology of Shimizu Corporation in Tokyo. The authors mentioned that, the HMD keeps the control force to zero when the building responses are below a prescribed level and, in the case of strong winds and earthquakes (when the building responses increase) the actuators start to operate automatically. From tests and observations during strong winds, it was concluded that the HMD is effective on suppressing the building responses during strong winds and earthquake loadings.

Taida et al. (1994) investigated the control of the bending and torsional vibrations of a six-stage structure equipped with two HMDs. For the control law of the systems, the LQ optimal control theory was used. The performance of the dampers was investigated in two cases; i) decomposing signals into bending and torsion and ii) separating the sensor signals. It was concluded that, in both cases the HMD were effective on controlling the bending and torsion of the structure. When comparing the two cases, the case (i) was proved to have a better overall performance.

Suzuki et al. (1994) presented a study on the performance of an AMD when controlling a real high-rise tower called "Riverside Sumida Building". For the control of the tower, the authors developed a controller based on control optimal theory. Moreover, they introduced a variable-gain algorithm allowed for the scaling of the control force based on the magnitude of the vibration of the building in order to achieve the most effective control possible. Based on vibration tests and earthquake response observations, the authors concluded that, their control approach achieved the control of multiple vibration modes without causing spillover.

Lopez-Almansa et al. (1994, 1995) investigated the implementation of predictive control on civil engineering applications. However, in this case, the authors used the predicted trajectory and the control force for one time - step only, to express their objective function.

Nagashima and Shinozaki (1997) considered the control of an AMD with the practical limit of the auxiliary mass stroke length. The authors proposed a variable-gain feedback control algorithm combined with static output feedback control. The effectiveness of the proposed hybrid control method was showcased using a single-DOF system. It was found that the proposed method had a good performance against both seismic and sinusoidal excitations with respect to the mass stroke, control power and control smoothness.

Nishimura et al. (1998) investigated the control of an active-passive composite TMD equipping an office building in Tokyo in 1993. The proposed device was installed to control random disturbances such as wind and seismic loadings. For the control of the proposed system, the authors used the acceleration feedback algorithm. Moreover, the optimum parameters, the control force minimisation, and the power and energy under various types of disturbances were obtained. The authors designed a state estimator and tuning adjustments were made possible electrically instead of mechanical stiffness adjustments. The control system application proved the feasibility of the control algorithm by comparing the observed control performance to the mathematical simulations.

Mei et al. (2001) in their study, focused on the general formulation of MPC for the real-time control of structural responses under seismic excitations. The optimisation objectives that were used in this study were; the minimisation of the difference between the predicted and desired response trajectories, and the control effort based on selected constraints. The prediction model was constructed using feedforward and feedback components to achieve maximum efficiency. The feedforward loop was designed based on the Kanai-Tajimi-type model for the earthquake input representation. Moreover, an auto-regressive model was used to constantly update the earthquake ground motion based on real-time on-line observations and thus, achieve predictive and adaptive nature in the control actions. After comparing the MPC scheme with H_2 control strategies, it was concluded that the MPC scheme can provide effectiveness comparable to the optimal control.

The performance of a new HMD system which consisted of a gear-type pendulum and a linear actuator was studied by Nagashima et al. (2001). Two HMD systems were used to control the transverse-torsional coupled vibration of a 36-storey high-rise building with a bi-axial eccentricity. A variable gain feedback (VGF) control technique was developed to achieve the maximum capacity of the HMD system. It was concluded that the maximum and RMS acceleration responses were reduced to 63% and 47% respectively, confirming in this way the control performance of the system.

The implementation of MPC scheme in the control of structures under earthquake loading was again studied by Mei et al. (2002). Their scheme used the acceleration feedback to estimate the states of the structure. The optimisation objectives of this study included the minimisation of the difference between the predicted and desired response trajectories, alongside the control effort based on specific constraints. To build the prediction model, accelerations measurements were contained in a feedback loop. Moreover, the states of the system were determined by a Kalman-Bucy filter state observer. Single-story and three-story buildings were tested using active tendon control and AMD control. It was concluded that the MPC scheme using acceleration feedback was an effective control method.

Mei et al. (2004) investigated the use of MPC scheme, applied on the structural control of a benchmark building which is subjected to wind excitations. The authors used an explicit prediction model of the system response to minimise the objective function and thus, determine the control actions. It is mentioned that, MPC optimisation objectives were the minimisation of the difference between the predicted and desired response trajectories, and the control effort which can be limited by various constraints. Moreover, the MPC scheme was tested in both, with and without constraint cases, and then it was compared to a LQG algorithm. The inequality constraints on the maximum control force and mass damper displacement were considered on the objective function. The authors concluded that, by using input/output hard constraints, optimal control force can be achieved through the MPC scheme which satisfies the prescribed constraints.

Kumar et al. (2007) stated that, it is a general belief that the fixed parameter controllers suffer from degradation in their performance when the system parameters are subjected to a change. It was noted that conventional controllers can become unstable with these parametric uncertainties. Generally, it is desirable that the closed-loop poles of the perturbed structural system remain at pre-specified locations for a range of system parameters. Their paper investigated the pole placement-based controller design techniques, aiming to obtain robust performance by manipulating the closed loop poles of the perturbed system. These techniques were studied on active vibration control applications. It was observed that the adaptive pole placement controllers are noise tolerant but require high actuator voltages to maintain stability. Moreover, the robust pole placement controllers require comparatively small amplitude of control voltage to maintain stability, but they are noise sensitive.

Yang et al. (2011) aimed to reduce the number of sensors required in real implementations by using the modified predictive control which was derived with the partial-state concept of direct output feedback. The proposed scheme computes the control forces by determining the actual output measurements which are then multiplied by a designated constant output feedback gain matrix. To produce the feedback gain in a symmetric and efficient manner, an off-line numerical method was introduced. Two control systems were tested, single-controller and multiple-controller, in order to validate the feasibility of the modified predictive control with direct output feedback. Moreover, the application of an AMD controlled by the proposed scheme was applied on a large-scale 5-story structural model. The results showed that the proposed scheme can achieve good performance under environmental excitations.

Banerji and Samanta (2011) in their paper investigated the mounting of a tuned liquid damper (TLD) on a secondary mass which is attached to the primary structure with a spring system. The authors state that for the hybrid mass liquid damper (HMLD) system, there is an optimum value of the spring connection system for which the HMLD can achieve maximum efficiency. Lastly, it was concluded that a HMLD with optimum design parameters can be more effective device than a standard TLD for both harmonic and broad-band earthquake motions.

Li et al. (2011) studied the performance of a hybrid control system on a nonlinear structure subjected to seismic excitation. For their hybrid system, an AMD was implemented on the top of the structure. The authors stated that, an AMD control system can cause a magnification of the interstory drift of a nonlinear building. This phenomenon is called interstory response amplification (IRA) and for its elimination, interstory dampers were utilised. The control algorithm that was used for the AMD was a fuzzy logic-based controller. Based on the numerical simulations it was concluded that the proposed hybrid system can eliminate the IRA phenomenon and achieve better vibration control when compared to a single AMD control system or to interstory dampers alone.

Noormohammadi and Reynolds (2013) developed a HMD for the vibration control of structures (i.e. stadia) subjected to human excitation. Their proposed HMD consisted of a PTMD with an actuator attached to the TMD mass. After comparing the proposed HMD to a PTMD, the authors concluded that the performance has considerably enhanced.

Mitchell et al. (2013) suggested the use of a wavelet-based fuzzy neurocontrol algorithm on a hybrid control system for the structural control of buildings under seismic excitations. The hybrid system consisted of an actuator, a TMD and viscous liquid dampers. The proposed algorithm was developed by integrating the discrete wavelet transform, an ANN and a Takagi - Sugeno fuzzy controller. When comparing the proposed system with the performance of passive viscous liquid dampers and an ATMD subjected to seismic excitations, the effectiveness of the proposed system was proven.

Li et al. (2014) proposed a fuzzy sliding mode control (FSMC) method for the control of a shear frame equipped with an ATMD. The authors mention that, their algorithm avoids the undue chattering effect which is the main disadvantage of conventional sliding mode controllers, without losing its robustness against parameter uncertainties. When compared to a PTMD and an AMD, the proposed scheme demonstrated better response control and stability.

A HMD aiming to reduce the resonant vibration amplitude of structures was proposed by Collette and Chesné (2016). The proposed hybrid system included passive and active components. In this case, the direct velocity feedback control was used, and two zeros were added to the controller allowing it to interact with the poles of the plant. When the proposed system was compared with an AMD system, it requires smaller active forces and thus less energy for a better damping performance.

Demetriou and Nikitas (2016) developed an energy and cost-efficient hybrid semi-active mass damper. For the design of this hybrid system, an active and a semi-active control component were used. After testing its performance on single and multi-DOF structures, it was found that the new configuration outperformed the conventional passive and semi-active systems. Moreover, it is stated that the performance of the new hybrid system was similar to the active configuration however, it consumed considerably less energy and reduced actuation demands. Thus, it satisfied the strict serviceability and sustainability requirements. The main difference between an ATMD and the novel hybrid system presented in this research is that, the ATMD adds and dissipates energy to the system while the proposed hybrid system just dissipates. It is noted that in this study, the semi-hybrid mass damper (SHMD) device was regulated by an optimal LQR controller, while the semi-active components were controlled via a direct output feedback displacement based ground-hook (DBG) controller. Based on the numerical results it was found that, the proposed device was effective in reducing both the steady-state and the peak frequency responses of the structural system while achieving similar performance gains to that of an ATMD-equipped structure. Lastly, it was shown that the successive action of active and semi-active elements allowed an improvement in efficiency both in terms of power and actuation demands. In a later work, Demetriou and Nikitas (2017) worked towards the optimisation of system's performance where, strict sustainability and serviceability requirements were satisfied, making it a practical and reliable control solution.

Etedali and Tavakoli (2017) studied the performance of proportional derivative (PD) and PID controllers for the seismic control of high-rise buildings. For comparison purposes, a LQR controller was also used. The numerical results showed that the PD/PID controllers performed better than the LQR in terms of reduction of the maximum top storey displacement, maximum absolute acceleration of stories as well as maximum drift of stories. Lastly, the authors concluded that, the PID had a better performance than the PD controller.

Chen et al. (2017) developed a novel fast model predictive control algorithm (NFMPC) for the control of large scale civil structures. The authors state that, most of the computation of the algorithm was done explicitly, allowing for a small amount of on-line computation, which guarantees the efficiency of the controller. When compared to a standard MPC on a ten-storey plane frame, on a three-dimensional cable-stayed bridge, and on a forty-story three-dimensional frame, the proposed MFMPC algorithm was proved to be an efficient control method.

Meinhardt et al. (2017) presented the installation of a HMD with passive, semi-active and active capabilities. It is interesting to note that, since the building was not completely built by the time their work was published, the control system was only treated as a PTMD.

Peng et al. (2017) demonstrated the effectiveness of their proposed novel fast model predictive controller with actuator saturation used for the control of a plane adjacent frame structure under seismic loading. When compared to a nominal MPC, it was found that the proposed controller is highly efficient and it is a good application for large-scale structural dynamic control problems.

Aiming to mitigate the stroke size of their previously proposed HMD system in Li and Cao (2015), Cao and Li (2018) proposed an enhanced hybrid active tuned mass dampers system (EHATMD) in order to attenuate undesirable oscillations of structures under ground acceleration. Their design consisted of two ATMDs with different mass ratios on top of each other. By employing the genetic algorithm, the effects of varying the key parameters on the optimum performance of the EHATMD were studied and compared to a hybrid mass damper (HMD) with optimum parameters. It was concluded that the proposed EHATMD outperforms the HMD and thus, it can be considered as a novel extension of the HMD.

Bhaiya et al. (2019) studied the hybrid control schemes using different combinations of MR and TMDs to minimise the seismic responses of buildings. To evaluate the performance of the proposed hybrid system, the authors used purely SATMD control systems. The responses were obtained using four control strategies i.e. LQR with clipped algorithm, passive-on, passive-off, and velocity tracking control. It was concluded that by using a combination of a TMD and fewer number of MR dampers, a 40–45% response control can be achieved.

Chang and Sung (2019) proposed a modal-energy-based neuro-control algorithm (v) for the control of civil structures under seismic excitations. The modal energy of the structure was used as an objective function for the controller training and the control signal and modal energy were used for minimisation by the controller. The authors used a three-storey nonlinear building equipped with an AMD. It was concluded that the algorithm was efficient on decreasing the structural responses and the modal energy. Lastly, nonlinear hysteretic behaviours occurred in the uncontrolled scenario however, in the MEBNC controlled case these nonlinear behaviours were almost disappeared.

Chen and Chien (2020) proposed a machine learning based optimal control method for the control of civil structures under earthquake loading. The authors mentioned that, optimal control methods require the full state feedback which may not be available on real applications and time-delay and state estimation errors may affect the control performance. Thus, they developed a multilayer perceptron (MLP) model and an autoregressive with exogenous inputs (ARX) model in machine learning. The goal was for the algorithm to learn the control forces generated from an LQR which was designed using a symbiotic organisms search algorithm. It was concluded that, when tested on a ten-storey building, both MLP and ARX were able to estimate the LQR forces with acceleration feedback, eliminating in this way the need for state estimators. Lastly, the machine learning approach was tested experimentally, with a model equipped with an AMD under seismic excitation. It was found that both MLP and ARX had a good performance on emulating the LQR performance when compared to a LQR with a Kalman filter.

Mamat et al. (2020) developed an adaptive nonsingular terminal sliding mode control algorithm for the control of seismically excited buildings. For the control device, the authors used a hybrid control system which consists of passive and active characteristics. For their simulations, they used the El Centro and the Southern Sumatra earthquakes and compared their algorithm performance with a fuzzy logic controller and a sliding mode controller. It was found that, the adaptive nonsingular terminal sliding mode control algorithm had a superior performance compared to the other two controllers in terms of displacement responses, performance indices, and the probability of building damage.

Kayabekir et al. (2020) modified a music-inspired harmony search algorithm for the parameters of an ATMD and of a PID-type controller. The authors demonstrated the effectiveness of their scheme on a ten-storey shear building. It was found that, the ATMD could reduce maximum displacement of the structure by 53.71% and had a 22.51% better performance than a PTMD.

Xu et al. (2020) investigated the performance of ATMDs for the control of adjacent buildings under earthquake loading. The authors implemented an observer-based active vibration control law and demonstrated its performance. The proposed scheme performance was tested on a 10 and a 6-DOFs adjacent buildings with two different actuator saturations (779 kN and 1000 kN). From the simulations it was found that the proposed scheme was efficient on reducing the structural responses. Lastly, it was mentioned that, when the actuator saturation changed from 779 kN to 1000 kN the control system had an enhanced performance of 52% on the structural displacement reduction.

Koutsoloukas et al. (2020) considered the vibration control of a real high-rise tower using an ATMD. For the control of the mass damper system, the authors developed an MPC with a Kalman filter. The performance of the algorithm was compared to a LQR and to a corresponding PTMD. It was concluded that, the MPC outperformed both the LQR and the PTMD.

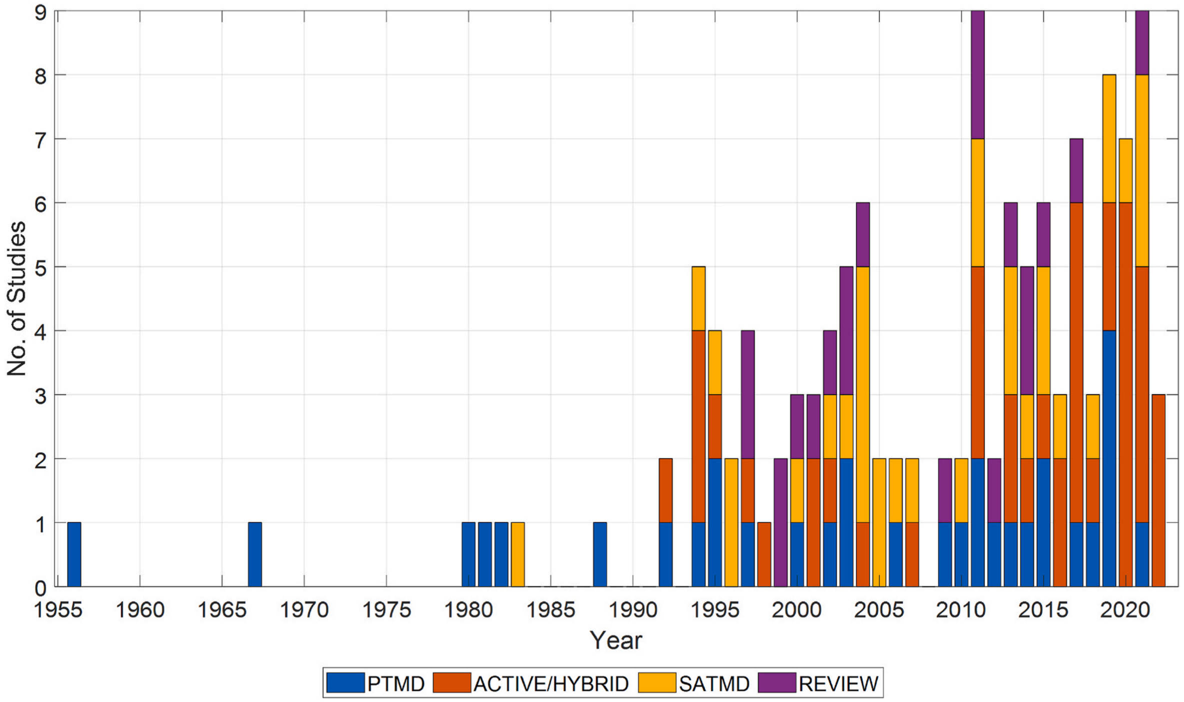

Fig. 2. Summary of the studies included within this work.

Table 1
Search phrase structure.

	Type of Control	Specification	Results
Scopus	"Mass Damper" "Mass Driver"	"High Rise" "Skyscraper" "Practical Application" "Building Application" "Real Application"	424
Other			37
Sum			461

Yan et al. (2020) studied the translation and rotation response control of structures under earthquake loading. For their simulations, the authors used a ten-storey steel building model equipped with two ATMD or TMD systems. For the control of the ATMDs, the authors implemented a LQR and a fuzzy neural network (FNN) control algorithm. They concluded that, the ATMD operating with both algorithms was more efficient on the response control of the structure compared to the passive TMD. Lastly, when considering the performance of the two control algorithms, the authors concluded that, the FNN can replace the LQR algorithm since it is efficient in controlling the system with an uncertain mathematical model which makes it a potential practical application

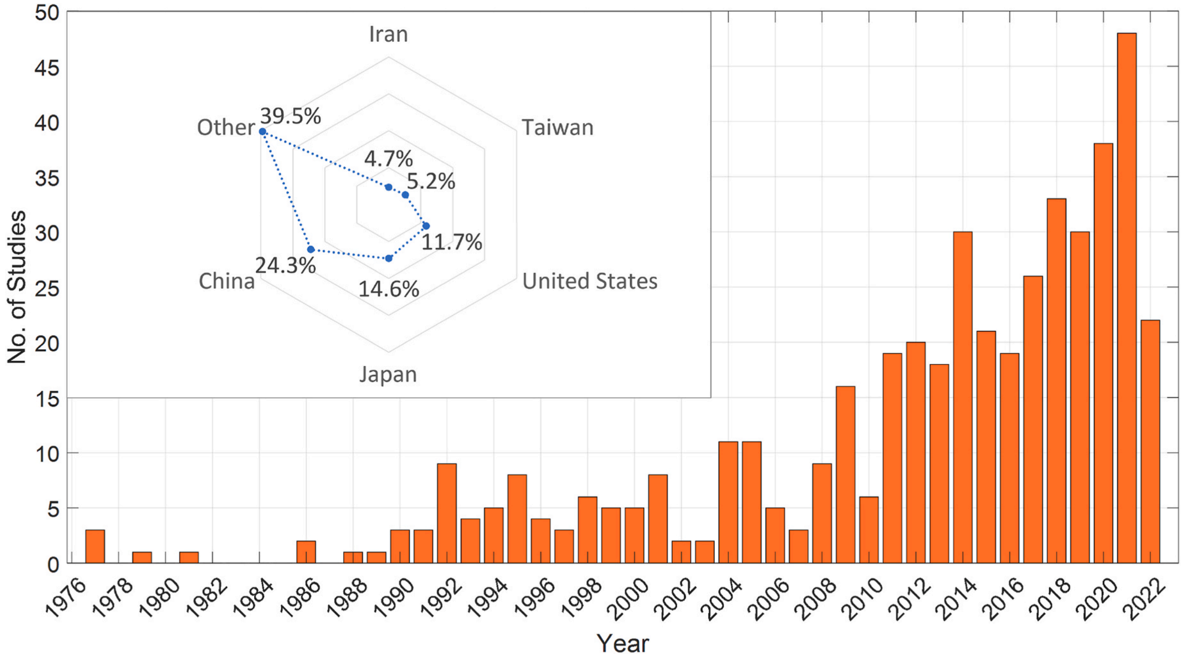

Fig. 3. Studies gathered from the systematic literature review approach.

Table 2

Summary of structural control applications around the world in a chronological order.

Structure	Year	Location	Type of Control
C N Tower	1973	Toronto	PTMD
John Hancock	1977	Boston	PTMD
Citicorp Building - 601 Lexington	1977	New York	PTMD
City Corp Center	1978	New York	PTMD
Sydney Tower	1980	Sydney	PTMD
Al Khobar Chimney	1980	Saudi Arabia	PTMD
Ruwais Utilities Chimney	1982	Abu Dhabi	PTMD
Deutsche Bundespost Cooling Tower	1982	Nurnberg	PTMD
Yanbu Cement Plant Chimney	1984	Saudi Arabia	PTMD
Hydro-Quebec Wind Generator	1985	Canada	PTMD
Metropolitan Tower	1985	New York City	PTMD
Chiba Port Tower	1986	Chiba	PTMD
BMW Factory floor	1988	Munich	PTMD
Arc de 124.5° Steel Scuplture	1988	Berlin	PTMD
Bin Qasim Thermal Power Station	1988	Pakistan	PTMD
Tiwest Rutile Plant Chimney	1989	Cataby	PTMD
Fukuoka Tower	1989	Fukuoka	PTMD
Henckels Zwillingwerke, Factory Floor	1989	Solingen	PTMD
Higashiyama Sky Tower	1989	Nagoya	PTMD
Kyobashi Seiwa Building	1989	Tokyo	AMD
Kajima Research Lab. # 21	1990	Tokyo	SATMD
Fernsehturm Tower	1990	Berlin	PTMD
Crystal Tower	1990	Osaka	PTMD
Huis Ten Bosch Domtoren	1990	Nagasaki	PTMD
Hibikiryokuchi Sky Tower	1991	Kitakyushu	PTMD
Shimizu Tech. Lab	1991	Tokyo	AMD
HKW Chimney	1992	Frankfurt	PTMD
BASF Chimney	1992	Antwerp	PTMD
Siemens Power Station	1992	Killingholme	PTMD
Sendagaya INTES Building	1992	Tokyo	AMD
Chifley Tower	1992	Sydney	PTMD
Applause Tower	1992	Osaka	HMD
ORC 200 Bay Tower	1992	Osaka	HMD
Kansai Int'l Airport	1992	Osaka	HMD
Rokko Island P and G	1993	Kobe	PTMD
Chifley Tower	1993	Sydney	PTMD
Al Taweeiah Chimney	1993	Abu Dhabi	PTMD
KS Project	1993	Kanasawa	HMD
Babcock, Steel Structure	1993	Munich	PTMD
Long Term Credit Bank	1993	Tokyo	HMD
Ando Nishikicho Building	1993	Tokyo	HMD
NTT Kuredo Motomach Building	1993	Hiroshima	HMD
Nishimoto Kosan Nishikicho Building	1993	Tokyo	HMD
Yokohama Landmark Tower	1993	Yokohama	HMD
Akita Tower	1994	Akita	PTMD
J City Tower	1994	Tokyo	HMD
Penta-Ocean Exp. Building	1994	Tokyo	HMD
Shinjuku Park Tower	1994	Tokyo	HMD
Dowa Fire & Marine Ins.	1994	Osaka	HMD
Hikarigaoka Office Building	1994	Tokyo	HMD
Göttingen Stack	1994	Göttingen	PTMD
Porte Kanazawa	1994	Kanazawa	AMD
Mitsubishi Heavy Ind.	1994	Yokohama	HMD
Hamamatsu ACT Tower	1994	Hamamatsu	HMD
Riverside Sumida	1994	Tokyo	AMD
Hotel Ocean 45	1994	Miyazaki	HMD
RIHGA Royal Hotel	1994	Hiroshima	HMD
Hikarigaoko J City Building	1994	Tokyo	HMD
Osaka WTC Building	1995	Osaka	HMD
Dowa Kasai Phoenix Tower	1995	Osaka	HMD
Sea Hawk Hotel and Resort	1995	Fukuoka	PTMD
Rinku Gate Tower Building	1995	Osaka	HMD
Hirobe Miyake Building	1995	Tokyo	HMD
Nissei Dowa Sonpo Phoenix Tower	1995	Osaka	HMD
Plaza Ichihara	1995	Chiba	HMD
Regensburg Siemens Building	1996	Regensburg	PTMD
Hamburg Stack	1996	Hamburg	PTMD
Nanjing Communication Tower	1996	Nanjing	AMD
Artwork The Asylum	1996	Rotterdam	PTMD
Rinku Gate Tower	1996	Izumisano	HMD
Herbis Osaka	1997	Osaka	AMD
Nisseki Yokohama Building	1997	Yokohama	HMD
Karlsruhe Building	1997	Karlsruhe	PTMD
T & C Tower	1997	Kaohsiung	HMD
Washington National Airport Tower	1997	Washington	PTMD
Petronas Twin Towers	1997	Kuala Lumpur	PTMD
Itoyama Tower	1997	Tokyo	HMD
Otis Shibyama Test Tower	1998	Chiba	HMD
Bunka Gakuen	1998	Tokyo	HMD
Oasis Hiroba 21-Oasis Tower	1998	Oita	HMD
Sendai AERU	1998	Sendai	PTMD
Kaikyo Messe Yume Tower	1998	Tokyo	HMD
Yoyogi 3-Chrome Kyodo Building	1998	Tokyo	HMD
Cooling Tower Fans	1998	Scholven Gelsenkirchen	PTMD
Odakyu Southern Tower	1998	Tokyo	HMD
Kajima Shizuoka Building	1998	Shizuoka	SATMD
Sotetsu Takashimaya Kyoto Building	1998	Yokohama	HMD
Burj Al-Arab	1999	Dubai	PTMD
JR Central Towers	1999	Nagoya	HMD
Emirates Towers	1999	Dubai	PTMD
Shinagawa Intercity Building	1999	Tokyo	HMD
Century Park Tower	1999	Tokyo	HMD
Millennium Dome	1999	London	PTMD
La Hague, SGN, Stack	1999	France	PTMD
Reichstag Spectator Balconies	1999	Berlin	PTMD
TC Tower	1999	Kaoshiung	HMD
Steel Chimney	1999	Bangkok	PTMD
Shin-Jei Building	1999	Taipei	HMD
Osaka Airport Control Tower	2000	Osaka	HMD
Cerulean Tower	2000	Tokyo	HMD
Stakis Metropole	2000	London	PTMD
Sarlux Cooling Tower Fan	2000	Sardinia	PTMD
Ube Stack	2000	Ube	PTMD
Park Tower	2000	Chicago, IL	PTMD
Incheon International Airport Control Tower	2001	Incheon	HMD
The Trump World Tower	2001	New York	PTMD
MS Deutschland, Cruise Liner	2001	Germany	PTMD
Nykredit's New Domicil floor	2001	Denmark	PTMD
One Wall Center Tower	2001	Vancouver	PTMD
Hotel Nikko Bayside Osaka	2001	Osaka	HMD
Dentsu Head Office Building	2001	Tokyo	HMD
Izumi Garden Tower	2002	Tokyo	HMD
Prudential Tower	2002	Tokyo	HMD
Spire of Dublin	2003	Dublin	PTMD
Nihon Terebi Tower	2003	Tokyo	HMD
Shiodome Tower	2003	Tokyo	HMD
Shiodome Media Tower	2003	Tokyo	HMD
Refab2	2003	Brazil	PTMD
Al Rostamani Tower	2003	Dubai	PTMD
Neue Terassen, Floor Slabs	2003	Dresden	PTMD
Bergen Gym Floor	2003	Bergen	PTMD
21st Century Tower	2003	Dubai	PTMD
Highcliff	2003	Hong Kong	PTMD
Roppongi T-Cube	2003	Tokyo	HMD
Kochi Airport Control Tower	2003	Kochi	HMD
Taipei 101	2004	Taipei	PTMD
Takamatsu Symbol Tower	2004	Takamatsu	HMD
Bloomberg Tower	2004	New York	PTMD
DoCoMo Telecommunications Tower	2004	Osaka	PTMD
New Kanden Building	2004	Osaka	HMD
Central Japan Airport Control Tower	2005	Aichi	HMD
NEC Tamagawa Renaissance City	2005	Kawasaki	HMD
Araucano Park	2005	Santiago de Chile	PTMD
Theatro Diana Spectator Balconies	2005	Guadalajara	PTMD
Bright Start Tower (Millennium Tower)	2005	Dubai	PTMD
Radar Tower	2005	Bilbao	PTMD
Refinery Tower	2005	Budapest	PTMD

(continued on next page)

Table 2 (*continued*)

Structure	Year	Location	Type of Control
Meteorological Radar Tower	2005	Catalunya Province	PTMD
Triumph Palace	2005	Moscow	PTMD
Akasaka Intercity	2005	Tokyo	HMD
Toranomon Towers Residence	2006	Tokyo	HMD
United States Air Force Memorial	2006	Virginia	PTMD
Anzen Building	2007	Tokyo	HMD
Grand Canyon Skywalk	2007	Arizona	PTMD
Aspire Tower	2007	Doha	PTMD
Villa Magura Odobesti	2008	Odobesti	PTMD
Al Mas Tower	2008	Dubai	PTMD
Jacky Wellhead	2008	UK	PTMD
Toronto Art Gallery Ceiling	2008	Toronto	PTMD
Shanghai World Financial Center	2008	Shanghai	HMD
Comcast Center	2008	Philadelphia, PA	PTMD
ShenZhen WuTong Mountain Tower	2009	ShenZhen	PTMD
Lanxess Chemical Plant	2009	Ontario	PTMD
Shanghai Expo Area Galleries	2009	Shanghai	PTMD
QEEC floor	2009	Doha	PTMD
Almas Tower	2009	Dubai	PTMD
Estela de la Luz	2010	Mexico City	PTMD
Danube City Tower	2010	Vienna	SATMD
Goldman Sachs Headquarters	2010	New York	PTMD
LAX Theme Building	2010	Los Angeles	PTMD
Offshore Windpark Belwind, OHVS Station	2010	Belgium	PTMD
Chimney Ramla	2010	Israel	PTMD
Singapur Skypark	2010	Singapur	PTMD
The Austonian	2010	Austin	PTMD
Canton Tower	2010	Guangzhou	HMD
Alphabetic Tower	2011	Batumi	SATMD
Kingkey Finance Tower	2011	Shenzhen	AMD
Civic Center	2011	New York	PTMD
Tokyo Skytree	2012	Tokyo	PTMD
Ivanpah Solar Tower	2012	California	PTMD
ArcelorMittal Orbit Tower	2012	London	PTMD
Windseeker-Carrowinds	2012	North Carolina	PTMD
23 Marina	2013	Dubai	PTMD
Giant Wheel - High Roller	2013	Las Vegas	PTMD
Shanghai Tower	2014	Shanghai	PTMD
Olympic Flame Monument	2014	Sochi	PTMD
Flagpole	2014	Wisconsin	PTMD
Abeno Harukas	2014	Osaka	HMD
Air Traffic Control (ATC) Tower	2015	Delhi	PTMD
432 Park Avenue	2015	New York	PTMD
Las Vegas Control Tower	2016	Las Vegas	PTMD
Socar Tower	2016	Baku	PTMD
Rottweil Test Tower	2017	Rottweil	HMD
Ping An Finance Center	2017	Shenzhen	HMD
150 North Riverside	2017	Chicago	PTMD
Nan Shan Plaza	2018	Taipei	PTMD
111 Murray Street	2018	New York	PTMD
520 Park Avenue	2018	New York	PTMD
50 West	2018	New York	PTMD
100 East 53rd Street	2018	New York	PTMD
Muscat International Airport	2018	Oman	PTMD
Madison Square Park Tower	2018	New York	PTMD
30 Hudson Yards	2019	New York	PTMD
53 West 53rd	2019	New York	PTMD
220 Central Park South	2019	New York	PTMD
The Centrale	2019	New York	PTMD
35 Hudson Yards	2019	New York	PTMD
The Address Residence Sky View Tower 1	2019	Dubai	PTMD
Crown Sydney Hotel and Resort	2020	Sydney	PTMD
One Vanderbilt Avenue	2020	New York	PTMD
Central Park	2020	New York	PTMD
Flagpole	2021	Egypt	PTMD
Turkevi Center	2021	New York	PTMD
111 West 57th Street	2021	New York	PTMD
Greenwich	2022	New York	PTMD
The One	UC	Toronto	PTMD
M3 at M City	UC	Mississauga	PTMD
Jeddah Tower	UC	Jeddah	PTMD

compared to LQR.

Chen et al. (2021) considered the active control of structures with AMD stroke limits. A variable gain state-feedback controller was designed to limit the mass strokes and relative velocities. The effectiveness of the proposed controller was demonstrated in the control of a high-rise building and a four-storey experimental structure. It was found that, the proposed scheme can limit the mass strokes while having a good response dissipation performance.

Ramírez-Neria et al. (2021) developed a generalised proportional integral observer-based active disturbance rejection control scheme for the control of seismically excited buildings. The performance of the proposed scheme was experimentally investigated on a five-storey structure equipped with an AMD. The authors concluded that the proposed scheme demonstrated an excellent vibration dissipation performance and robustness in the presence of unknown external disturbance inputs.

Concha et al. (2021) proposed an automatic tuning algorithm for a sliding mode controller based on Ackermann's formula. The algorithm was investigated in the control of a seismically excited building equipped with an ATMD. The authors mention that, their tuning algorithm selects the sliding mode controller parameters in order to guarantee sufficiently fast and damped transient responses of the structure and the ATMD, and the control force and the responses of the building and the ATMD to be within acceptable limits under the frequency band of the seismic excitation. The algorithm was experimentally investigated and compared against a LQR and an optimal sliding mode controller showcasing its effectiveness.

Zhu et al. (2021) proposed a hybrid vibration mitigation method for the control of a footbridge using a PTMD and the crowd flow control theory (Carroll et al. (2012); Helbing et al. (2002)). The authors mentioned that, they proposed their hybrid method to eliminate the detuning effect and the lack of adaptability that the PTMD has which makes it a less efficient control method for footbridges. The crowd flow control theory can alter the pedestrians' velocity and walking frequency by arranging temporary or permanent measures on the structure in strategic positions (Helbing et al. (2005); Venuti and Bruno (2013)). The authors used the eddy current technique (Liu et al. (2020)) to optimise the mitigation performance of the PTMD. To simulate the crowd load, the authors used the social force model (Helbing and Molnár (1995)) which is based on the Kurt Lewinde's social psychology hypothesis (Billig (2015)). To evaluate their proposed scheme, the authors used three layouts simulating; pedestrian diversion separation; bottle neck effect; and a nonlinear layout which was a combination of the first two layouts. It was found that the hybrid control method was efficient on limiting the peak acceleration of the long-span footbridge (case-study) within the serviceability limit to avoid human discomfort.

Koutsoloukas et al. (2022a) investigated the performance of an ATMD for the vibration control of a real high-rise tower. For the control law of the system, the authors derived a robust model predictive control (RMPC) algorithm. The proposed algorithm was compared to the well established robust controller within the structural control field, H_∞, and to a PTMD. To assess their robustness, four different scenarios with parametric (± 2% and ±10% in stiffness and damping) uncertainties and actuator (±5%) uncertainty were introduced. To demonstrate the capabilities of the proposed scheme, the authors derived two controllers, one emphasising on the vibration mitigation of the tower and one emphasising on the power consumption of the system. It was concluded that the RMPC schemes outperformed the H_∞ controller and the PTMD in all uncertainty scenarios.

Zhou et al. (2022) studied the vibration dissipation performance of an ATMD equipped on a 600 m tall tower. For the control of the ATMD, the authors used an LQR with variable gain algorithm. The performance of the system was investigated during the Super Typhoon Hato and it was proven efficient for the vibration mitigation of the tower.

Koutsoloukas et al. (2022b) investigated the performance of the reinforcement learning deep deterministic policy gradient (DDPG)

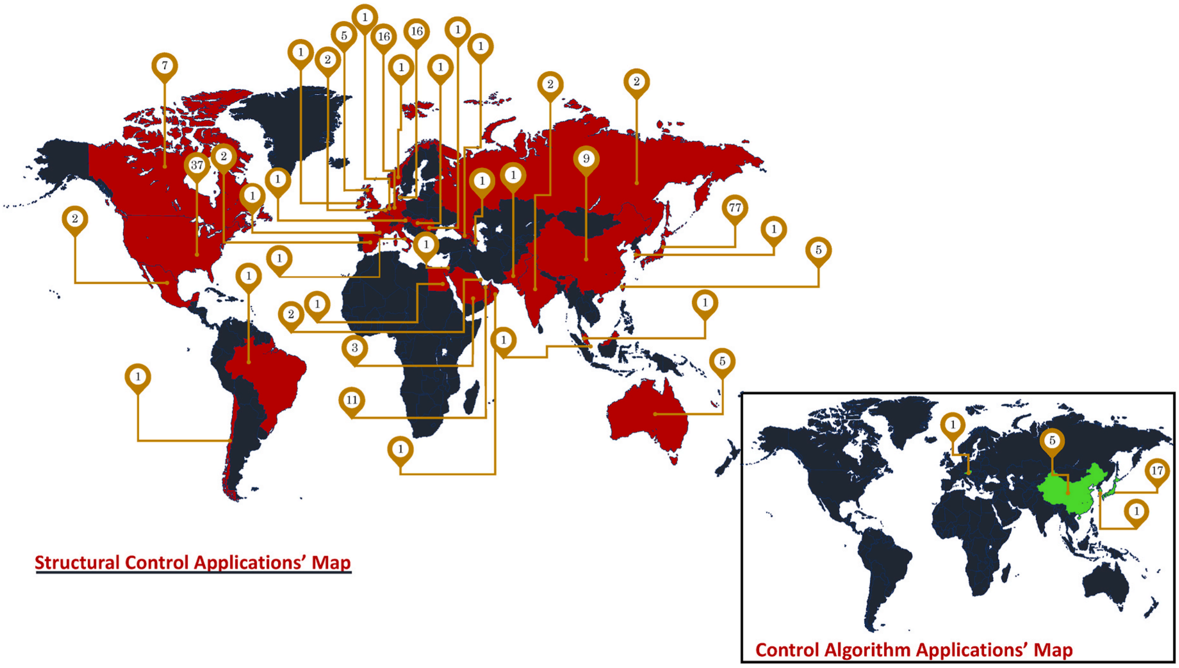

Fig. 4. Maps of mass damper applications and control algorithms on real building-like structures.

algorithm for the vibration dissipation of a real high-rise tower using an ATMD. The performance of the DDPG was compared to a PTMD and to a LQR. To investigate the robustness of the reinforcement learning algorithm, a scenario with parametric uncertainty was introduced ($-$ 10% stiffness and damping uncertainty). It was found that, in both the nominal and the uncertain scenarios, the DDPG had a similar performance to the LQR and they both outperformed the PTMD.

4.4. *Synopsis*

Section 4 discussed the research done by the structural control research community for passive, semi-active, active and hybrid mass dampers. Fig. 2 shows a summary of all the studies included within this work. When considering the semi-active, active and hybrid systems, various control algorithms were investigated. More specifically, the efficiency of control techniques such as adaptive, intelligent (e.g. AI), optimal, self-organised, robust and stochastic was presented. All the aforementioned control techniques were proven adequate on effectively controlling the responses of the considered, many time fictitious, structural systems. However, it is rather essential to investigate whether the aforementioned ingenious control techniques are adopted in real-life applications. To achieve that, a systematic evaluation of literature is contacted in a later section of this work. Furthermore, the mass damper technologies have a number of limitations which could cause hesitation in the industry professionals and building owners to invest on their installation.

5. Limitations of the control systems

Aside from the promising nature of the structural control schemes presented in Section 4, the literature includes various control limitations that cause control systems to malfunction. Thus, it is important for the structural control research community to identify in-full the limitations that each control system suffers from, and develop smart techniques to eliminate them. This section includes the limitations of the mass damper technologies that arise in the relevant literature categorised in hardware or software-related.

5.1. *Hardware-related limitations*

Considering the PTMDs, Bachmann and Weber (1995) showed that the efficiency of the TMD is much more sensitive to the error in the tuning of the TMD frequency than the error in the tuning of its damping. Rana and Soong (1998) stated that, under seismic excitation, the TMD system suffer from detuning. In their study, they concluded that, for a structure subjected to an earthquake motion, the effects of detuning in the parameters of the TMD became less detrimental with increasing the mass and/or damping ratios of the TMD. Moreover, based on the time history analyses of a single-DOF with a TMD system, it was observed that for large damping of the structure, the TMD did not give much response reduction. The problem of the TMD off-tuning (detuning) is also reported in (Setareh (2002); Shih and Sung (2021); Noormohammadi and Reynolds (2013); Setareh et al. (2007); Maślanka (2019)). Gutierrez Soto and Adeli (2013) mentioned that, a disadvantage of PTMDs is that they can only be tuned in one frequency which is subject to uncertainty or it could change during ground motions. Moreover, the authors add that, the TMDs require high installation and maintenance costs. Lastly, Elias and Matsagar (2017) advised that open research problems regarding the TMD and multiple TMDs are; the off-tuning of the oscillations and the influence of the flexibility of the foundation.

The literature shows that, despite their promising capabilities, the active/hybrid structural control strategies are subject to several hardware-related problems that affect their performance. Firstly, Elias and Matsagar (2017) state that the operation of the active control systems is totally depended on external power supply and it requires a complex sensing and signal processing system. Ahlawat and Ramaswamy (2002) mention that, being completely depended on external power, the active systems are vulnerable to power-failure which occurs often during strong earthquakes. Moreover, due to the size of the civil engineering structures, big capacity actuators are required which translate to high costs (purchase and operation) and thus, limited interest. Demetriou and Nikitas (2016) state that the active TMDs gain their flexibility and adaptability by consuming high power and their performance is highly depended on the actuator capacity and the auxiliary mass strokes. Casciati et al. (2012) mentioned that, the actuation time lags are the main reason of causing a time delay in the control loop and thus, it has been a big concern in the research area of structural

Table 3
Algorithms considered on real building-like structures.

Structure	Type of Control	Algorithm	Reference
Kyobashi Seiwa Building	AMD	LQ Optimal theory-based	Kobori et al. (1991) Sakamoto et al. (1992)
Yokohama Landmark Tower	HMD	LQ Optimal theory-based	Yamazaki et al. (1992)
Riverside Sumida Building	AMD	Optimal Feedback-VG	Suzuki et al. (1994)
		LQR, H_∞	Smith and Chase (1996)
Ando Nishikicho Building	HMD	Velocity-feedback optimal	Sakamoto and Kobori (1995)
Shinjuku Park Tower	HMD	LQ Optimal theory-based	Tanida et al. (1994)
Nanjing Communication Tower	AMD	LQR, Nonlinear Feedback Control	Cao et al. (1998)
		Continuous Sliding Mode	Wu and Yang (1997)
		LQG, H_∞, Continuous Sliding Mode	Wu and Yang (1998)
		LQG	Wu and Yang (2000)
ORC 200 Bay Tower	HMD	Optimal State-Feedback GS	Saito et al. (2001)
Hotel Ocean 45	HMD	Optimal State-Feedback GS	Saito et al. (2001)
Kajima Shizuoka Building	SATMD	LQR-based	Kurata et al. (1999)
Sendagaya INTES Building	AMD	LQ Optimal theory-VG	Yamamoto et al. (2001)
Applause Tower	AMD	LQ Optimal theory-based with VG	Yamamoto et al. (2001)
Porte Kanazawa	AMD	LQ Optimal theory-based with VG	Yamamoto et al. (2001)
Herbis Osaka	AMD	LQ Optimal theory-based with VG	Yamamoto et al. (2001)
Hikarigaoka Office Building	HMD	H_∞, VG	Fujinami et al. (2001)
Hirobe Miyake Building	HMD	LQ Optimal theory-based with Active-Passive SM	Nakamura et al. (2001)
Bunka Gakuen	HMD	LQ Optimal theory-based with Active-Passive SM	Nakamura et al. (2001)
Oasis Hiroba 21-Oasis Tower	HMD	H_∞ -based with Active-Passive SM	Nakamura et al. (2001)
Dentsu Head Office Building	HMD	LQR	Yamanaka and Okuda (2005)
Incheon International Airport Control Tower	HMD	H_∞ with a bilinear transform	Park et al. (2006)
Canton Tower	HMD	LQR, H_∞	Tan et al. (2012)
Shanghai World Financial Center Tower	HMD	LQ Optimal theory-based with Active-Passive SM	Lu et al. (2014)
Danube City Tower	SATMD	Adaptive nonlinear control	Weber et al. (2016)
Kingkey Finance Tower	AMD	LQR, PA, FNN, VG	Teng et al. (2014)
		VG state feedback	Chen et al. (2021)
Ping An Finance Center	HMD	LQR, VG with Active-Passive SM	Zhou et al. (2022)

Abbreviations: **LQ** = Linear Quadratic, **VG**=Variable Gain, **SM**=Switching Mode, **LQR** = Linear Quadratic Regulator, **LQG** = Linear Quadratic Gaussian, **GS** = Gain Scheduling, **PA**=Poll Assignment, **FNN**=Fuzzy Neural Networks.

control. The authors added that, this topic is currently under review by the structural control research community. The influence of time delay was also discussed and investigated in Teng et al. (2016). Moreover, Bhaiya et al. (2019) mention that, a delay could occur due to processing feedback information which makes the active control not a reliable control method. Chen et al. (2021) mention that, it is important to limit the stroke of the AMDs since, when the mass damper has excessive strokes and its relative velocity is in the same direction as the direction of the strokes then, the mass could probably collide on the anti-collision device on the building resulting during increased structural responses to safety problems.

5.2. Software-related limitations

It is important to note that, the control algorithm is one part of the control strategy. In order for the control algorithm to compute the required actions, information about the states of the structure in real-time is required. As explained in the Introduction, the semi-active, active and hybrid control systems require sensors located on selected areas of the structure in order to provide essential feedback regarding the state of the structure, i.e. displacements, velocities, accelerations. However, it is often that the feedback is noisy or incomplete. Incomplete feedback occurs when measurements are taken from limited DOFs of a system. For this reason, it is sometimes impossible for the control algorithm to identify all the states of the structure. To overcome this, an observer must be utilised since, it is capable of computing the full vector of structural response by using limited number of states (Miah et al. (2015)). Applications of observer algorithms in semi-active and active structural control can be found in (Mei et al. (2002); Yan et al. (2007); Miah et al. (2015); Azam et al. (2017)) where Kalman filters were utilised. Aghajanian et al. (2017), and Hillis (2010) implemented the Luenberger observer in their control schemes. Moreover, the use of the disturbance observer can be found in the control scheme of Nyawako et al. (2016). Alt et al. (2000) reported that, during an earthquake, the measured signals from the sensors may deviate from the real ones and this could result to a detrimental effect on the controlled structure.

Being highly depended on the utilised actuators, the active and hybrid mass damper control design should also take into account their explicit dynamic characteristics i.e. actuator dynamics (Wu and Yang (2004)). The effect of the actuator dynamics can be critical in the overall performance of the control system (Dyke et al. (1995)). Aiming to minimise the effect of the actuator dynamics and the computational phase delay, Nikzad et al. (1996) developed two controllers (i.e. a conventional feedforward controller and a neurocontroller) and investigated their performance. It was found that the neurocontroller was more effective on eliminating the effect of the actuator dynamics and time delay. In their study, Dyke et al. (1995) showcased the importance of accounting for the control-structure interaction and the actuator dynamics when designing a control system. The authors showed that, there is a natural velocity feedback interaction path in the case of hydraulic actuators. They concluded that, the consideration of the actuator dynamics and the control-structure interaction can lead to a considerably improved and reliable control system. However, it was mentioned that, most researchers neglect the effects from the actuator dynamics. This can result in time lag and mismatches when generating the control forces.

5.3. Reflection

Section 5 reported several limitations of passive, semi-active, active and hybrid mass dampers as these were identified in current literature. It is rather important to present these limitations of each control system in

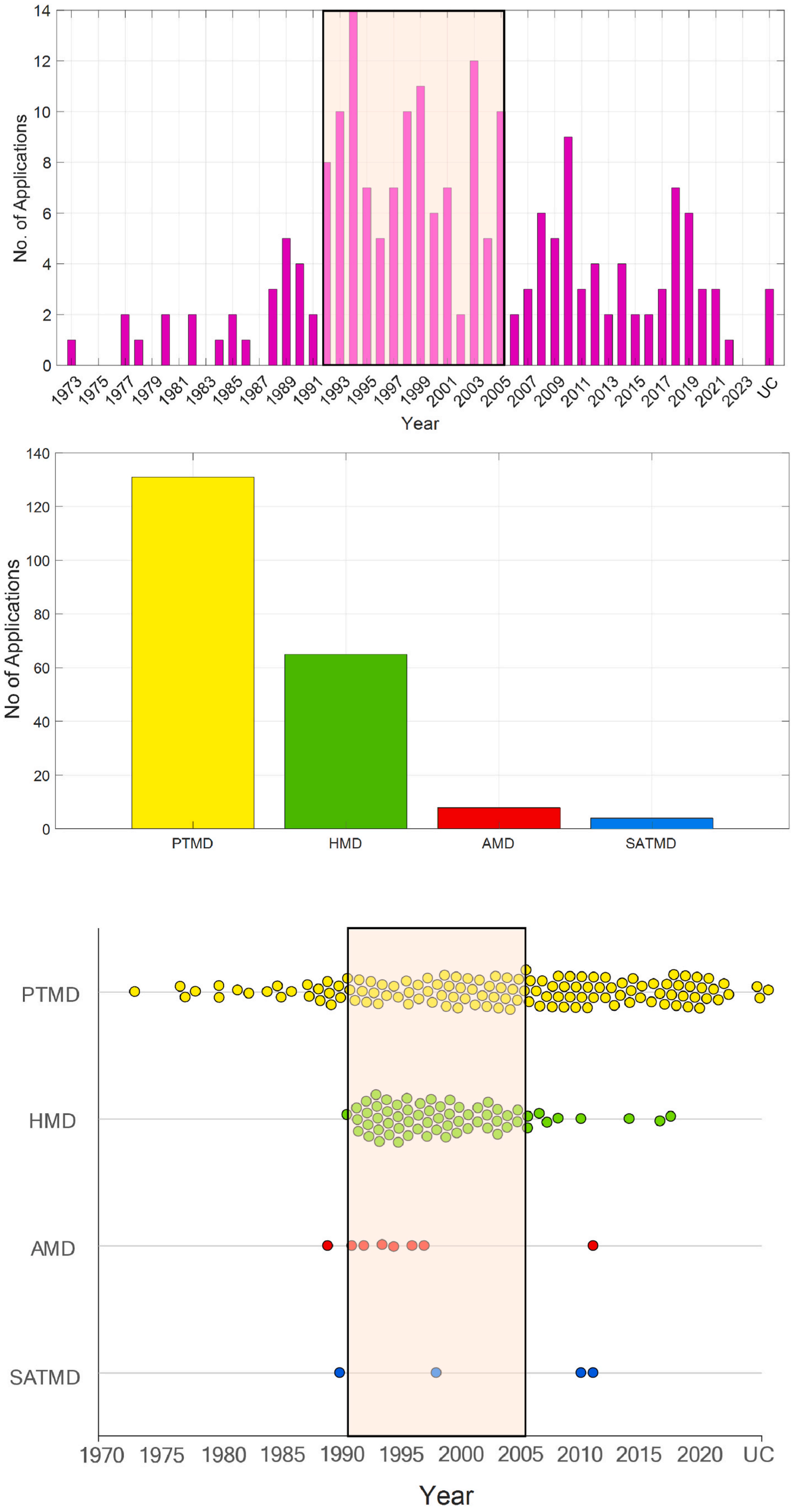

Fig. 5. Total control system applications as per the literature.

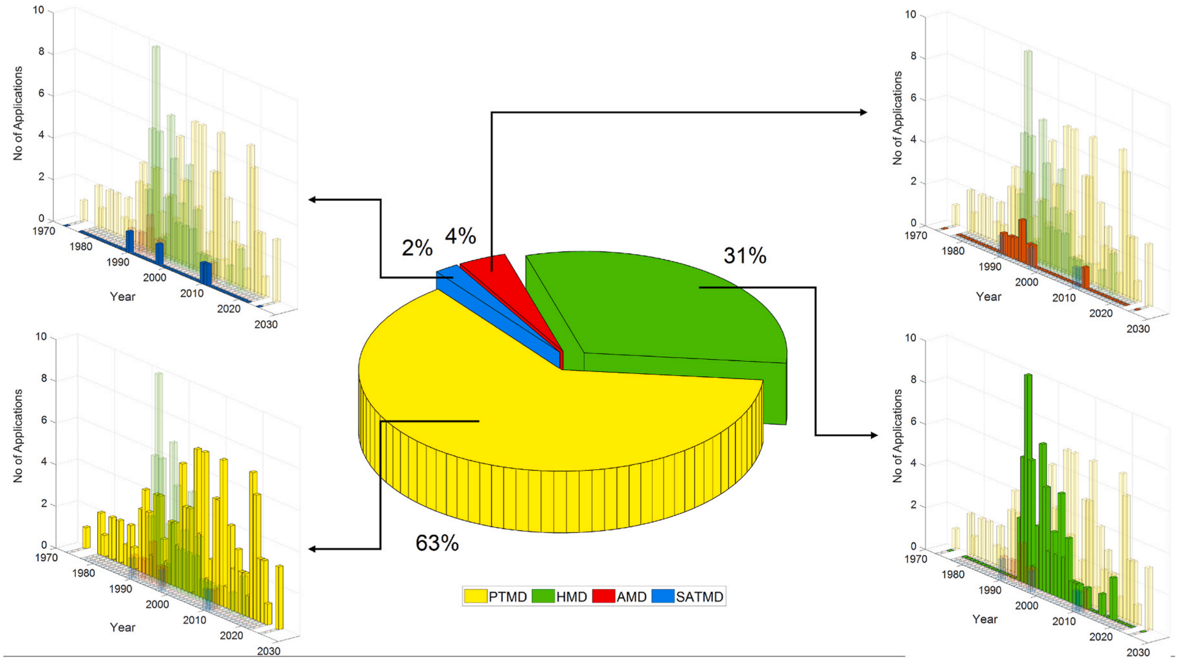

Fig. 6. Control system application trend as per the literature.

order to provide a clear direction on future research required by the community. Besides, by recognising the control systems' limitations, more accurate conclusions may be drawn in the following sections where, the installations of mass damper devices on real building-like structures will be presented and investigated.

6. Systematic evaluation of literature with control system applications

The concept of systematic literature review arose from the medical research field and its main use was to provide evidence-based medicine treatment (Kitchenham and Charters (2007)). The difference between a traditional, or experiential, literature review (even in very successful examples as e.g. Kiranyaz et al. (2021); Avci et al. (2021)) and a systematic one is the fact that the latter uses a structured search approach and formalised objectives. Reymert et al. (2022) state that, systematic reviews are not common in the civil and structural research fields. The systematic search provides a well-defined search methodology which helps to reduce bias and allows for generating more general conclusions (Petersen et al. (2008); Kitchenham and Charters (2007)). In this part of the current work, the use of systematic evaluation literature is considered to be essential since, it will only then allow for statistical analysis to be conducted. More specifically, by analysing the findings of the systematic evaluation, patterns and trends will be uncovered which will lead to several important conclusions around mass damper installations on real building-like structures. Other examples of the systematic literature review approach in the civil and structural engineering research area can be found in Panah and Kioumarsi (2021) where the application of building information modelling (BIM) in the health monitoring and maintenance processes was reviewed; in Kc and Gautam (2021) where the progress in sustainable structural engineering was investigated and; in Flah et al. (2021) where the application of machine learning algorithms in structural health monitoring was reviewed. Moreover, Babaei et al. (2021) used the systematic literature review approach for reporting the issues around the front-end of infrastructure megaprojects, Manzoor et al. (2021) systematically reviewed the influence of artificial intelligence in civil engineering in relation to sustainable development and Medel-Vera and Ji (2015) reviewed the seismic protection technologies applied on nuclear power plants.

To further clarify the differences between a systematic literature search and a conventional literature review, the main features addressed by Kitchenham and Charters (2007) will be discussed. Firstly, the systematic literature review starts by defining a search objective in order to express the search question. Moreover, the systematic reviews use a structured search strategy, that is documented to the readers, in order to cover as much of the relevant literature possible. After gathering the relevant literature a screening process should take place. This means that, inclusion and exclusion criteria should be set in order to discard non-applicable studies. Finally, the information to be obtained by each primary study should be clearly specified.

6.1. Systematic evaluation objectives

The objectives of this systematic evaluation is to firstly search for relevant literature which includes real-life applications of mass damper systems on building-like structures. This means that, bridges, wind turbines, and experimental schemes applied on laboratory environments are not included within this application list. Control system applications that are not mass-damper-based (i.e. even tuned liquid dampers (Ghisbain et al. (2021))) are also excluded. Secondly, any algorithms used for the control of the real-life applications will also be extracted from the relevant literature.

6.2. Search strategy

The database search method used herein is based on Reymert et al. (2022), and is considered to be adequate and efficient fitting the purpose of this work. The systematic literature search was conducted by using phrase search with Boolean *AND OR* operators. Table 1 shows how the phrase search was structured where, the *OR* operator was used between the terms of each column and the *AND* operator between each column. An iterative method was used to develop the phrase search in order to achieve an acceptable and complete literature search. At first, a Scopus search was conducted where, a broad phrase selection was used in order to assess the quantity of the relevant data and then, progressive phrase constraints were added in order to achieve satisfactory precise results. This study aims to provide two, as complete as possible, mass damper and control algorithm applications lists, widening previous coverage of

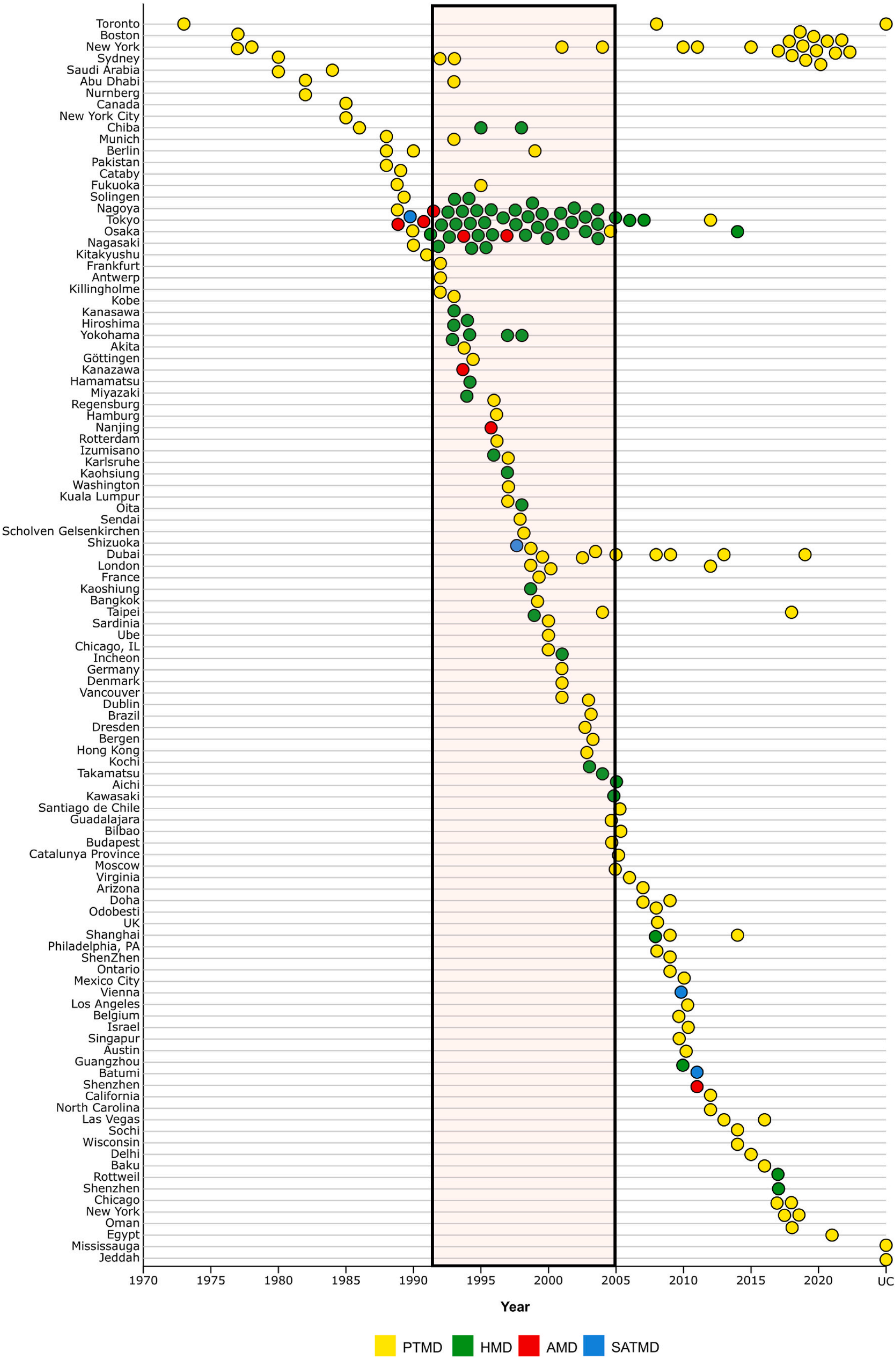

Fig. 7. Control system applications around the world as per the literature.

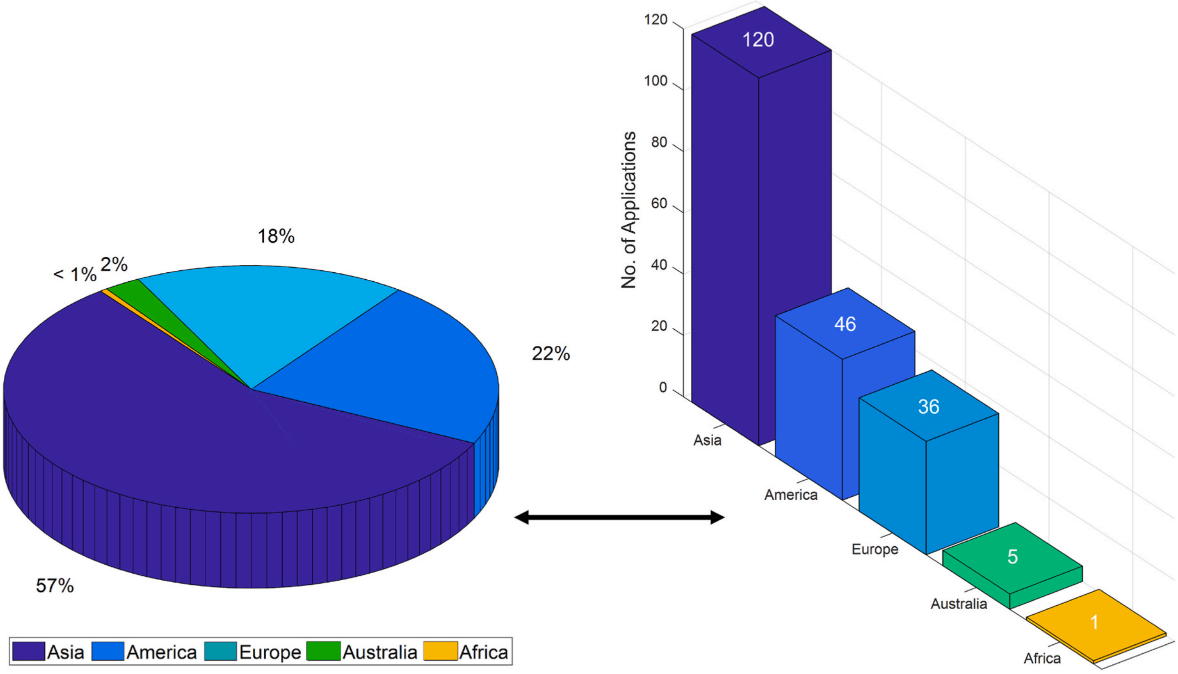

Fig. 8. Control system applications in different continents as per the literature.

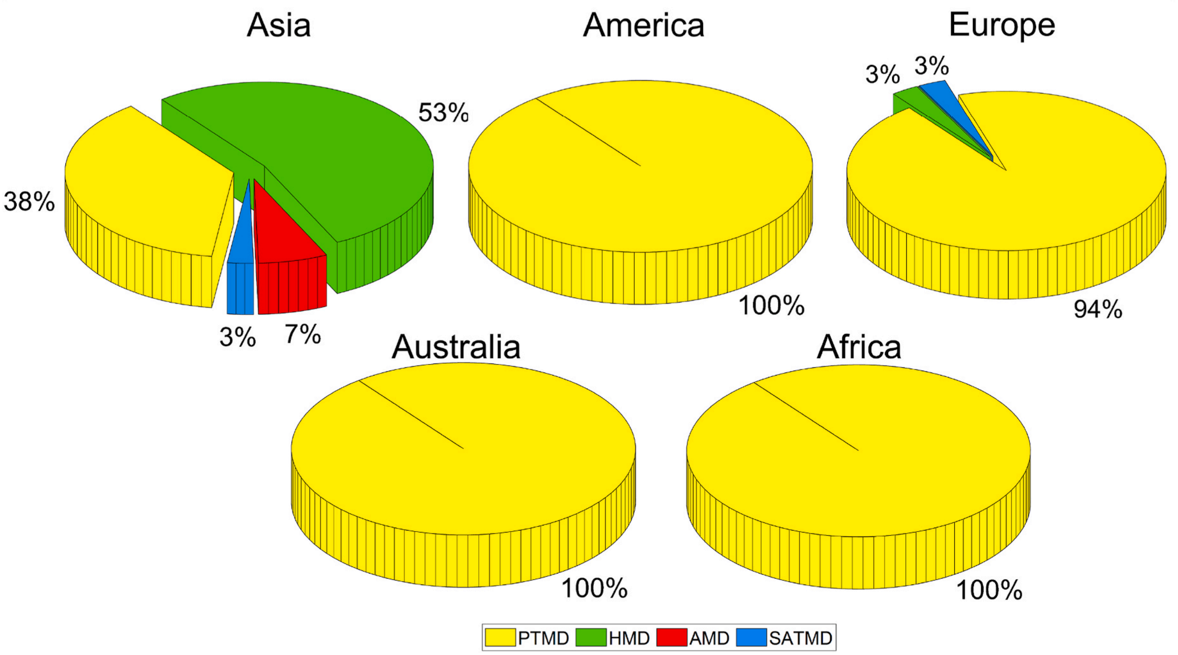

Fig. 9. Break up of applications in different continents as per the literature.

the relevant literature data.

6.3. Screening process

To gather the most relevant literature, a screening process was conducted. Search results that were not written in English, did not align with the objective of this systematic evaluation, or they were duplicates of existing results were excluded. Using the Table 1 phrase search approach, a total of 424 unique results were gathered. Moreover, due to the uniqueness of the search subject of matter, 37 more results were gathered from cited studies within the results. From the total of 461 studies, 70.5% were journal articles, 26.0% were conference papers and 3.5% were books, book chapters, and technical reports. Fig. 3 shows a plot of the unique results based on the year they were published. From this, one may notice that, there is an increase in the interest of structural control using mass damper technology over the years, especially after 2009. Further to that, the figure shows the five countries where the most documents were produced. As it can be seen, China, Japan, United States, Taiwan and Iran produced 61.5% of the documents that were gathered through the aforementioned process. In the following sections, the data accumulated from the 461 documents will be analysed and the findings will be discussed thoroughly.

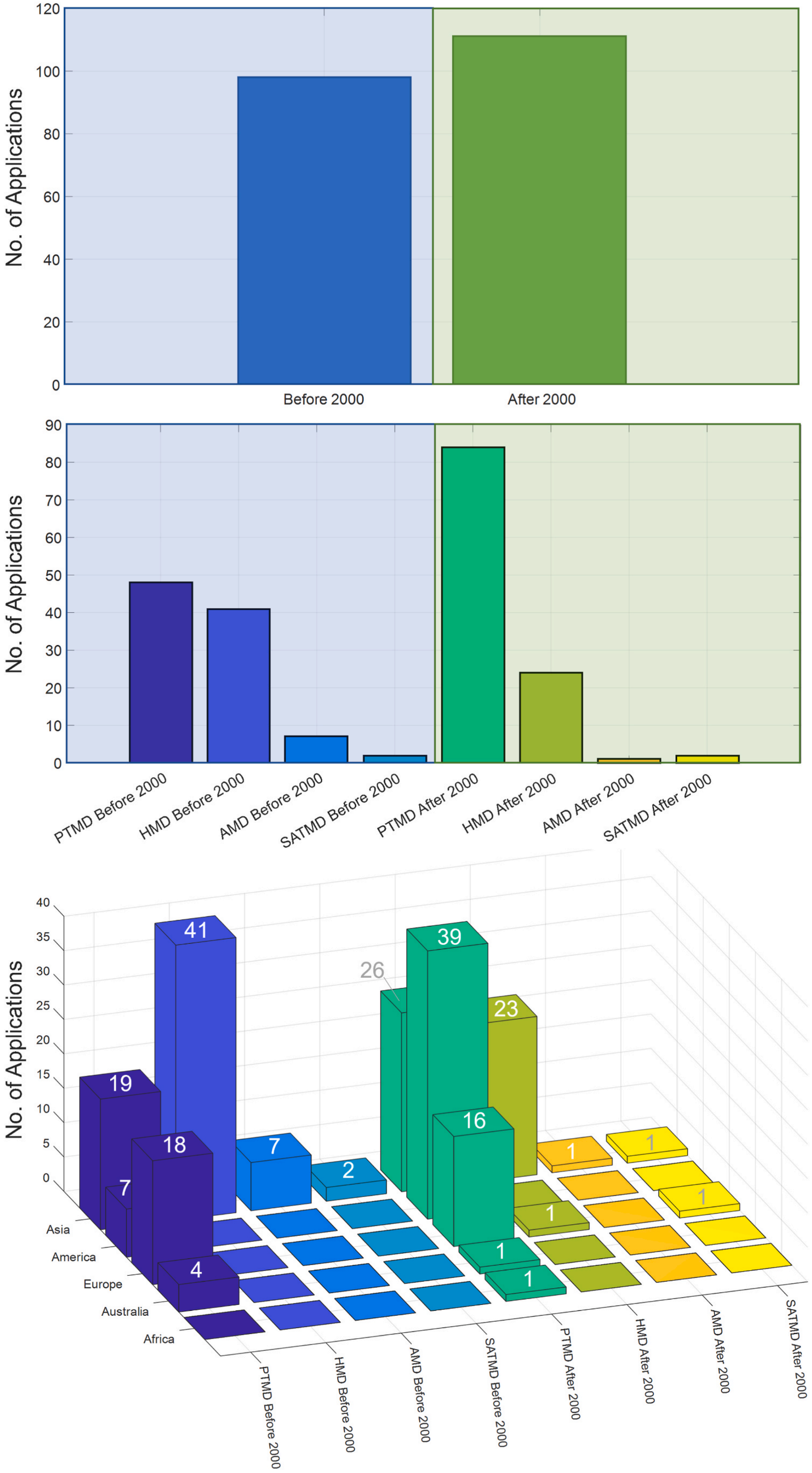

Fig. 10. Control system applications in different continents before and after 2000 as per the literature.

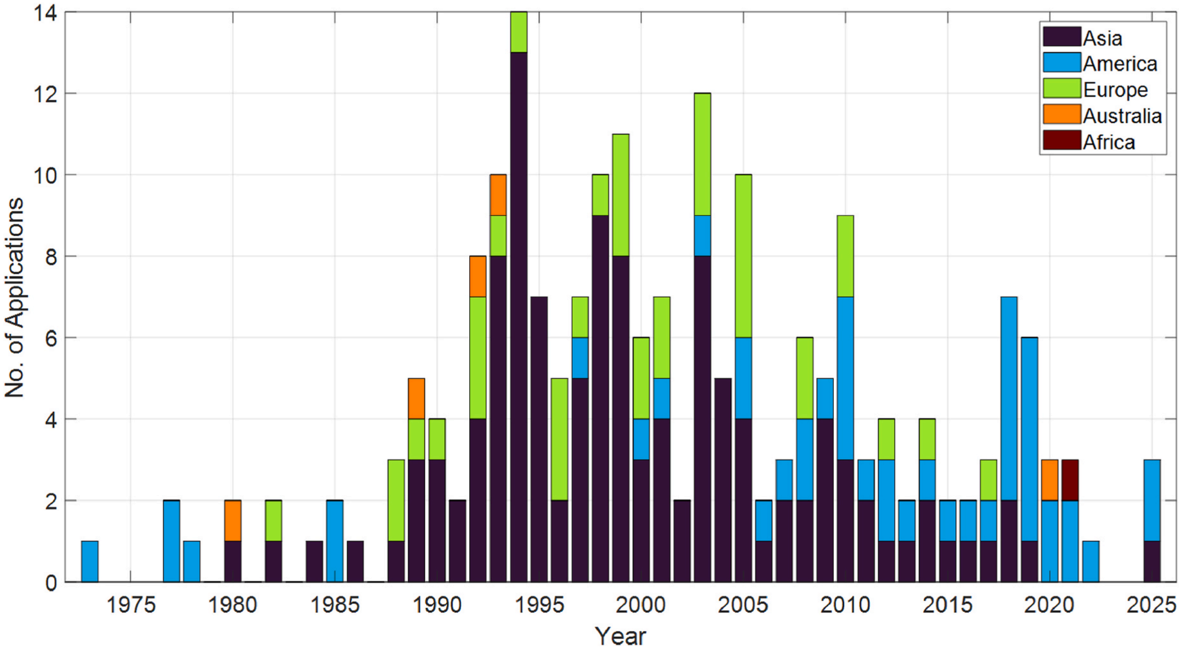

Fig. 11. Control systems installation over the years in different continents as per the literature.

7. Literature search data gathered

Over the last two decades, many significant efforts have been made to transfer theoretical structural control knowledge to real-life structures. Table 2, demonstrates the use of structural control systems in real-life applications organised in chronological order and the colour selection is based on the year of construction of each structure (i.e. different year designated in different background colour). As explained in the Introduction, there is an inconsistency with the terminology used by the structural control research community for describing the different types of mass dampers. Therefore, the terminology used for the control type description in this work is based on Soong and Spencer (2000) to keep consistency. Table 2 includes 208 building-like structures that utilise at least one type of control system i.e. passive, semi-active, active and hybrid mass dampers. It is noted that, when compared to the total number of tall structures that are being built around the world (Jafari and Alipour (2021)), the utilisation of mass damper technology is still not broadly used. Moreover, structural control applications' maps are included in Fig. 4, which show all the control system applications listed in Tables 2 and 3. As it can be seen, Japan is the country with the most structures equipped with a control system (77). After Japan, the country with the most applications, yet with a notable difference, is the U.S.A with 37, followed by Germany with 16, making the three countries with the most structures equipped with structural control applications.

From the analysis of the accumulated data, this study aims to address three questions:

1. *What type of mass damper system is more preferred by the engineering industry?*
2. *How are mass damper systems distributed around the world?*
3. *Is the research done by the structural control research community adopted by the engineering industry?*

The consideration and discussion of the above-mentioned questions are believed to be crucial for the research area of structural control since, they will highlight gaps and future research steps to be followed.

7.1. What type of mass damper system is more preferred by the engineering industry?

As it can be seen in Figs. 5–6, from the total number of control systems that are included in Table 2, the 131 are PTMDs which correspond to a 63% of the total applications included herein, the hybrid systems are 65 which correspond to the 31%, the AMDs are 8 which correspond to the 4%, and the SATMDs are 4 which correspond only to 2%. The most applications installed in a single year were 14 in 1994. Moreover, Fig. 5 shows the number of application installations in every year since 1973 (49 years). It is observed that 55% of the total number of applications were installed within 13 years (between 1992 and 2005) which account for the 26.5% of the total years considered. This mainly occurred because, as seen in Fig. 5, between the years 1992 and 2005, 91% of the total number of HMDs were installed. Fig. 7 shows that, between the years 1992 and 2005, there was an increasing trend in Japan for installing HMDs. Fig. 5 shows that, more applications were installed after 2005 than before 1992. It is noticed that, after 2005, only 7 HMDs were installed however, more PTMDs were installed than before 1992 (seen in Fig. 5). The trend of installation of the different types of mass dampers is presented in Figs. 6–7. As it can be seen, there is a positive trend in the installation of PTMDs, contrary to the AMDs and HMDs.

7.2. How are mass damper systems distributed around the world?

Fig. 8 shows that, Asia is the leading continent for structural control applications with 120 applications making the 57.7% of the total control systems around the world. America (both North and South) is the continent with the second highest number of applications with 46 (22.1%), followed by Europe with 36 applications (17.3%), Australia with 5 applications (2.4%) and last Africa with 1 application (0.5%). Fig. 9 shows that, 47% of the systems were installed before 2000 from which, 48 (49%) were PTMDs, 41 (42%) were HMDs, 7 (7%) were AMDs, and 2 (2%) were SATMDs. From the remaining 53% of the applications that were installed after 2000, 83 were PTMDs corresponding to 75.5%, 24 were HMDs corresponding to 21.8%, 2 were SATMDs corresponding to 1.8% and 1 (0.9%) was AMD.

Taking a closer look at the installation of mass damper devices in different continents, (starting the discussion in ascending order), Africa is the continent with the fewest installations. As seen in Fig. 9, Africa has only 1 PTMD application which was installed in 2021 in Egypt.

Australia has only 5 mass damper applications. As it can be seen in Fig. 9, Australia has only PTMDs. More specifically, 4 applications (80%) were installed before 2000 while 1 (20%) was installed after 2000 (seen in Fig. 10).

There is a total of 36 control systems located in Europe. Fig. 9 shows that 94.4% are PTMDs, 2.8% are HMDs and 2.8% are SATMDs. Moreover, 18 PTMDs were installed before 2000 which correspond to 50% of the total systems installed in Europe. From the remaining 50%, 44.4% are PTMDs and the rest 5.6% is divided between the HMDs and the SATMDs (seen in Fig. 10).

America is the second continent with the most control system applications As it can be seen in Figs. 9 and 100% of the applications in America are PTMDs. From the total of 46 systems, only 7 were installed before 2000 which is the 15.2%. Thus, the remaining 39 systems (84.8%) were installed after 2000 (seen in Fig. 10). Fig. 11 shows that, after 2005 there was a steady increase in the installation of mass dampers in America resulting in a strong positive trend.

Asia is the continent with the most control system applications. More specifically, there are 120 applications located in Asia which make the 57.7% of the total applications around the world. As it can be seen in Figs. 9 and 53.7% of the systems in Asia are HMDs, 37.5% are PTMDs, 6.7% are AMDs and 2.5% are SATMDs. It is noticed that, 58% of the total applications in Asia were installed before 2000. It is worth noting that, 64.2% of the total applications in Asia were installed in the Japan. As seen in Fig. 7, there was a sudden increase in the installation of HMDs in Japanese cities such as Tokyo and Osaka after 1992. Even though Asia has the most mass damper applications since 1973, Fig. 11 shows that there was a sudden increase in the mass damper installations between 1992 and 2005 and after that period, the installation of mass dampers was considerably decreased.

7.3. Is the research done by the structural control research community adopted by the engineering industry?

It is rather important to investigate the control algorithms applied within the control of real structures. This will provide an understanding on how the research done by the structural control community is incorporated in real applications. Table 3 includes 24 structures equipped with semi-active, active and hybrid mass dampers. More specifically, the table includes 2 structures equipped with SATMDs, 8 with AMDs and 14 with HMDs. The majority of the structures reported on the table are located in Japan (17), 5 are located in China, 1 in South Korea and 1 in Austria. The first thing to notice in this section is the lack of studies discussing the implementation of advanced mass damper systems (semi-active, active and hybrid) in real applications. More specifically, from the total of 77 semi-active, active and hybrid mass damper applications included in Table 2, the implementation of only 24 (31%) was presented in the literature. This demonstrates the scarcity of studies that present the real challenges that arise during and after the implementation of advanced mass damper systems on real applications.

On the algorithmic side, the majority of controllers that their performance was studied on real structures are based on the optimal control theory. Moreover, the H_∞ and the sliding mode controller were also fairly considered. As discussed in Section 4.4, the structural control research community studied and demonstrated the performance of adaptive, intelligent (AI), optimal, self-organised, robust and stochastic controllers. These controllers were proven to be efficient on controlling the vibrations of civil structures under wind, earthquake and human-induced excitations. However, it is noticed that the industry professionals seem to prefer algorithms which are well-established in the broadest area of control engineering. The readers are also referred to the study of Spencer and Nagarajaiah (2003) where, the algorithms employed on structural control of bridges were reviewed. From their work, it is noticed that, the majority of algorithms implemented for the control of bridges are H_∞ and optimal/sub-optimal based. The rest are fuzzy controllers, variable-gain direct velocity feedback controllers, and feedback controllers. Again, this demonstrates that the civil engineering sector is conservative in the implementation of new control techniques for mass damper applications and instead they tend to show trust on long-established controllers for which, their performance was more widely investigated and verified.

7.4. Discussion

From Section 7.1, one may conclude that, the industry does not show trust to the active and hybrid technology and chooses the more conventional PTMDs. Despite the enhanced performance of active and hybrid mass dampers, the reason that the industry does not trust them more over the PTMDs after 2005 may be related to their high power consumption or extra costs due to the need for high-capacity actuators. There is also the possibility that the active and hybrid systems that were installed, misperformed in real-life compared to the expected performance from the simulations. If this was the case, the active and hybrid systems may have experienced issues related to the installed actuators (e.g. actuation delays, maintenance etc). Additionally, robustness issues may have occurred due to parametric uncertainties that usually arise from modelling errors, environmental effects and structural damage. The robustness issues are directly related to the deployed control algorithm in each case. However, there is no substantial evidence in the literature that even indicates that the installed active and hybrid systems demonstrate issues that make them ineffective. One may find articles discussing the application of active, semi-active and hybrid mass dampers on real structures however, there is lack of information on how the systems perform, what their possible malfunctions are, and what their operational and management costs rise to. So, this makes it difficult to confidently reason the decrease in the use of active and hybrid technologies.

Based on the analysis that was presented in Section 7.2, one of the questions that comes up is, ”why the technologically advanced continent with the second highest number of control applications includes only passive systems?” The basis of the answer to this question can probably be found in Spencer and Nagarajaiah (2003). In their discussion they mentioned that, the civil engineering sector and construction industry in the U.S.A. (the country with the most applications in America) can be described as conservative and not open to the utilisation of new technologies. Moreover, it is noted that the lack of research and development expenditure by the construction industry along with the minimal to none verified analysis and design approaches make the implementation of semi-active, active and hybrid control systems in the U.S.A. almost impossible. In contrast to the U.S.A., the Japanese construction industry invests heavily in the research and development of new technologies. However, even in Japan, it is noticed that the purely active and semi-active control schemes remain in modest numbers. This demonstrates that there are still open challenges with regards to the semi-active and purely active systems in order to gain acceptance by the construction industries all over the world. Nishitani and Inoue (2001) state that, after the Kobe earthquake (1995), the use of active technology on civil structures in Japan was dramatically decreased in contrast to the base isolation devices ($\geq$700 installations). The authors explain that the reason for this was that after the earthquake, the Japanese engineering community was seeking immediate solutions on how to provide mitigation strategies for severe disasters. At the time, the active technology did not prove to be capable of controlling structures under severe natural hazards and thus, the local engineering community did not re-consider it. The authors commented that, the semi-active technology is very promising and could be inspiring the next-generation control systems. In this study, it is shown that, indeed this statement could be true when facing the development of purely actives systems (i.e. AMDs). As seen in Fig. 7, the installations of AMDs were considerably decreased after 1995 however, the installation of HMDs prospered until 2005.

Spencer and Nagarajaiah (2003) mentioned that, it is a challenging task to develop control strategies for the semi-active control schemes due to their intrinsically nonlinear nature. Therefore, despite their potential effectiveness and benefits they provide, their full-scale implementation is difficult. This study shows that, to date, the full-scale installation of SATMDs remains in very low levels (only 4). This demonstrates that the advantages of the SATMDs are still not fully recognised and realised.

Trying to grasp the bigger picture, one may refer to Soong and Spencer (2002) who stated that, the acceptance of the control systems is based on a combination of their enhanced performance and their installation, maintenance and future costs. It is evident that, the structural control research community mainly emphasises on enhancing the performance of the different types of control systems without considering any related costs and practicalities. Additionally, based on the findings of Section 7.3, the literature lacks of studies discussing the application of advanced mass damper systems on real civil structures. This demonstrates that the community does not share experience which would be beneficial on tackling the challenges that arise. Moreover, it is evident that there are no strict methodologies to be followed for the installation of mass damper systems on real structures. On the contrary, it was noticed that, the studies considering the implementation of mass damper technologies on real structures were focusing explicitly on very custom approaches. It is possible that, the current hesitation on the installation of such technologies may be the result of the absence of solid guidelines. Finally, the lack of training of civil engineering professionals in the area of control is identified as a bottleneck and as a major reason for the hesitation in implementing advanced mass dampers within latest vibration control practices.

8. Conclusions

In this work, an up-to-date literature review of studies considering mass damper technology was carried out. Studies that investigated passive, semi-active, active and hybrid control using mass dampers were included and their findings were discussed. New innovative control approaches proposed by the structural control community even up to this day were presented. Moreover, the limitations of each type of control system were reported in order to highlight the research gaps that have to be tackled.

In Section 6, a systematic literature search was conducted in order to gather mass damper applications on building-like structures in order to provide an image of real-life applications and identify potential gaps and future research needed. Eventually, a most complete table with real-life control applications is presented. The table includes 208 structures around the world. The applications were analysed based on where they are located and when they were implemented. The studies considering the control of real building-like structures were also gathered and presented in a tabulated form. In addition to that, a novel list of control algorithms utilised on real-building like structures was devised. The main findings of this work are:

1. Asia is the continent with the most structural control applications (120) with around 3 times more applications than the second continent with most applications (America with 46). The third continent with the most structural control applications is Europe with 36, fourth is Australia with 5 and last is Africa with only 1 application
2. 47% of the total applications were installed before 2000
3. the large majority of mass damper installations were PTMDs with 131 applications (63% of the total number systems) where, the second most used system is the HMD with 65 applications (31% of total number of systems)
4. 55% of the total applications were installed between the years 1992 and 2005 which is due to the sudden increase in the installation of HMDs in Japan
5. after 2005 the installation of the HMDs has considerably decreased and a preference in PTMDs was shown even though there was an increase in HMDs research (as seen in Fig. 2)
6. despite the high quality research done by the structural control community (demonstrated in Section 4), the algorithms utilised on real applications of semi-active, active and hybrid mass dampers were mostly based on the optimal theory, H_∞ and continuous sliding mode control, most likely due to their successful establishment in many control applications outside civil engineering
7. the structural control literature lacks of experience sharing with regards to the installation and management of advanced mass damper technologies (i.e. semi-active, active and hybrid) on real applications

As discussed in Section 7.4, to date there are open challenges considering the active and semi-active control systems that causes scepticism in the engineering industries around the world when considering their implementation on real-life structures. The decrease in the installation of HMDs demonstrates that there are potential issues with their installation which were discussed in Section 7.2. Thus, the research community should understand the real problems that arise from the active, semi-active and hybrid mass dampers, and provide confidence to the industry that the aforementioned systems are more reliable and truly superior over PTMDs. Based on the findings of this work, future research should focus on:

- Development of an experience-sharing culture within the research community regarding the installation and management of advanced mass damper systems for decreasing the self-learning practice that currently occurs
- Provision of information about the performance of already installed systems and their possible performance gaps in order to form necessary new research initiatives and allow the community to tackle real practical issues
- Use of realistic control system specifications (e.g. mass size, actuator capacity, etc) and realistic (and severe) excitations within research studies
- Large-scale experimental and analytical investigation of the performance of mass dampers should be enhanced
- Consideration of the short and long-term cost associated with the control system and, methods to decrease it
- Development of energy harvesting methods which will lead to a new generation of adaptive structural control systems with minimal, or even zero, energy requirements
- Design optimally (e.g. reducing section sizes) by making mass damper systems a starting point in the design process rather than a final step add-on

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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