Chapter

Data Mining Technology for Structural Control Systems: Concept, Development, and Comparison

Meisam Gordan, Zubaidah Ismail, Zainah Ibrahim and Huzaifa Hashim

Abstract

Structural control systems are classified into four categories, that is, passive, active, semi-active, and hybrid systems. These systems must be designed in the best way to control harmonic motions imposed to structures. Therefore, a precise powerful computer-based technology is required to increase the damping characteristics of structures. In this direction, data mining has provided numerous solutions to structural damped system problems as an all-inclusive technology due to its computational ability. This chapter provides a broad, yet in-depth, overview in data mining including knowledge view (i.e., concept, functions, and techniques) as well as application view in damped systems, shock absorbers, and harmonic oscillators. To aid the aim, various data mining techniques are classified in three groups, that is, classification-, prediction-, and optimization-based data mining methods, in order to present the development of this technology. According to this categorization, the applications of statistical, machine learning, and artificial intelligence techniques with respect to vibration control system research area are compared. Then, some related examples are detailed in order to indicate the efficiency of data mining algorithms. Last but not least, capabilities and limitations of the most applicable data mining-based methods in structural control systems are presented. To the best of our knowledge, the current research is the first attempt to illustrate the data mining applications in this domain.

Keywords: data mining, structural damped systems, vibration control, machine learning, artificial intelligence, statistical analysis

1. Introduction

In recent years, there has been a vast theoretical and experimental investigations in various problems encountered in different structures, from basic structural components (e.g., beams and plates) to complex structural systems (e.g., bridges and buildings). This is due to the fact that structures are built to support a load, namely, static or dynamic loads, incoming from different forces (e.g., tension, compression, torsion, bending, and shear). In this direction, many structures need to be designed to withstand dynamic loads even though they spend most of the time supporting static loads [1, 2]. Static loads are those that are gradually applied and remain in place for longer duration of time. These loads are not time dependent. As an illustration, a live load on a structure is considered as a static load. Besides, most of the loadings applied to civil engineering structures, including seismic loadings, are usually considered as equivalent static loads [3, 4]. On the other hand, time-dependent dynamic loads such as machinery vibrations, earthquakes, wind storms, sea waves, and traffic can cause intensive and continuous vibrational motions which can cause changing of the structural properties (i.e., mass, stiffness, or damping) and loading to change in the dynamic responses, such as natural frequencies, mode shapes, and damping ratios [5–8]. Therefore, in-service structural systems in civil engineering such as tall buildings, long hydraulic structures, and long-span bridges are damage-prone under these loads during their service life [9–14]. Moreover, these loads can cause intensive and stable vibrational motions, which can be damaging to human inhabitants. Based on these explanations, vibration is a serious concern in civil structures. It is due to the fact that existence of damage can disturb functionality and safety of the structure. However, the risk of occurrence of structural damage can be decreased by using a controlled vibration system to increase the damping characteristics of the structure. Accordingly, the advantage of using damping device is that damping system can improve the ability of the structure to dissipate a portion of the energy released during a dynamic loading event [15–18].

Over the last few decades, taller and wider structures have been built because of enormous developments in civil engineering area. As mentioned earlier, these structures will be subject to external loads which can cause vibrational problems. Consequently, it is essential to control the vibrational motions to reduce the response and to improve structure performance, safety, flexibility, serviceability, and structural reliability of these structures. Generally, structural control systems include four main groups which are passive, active, semi-active, and hybrid devices. Classification of these energy dissipation supplements is based on their operational mechanisms [19–21].

Data mining is the analysis of datasets to discover the relationships, new correlations, and trends and to extract the useful data in the form of patterns. Therefore, this process has been used to identify valid, valuable, and understandable forms of data [22, 23]. Accordingly, in recent years, this technology has provided various solutions to structural damped systems because of its powerful computational capacity. In this matter, many researchers have studied and examined various data mining techniques for passive, semi-active, active, and hybrid damped systems. In the same line, this chapter attempts to present the recent developments of well-known data mining techniques in vibration control devices. Before going into the details, it is important to point out the fundamental principles of data mining. Hence, data mining concepts including definition, background, functions, and techniques are discussed in the following section. Then, the concepts of applicable algorithms and their applications in damped systems are detailed in Section 3. Furthermore, applicable examples of data mining algorithms are presented for better understanding.

2. Data mining concept

Data can be defined as any fact, number, or text which can be proceeded by a computer. As the obtained pattern through data mining may be very difficult to find, it is sometimes compared to gold mining in rivers (**Figure 1**). The term “gold mining” refers to the search for gold in rocks or sand. Data mining is a search for information and knowledge. The origination of data mining traces back to the development of artificial intelligence in the 1950s. The development of data mining is shown in **Figure 2**.

In general, data mining has two classes which are descriptive mining and predictive mining using various techniques and functions (see **Figure 3** and **Table 1**).

The techniques play important roles to obtain effective models from observations. Besides, data mining techniques have also three main groups which are statistical techniques, machine learning techniques, and artificial intelligence techniques. It is noted that each of these techniques has particular algorithms for running the models to get the best solution. For instance, artificial neural network (ANN), Bayesian analysis, ant colony optimization, ICA, support vector machine, principal component analysis, particle swarm optimization (PSO), genetic algorithm, fuzzy logic, regression analysis, clustering, classification, and decision tree are classified under data mining techniques. Furthermore, the functions of data mining are categorized into clustering, prediction, classification, exploration, and association. The purpose of clustering is to divide the samples into groups with related behavior. The numerical prediction activity determines patterns, rules, or models to predict continuous or discrete target values which can also be used for other functions. Classification is used to recognize several rules which can be applied in future work to determine whether a previously unknown item belongs to a known class. Exploration is used to find out dimensionality of an input data, and, eventually, the association activity is used to frequently detect occurring related objects. Based on their particular utilizations in consequence of their assumptions and drawbacks, one or a combination of some of these tasks can be used to find the hidden information [24–27].

Figure 1.
Gold mining and data mining.

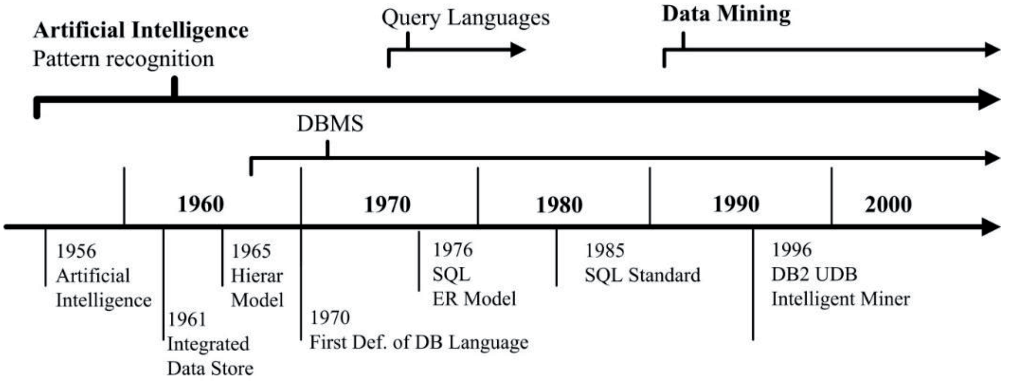

Figure 2.
History of data mining development.

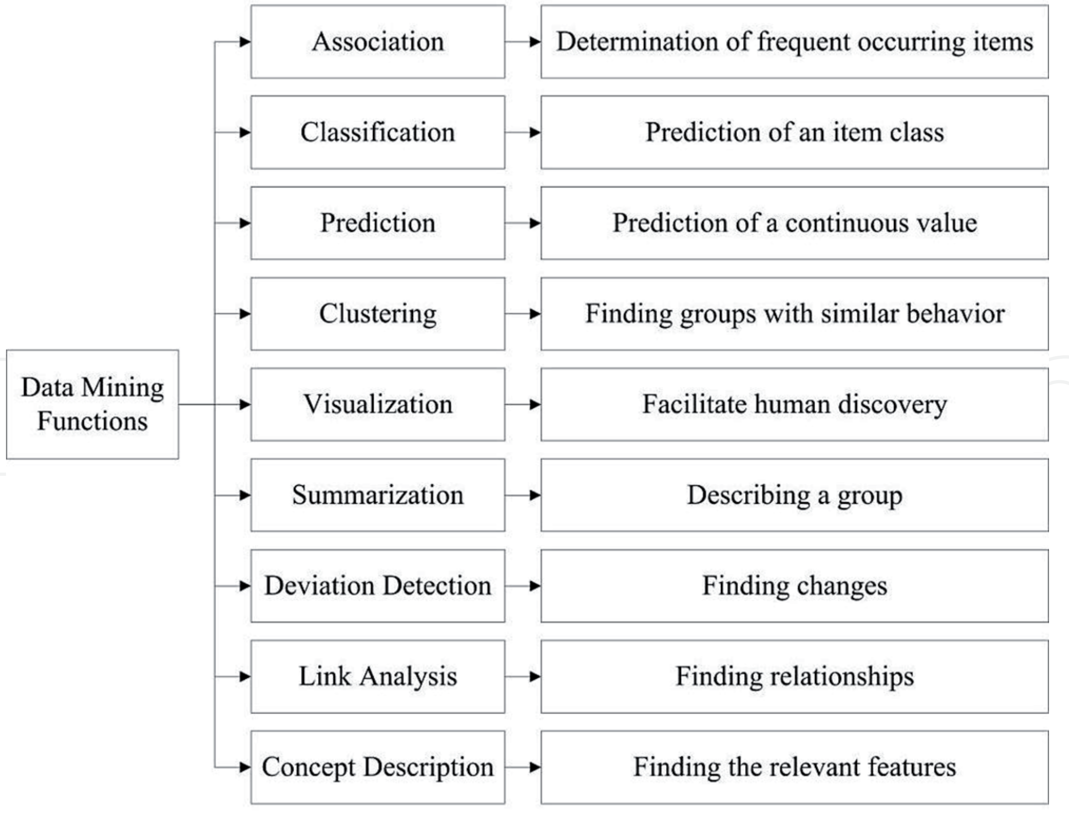

Figure 3.
Data mining functions.

Data mining technique	Category	Learning type
Artificial neural network	Artificial intelligence	Supervised/unsupervised
Support vector machine	Machine learning	Supervised
Decision tree	Statistical	Supervised
Clustering	Statistical	Unsupervised
Principal component analysis	Machine learning	Unsupervised
Regression	Statistical	Supervised
Fuzzy	Artificial intelligence	Supervised/unsupervised
Meta-heuristics	Artificial intelligence	–
Classification	Statistical	Supervised
Bayesian	Machine learning	Supervised

Table 1.
Data mining techniques.

3. Data mining algorithms

3.1 Support vector machine (SVM)

SVM is one of the classification- and prediction-based techniques which was first introduced by Vapnik in 1963 [28]. It works based on learning theory and because of its high accuracy and good generalization capability; it has the potential to produce high-quality predictions in numerous tasks. Therefore, SVM has various applications which can be found in several areas such as machine learning, data classification, and pattern recognition [29, 30]. Basic models of SVM are linear SVM with linear functions and nonlinear SVM with kernel functions. Moreover, the aim of SVM classifier is to determine a separating hyperplane to divide the given data into two classes (i.e., positive class and negative class) in the optimal form. Therefore, the optimal separating hyperplane is determined by solving an optimization problem [31].

SVM has been used in structural control systems. For instance, a SVM-based semi-active control strategy was reported by [32] for the numerical model of a multi-storey structure. In this study, four seismic waves including the El Centro, Hachinohe, and Kobe waves, as well as the Shanghai artificial wave, whose peak ground accelerations were all scaled to 0.1 g, were taken into consideration. As shown in **Figure 4**, a three-storey shear-type frame structure with dampers was considered as a case study in this work.

The seismic responses of structural top storey with the structure-damper system, structure-SVM system, and no-control device are shown, respectively, in **Figure 5**. It is seen from this figure that the structure-SVM system model has perfectly learned the control effectiveness of the structure-damper system. This observation indicated that the structure-SVM system model was significantly better than the structure-damper system.

In order to further examine the seismic response reduction of the controlled structure using the present algorithm, the displacement response of every floor under these four seismic waves is shown in **Figure 6**. It is seen that under the Hachinohe wave, the peak displacement response of every floor, especially the top floor, with the structure-SVM system model, was remarkably smaller than that with the structure-damper system. The authors verified once again that the proposed structure-SVM system model will render better effectiveness than the structure-damper system.

Comparative results of this study demonstrate that general semi-active dampers designed using the SVM-based semi-active control algorithm was capable of providing the higher level of response reduction.

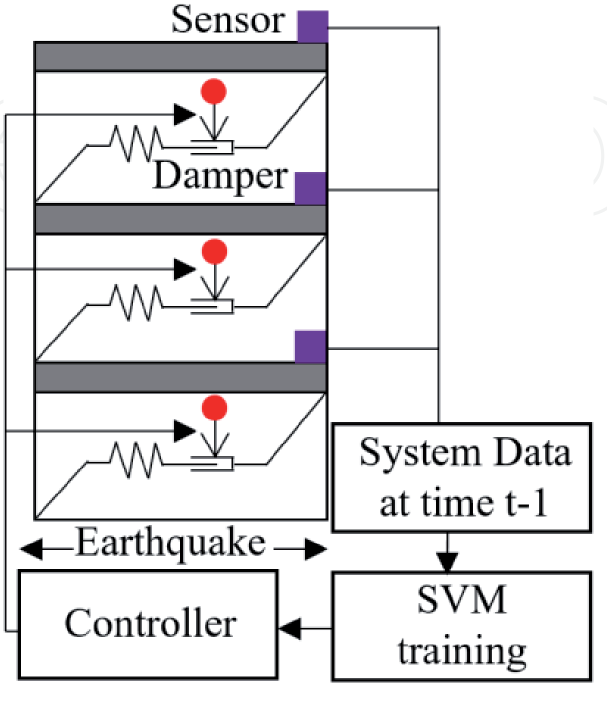

Figure 4.
Structure-SVM semi-active control system model and implementation flow chart.

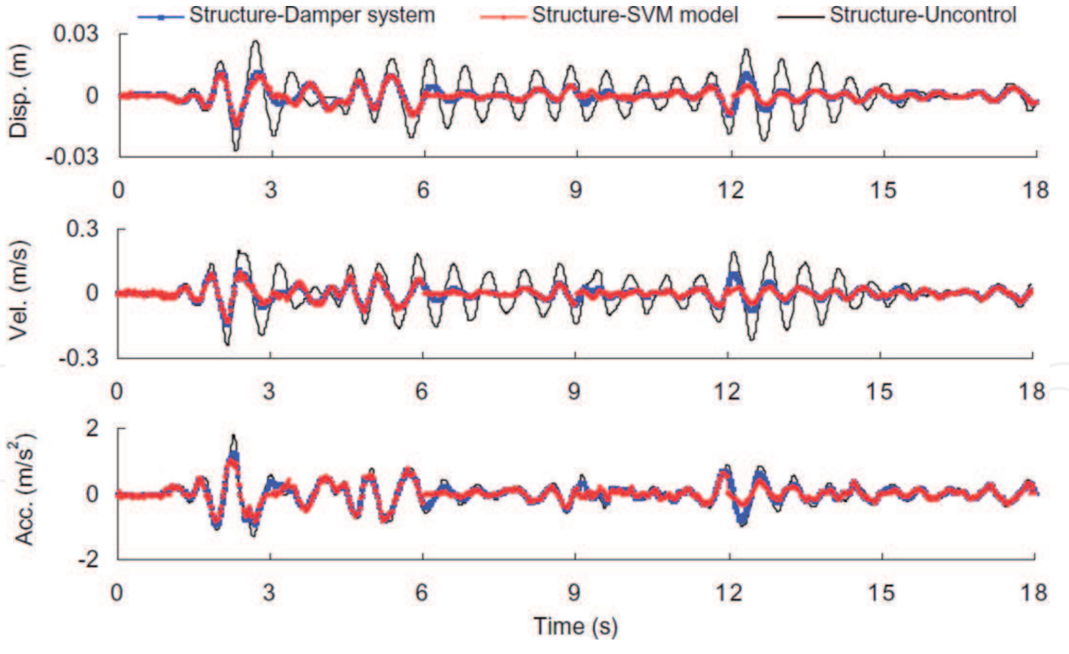

Figure 5.
Seismic responses of the structural top storey under the El Centro wave with PGA = 0.1 g using general semi-active dampers and SVM-based semi-active control algorithm.

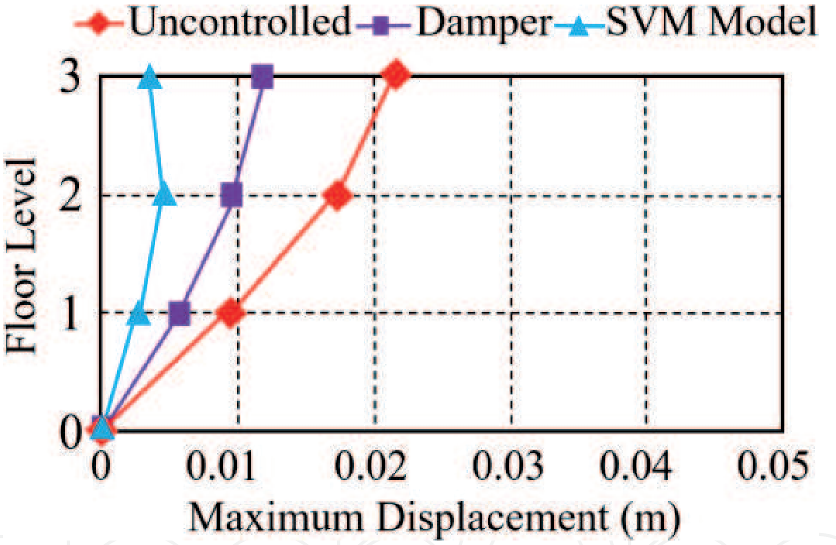

Figure 6.
Displacement responses of every storey under the Hachinohe seismic wave using general semi-active dampers and SVM-based semi-active control algorithm.

3.2 Artificial neural network (ANN)

Artificial neural network, which is a self-organizing prediction-based computational technique, was first proposed in the 1980s. This algorithm can solve many functions through pattern recognition [33]. It also can effectively be used to reconstruct nonlinear relationship learning from training [34]. A typical ANN model has two parts, that is, processing units (neurons) and connections between elements [34], in which neurons are located in layers of the network. A layered ANN structure, called multilayer perceptron (MLP), is one of the most widespread ANN methods. Generally, a conventional ANN has three layers which are input layer, hidden layer, and output layer. ANNs also can be categorized by their network topology such as feed forward and feedback or by their learning algorithms such as supervised learning and unsupervised learning [35].

There are a variety of researches focusing on the application of ANN in structural control systems. For instance, according to reports by [36, 37], ANN has a great capacity to improve the functionality of active control systems due to its high pattern recognition capability. It also could be used for semi-active [38, 39] and passive damping systems [40]. The following are the review of some related examples which indicate the applicability of ANN in damping systems.

Suresh et al. [36] applied a nonlinearly parameterized neural network as a novel controller scheme for the active control of earthquake-excited nonlinear base-isolated buildings. Numerical simulations were performed on a full-scale numerical test-bed base-isolated building with an isolation system comprising hysteretic lead-rubber bearings. They showed that the proposed approach could achieve good response reductions for a wide range of near-fault earthquakes, without a corresponding increase in the superstructure response.

Figure 7 demonstrates a neural network model that was developed by [40] which shows the application of ANN in passive damping devices. In this study, the ANN was employed in order to predict the inelastic demand of structural systems with viscoelastic dampers in terms of peak displacement, effective damping, and effective time period. The authors established that the ANN could be effectively used for new designs as well as for checking the response of any retrofitted structure for the chosen design spectrum. In addition, they concluded that artificial neural networks also were useful in quickly deciding the amount of damping and the number of dampers required to reduce the peak displacement and help in restricting further damage.

A smart active control system, called NEURO-FBG combining fiber Bragg grating (FBG) sensors and neural networks, has been proposed by [41] in a steel building. In this study, an attempt has been made to illustrate the development procedure of the converter and controller by means of "NEURO-FBG converter" and "NEURO-FBG controller." In this regard, the NEURO-FBG smart control system was designed to be a robust and reliable active control system with "smart" performance. To achieve this goal, a specific methodology was proposed comprising three parts, that is, a structural surveillance system, three converters, and a controller (see **Figure 8**). The analytical results show that the NEURO-FBG system could effectively control the response of the structure and provide a more reliable system than ordinary active control. Later on, the authors verified their method using an experimentation [42]. According to their experimental results, the proposed active control system can be successfully applied to buildings.

Figure 9 shows the architecture of an ANN-based real-time force tracking scheme for magnetorheological (MR) dampers, which was applied numerically and

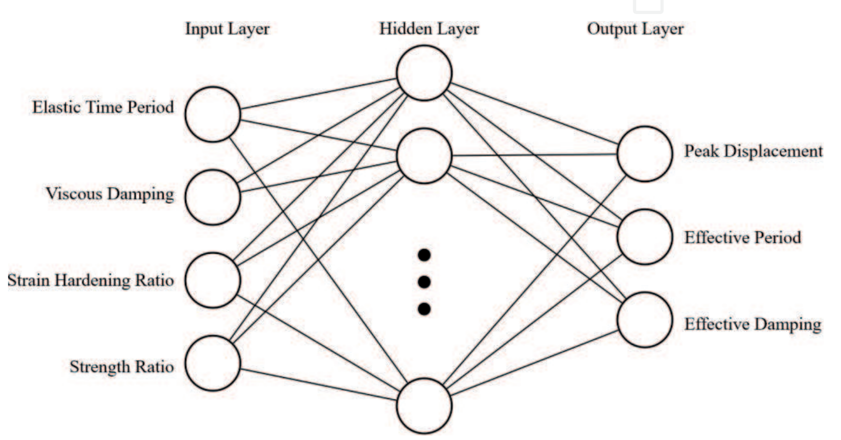

Figure 7.
Neural network model for a passive control system.

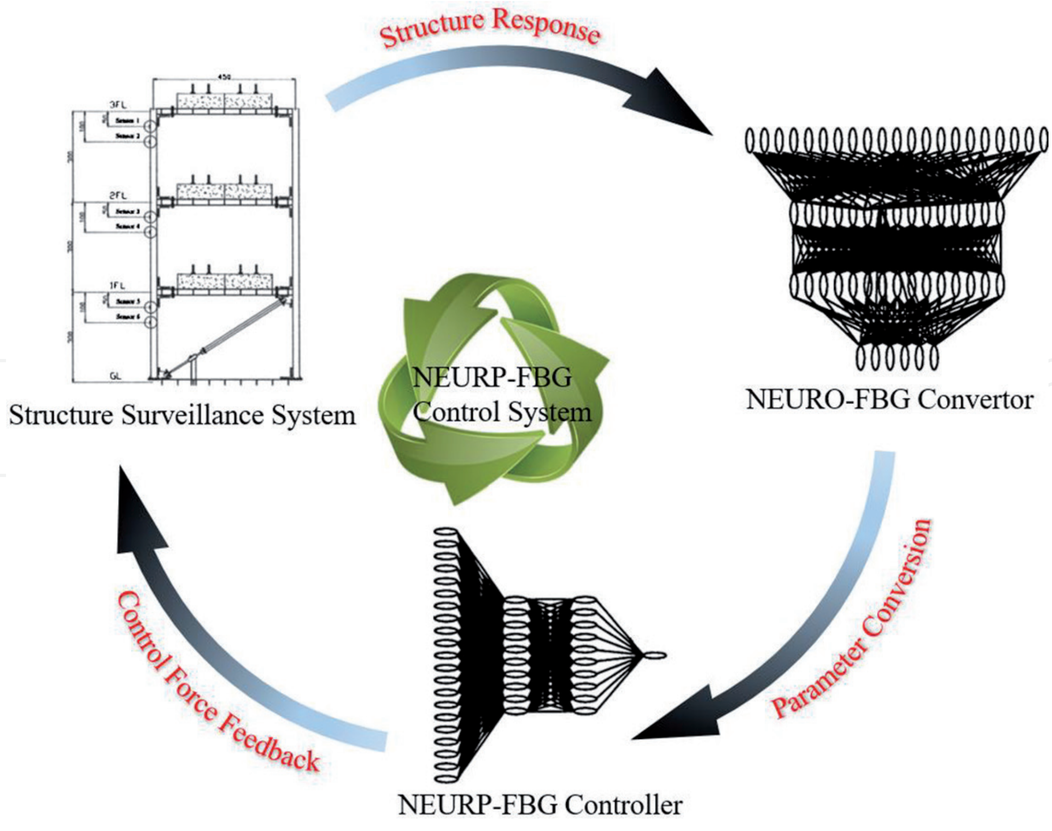

Figure 8.
Block diagram of NEURO-FBG smart control system.

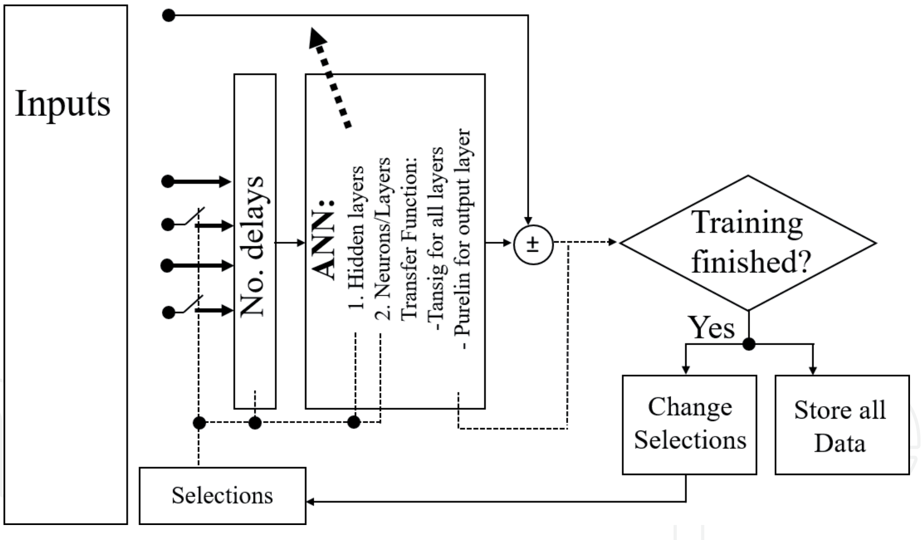

Figure 9.
The architecture of the neural network modeling.

experimentally on a five-storey shear frame by [43]. In this study, the forward and inverse MR damper dynamics were modeled by the neural network method using constant and half-sinusoidal current tests. As it can be seen in **Figure 9**, the ANN modeling was implemented for the forward and inverse MR damper model. It was concluded that the experimental validation of the neural network modeling both the forward and inverse MR damper dynamics showed the accuracy of these models.

A semi-active control strategy that combined a neuro-control system including a multilayer ANN with a back-propagation training algorithm with a smart damper was proposed to reduce seismic responses of structures [38]. A set of numerical simulations was performed to verify the effectiveness of the proposed method.

To aid the aim, two controllers were used, that is, (1) a primary control algorithm based on a cost function, and the sensitivity evaluation algorithm was employed in order to replace an emulator neural network as well as produce the desired active control force and (2) a secondary bang-bang-type controller caused the smart damper to generate the desired active control force, so long as this force was dissipative. It should be noted that cost function is defined as the squared sum of offset between the actual and the desired responses. Therefore, the main purpose was to minimize the cost function during training the network. **Figure 10** demonstrates the diagram of control for semi-active neuro-control using smart damper as well as a three-storey building with a single smart damper which was used as a numerical modeling. The authors showed that the proposed semi-active control system using ANN and smart dampers was a promising tool for control of real structures.

3.3 Fuzzy logic

Fuzzy logic was proposed by Lotfi Zadeh for the first time in 1965. It has been employed in different applications such as pattern recognition, classification, decision-making, etc. [44]. The basic configuration of a fuzzy technique consists of four important components, which are fuzzification, fuzzy rule base, fuzzy inference, and defuzzification. Fuzzification is a mapping from a crisp input to fuzzy membership sets. The fuzzy rule base has set rules of fuzzy variables described by membership functions. Fuzzy inference is a decision-making mechanism of the fuzzy system. The defuzzifier changes the fuzzy consequences from different rules into crisp values [45]. Fuzzy is a model-free technique for structural system identification, where the most important advantages of fuzzy systems are their high parallel implementation, nonlinearity, and being capable of adapting [46]. Applications of fuzzy logic in SHM are detailed in **Table 2**.

Adaptive fuzzy control strategy [47], fuzzy gain scheduling [48], semi-active fuzzy logic control system [49], model-based fuzzy logic controller (MBFLC) [50],

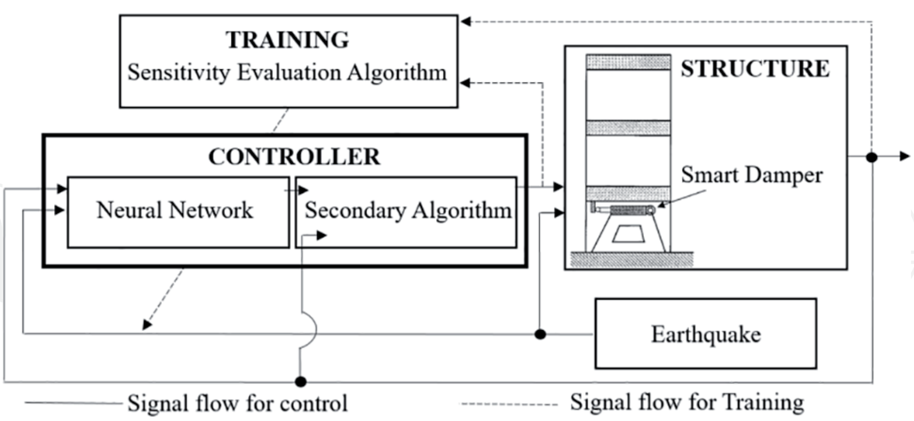

Figure 10.
Diagram of control for semi-active neuro-control using smart damper.

Case	Wind speed (m/s)	Maximum torsion (rad)
Uncontrolled	55.52	0.02
Controlled with passive TMD	98	0.02
Controlled with STMD-FLC	110	0.0063

Table 2.
Comparison of the effectiveness of passive TMD and STMD-FLC.

optimal fuzzy logic controller [51], fuzzy controller [52–54], neuro-fuzzy [55–57], genetic fuzzy logic controller (GFLC) [58], fuzzy control strategy based on a neural network forecasting model [59], and wavelet-neuro-fuzzy control [37] are some of the important applications of fuzzy logic in structural control systems. The following examples illustrate the applicability of fuzzy in damping systems.

A semi-active fuzzy control system was introduced by [49] to reduce the seismic responses in variable orifice dampers. In this direction, a numerical study was conducted to investigate the effectiveness of the proposed approach. Results revealed that the fuzzy logic controller (FLC) was capable of improving the structural responses. Another semi-active fuzzy control system comprising a semi-active tuned mass damper (STMD) system with variable damping was proposed by [60] to control the flutter instability of long-span suspension

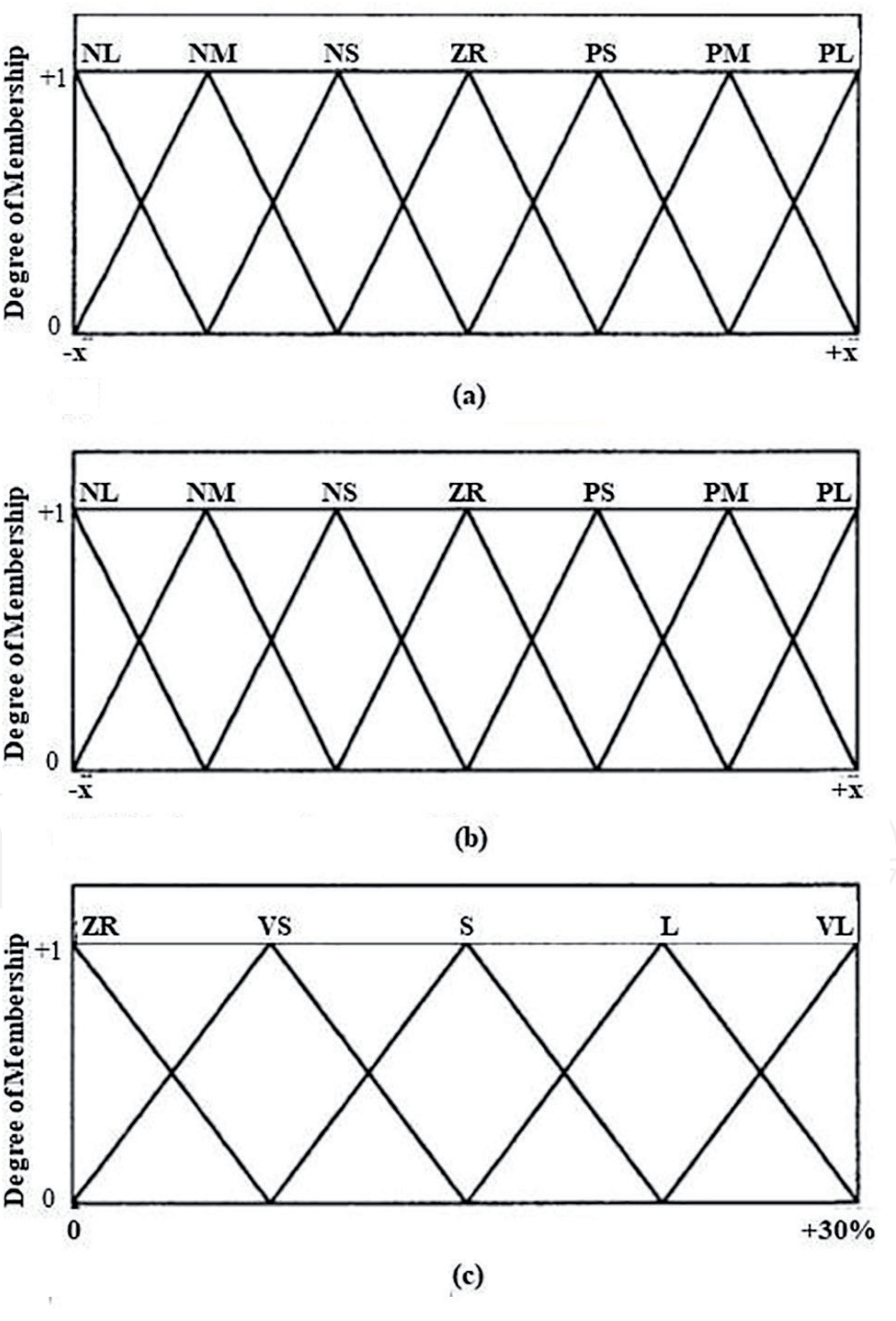

Figure 11.
Membership functions of the fuzzy logic controller variables: (a) membership functions for displacement, (b) membership functions for velocity, and (c) membership functions for semi-active tuned mass damper (TMD) damping ratio [60].

bridges. In this study, the variable damping of the system was chosen through a fuzzy logic controller. The STMD-FLC methodology was applied to increase the flutter wind speed of the test structure which was a suspension bridge. To do so, in order to select the level of semi-active damping ratio, a fuzzy logic feedback controller was incorporated into a closed-loop control system. The displacement and velocity quantities were used as the input to the fuzzy logic controller, and the level of STMD damping ratio was its output for each degree of freedom, namely, vertical and torsional (see **Figure 11**). The FLC system was designed based on the Mamdani's fuzzy inference method.

In addition, a comparison of the effectiveness of passive TMD and STMD-FLC was carried out in this research, which is shown in **Table 2**. The table clearly shows the superior performance of semi-active control over the passive control.

The description of the fuzzy input membership function abbreviations is as follows: NL = negative large, NM = negative medium, NS = negative small, ZR = zero, PS = positive small, PM = positive medium, and PL = positive large; and those of the output are as follows: ZR = zero, VS = very small, S = small, L = large, and VL = very large.

Adaptive network-based fuzzy inference system (ANFIS) is a hybrid learning algorithm which combines the back-propagation gradient descent and least squares techniques to generate a fuzzy inference system. The membership functions in ANFIS are adjusted according to a given set of input and output data. The main objective of ANFIS is to integrate the finest features of neural networks and fuzzy systems. Accordingly, the outputs of ANFIS can be seen in two steps, that is, (1) representation of prior knowledge into a set of constraints to reduce the optimization search space from fuzzy system and (2) adaptation of back-propagation to structured network to automate fuzzy control parametric tuning from neural network. Therefore, ANFIS is one of the best trade-offs between neural and fuzzy systems providing smoothness due to the fuzzy control interpolation and adaptability, due to the neural network back-propagation [61].

ANFIS has proven to be an excellent function approximation tool. For example, an ANFIS controller was developed by [61] for reduction of environmentally induced vibration in multiple-degree-of-freedom building structure with MR damper. The systems were excited using two different earthquake random vibration loadings. **Figure 12** illustrates the comparison of the displacement response at the top of the structure with and without control under El Centro and Hachinohe earthquakes. The figure shows that ANFIS clearly could reduce the displacement amplitude in both vibration loadings.

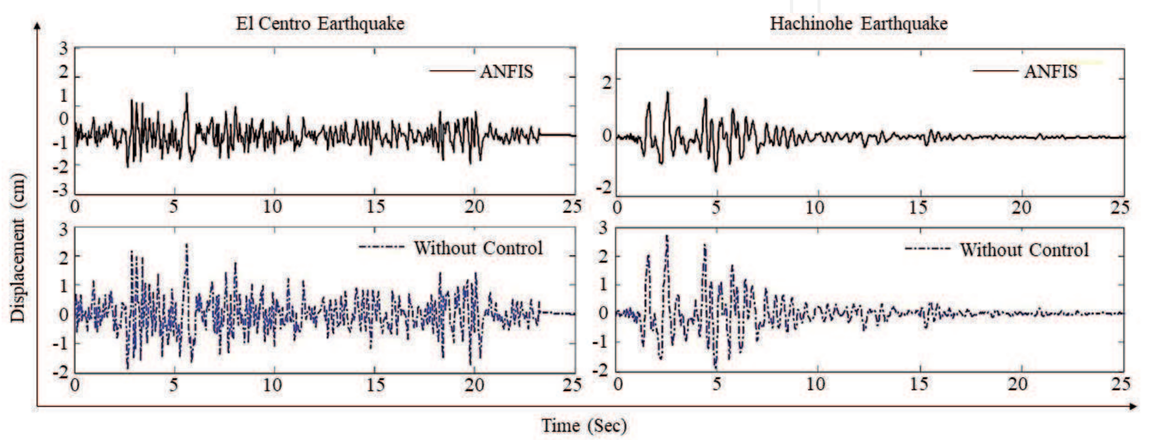

Figure 12.
Displacement response of the structure under El Centro and Hachinohe earthquakes.

3.4 Clustering

Clustering is an unsupervised statistical data analysis technique, which is used in pattern recognition, image analysis, and bioinformatics. This method is employed to divide datasets into separated similar subsets (clusters) according to typical patterns identified in the clustering analysis [62]. In order to have a successful clustering, maximum intra-cluster similarity as well as minimum inter-cluster similarity is required. The K-means is one of the most descriptive partitioning clustering algorithms with a quite reliable effectiveness at local optimum. However, it can be employed only to numerical datasets. Furthermore, K-means has poor handling for data prone to noise and outliers [63]. Clustering can also help to decrease the distance between datasets and improve the similarity of datasets in each cluster [64, 65].

A combination of fuzzy C-means clustering and subtractive clustering has been developed numerically for nonlinear system identification of a seismically excited building-MR damper system. It was demonstrated from the simulation that the proposed fuzzy model is effective in identifying nonlinear behavior of the building-MR damper system subjected to the 1940 El Centro earthquake. **Figure 13** compares the displacement and acceleration responses of the original simulation model with those of the identified model. Note that the original simulation model means an analysis model of the building equipped with an MR damper. As can be seen from the figure, overall good agreements between the original values and the identified model were found in the time histories of both displacement and acceleration responses [66].

3.5 Genetic algorithm (GA)

GA, which is one the most powerful optimization-based algorithms, was first proposed by John Holland in the 1970s. In GA, a chromosome is used to determine the solution. The chromosome includes a group of genes that optimize parameters. This algorithm employs a random solution from a current population. Then, the next generation will be created using crossover and mutation operators [67]. In general, GA is an attractive tool to optimize difficult problems due to its benefits such as parallelism, convergence to global optima, adaptation, and no need for the gradient of the objective function. Considering these benefits, GA has been successfully applied in optimal design of TMDs [68–70] and multiple tuned liquid column damper (MTLCD) [71], optimization of earthquake energy dissipation system [72], optimization of active control systems in high-rise buildings [73], optimal damper distribution [74], smart control systems [75], etc.

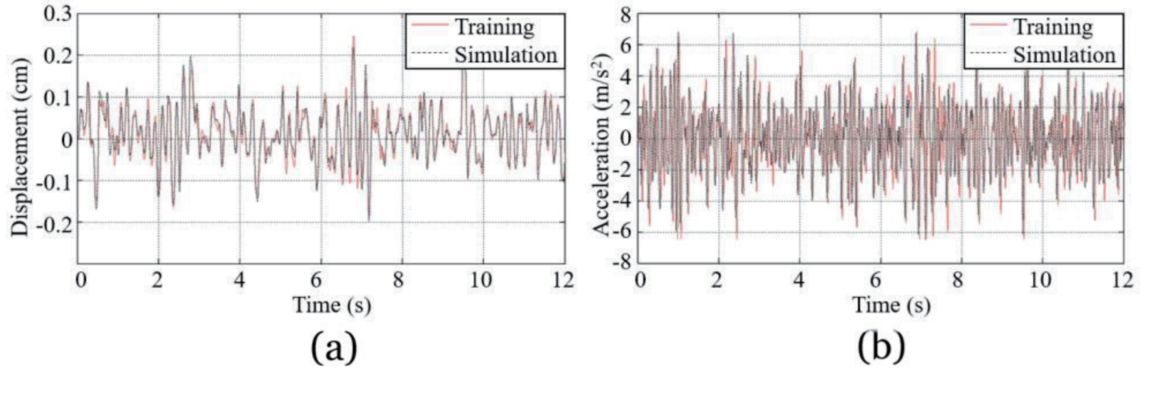

Figure 13.
Comparison of original simulation and obtained results from the proposed model. (a) displacement response, (b) acceleration response.

An optimization strategy of hydraulic actuators, that is, an implicit redundant representation (IRR) genetic algorithm with a non-dominated sorting II (NS2) GA, namely, NS2-IRR GA, was implemented numerically by [73] in order to minimize the distribution of control devices in large-scale structures as well as optimize the dynamic responses of structures. It was shown that the proposed NS2-IRR GA-based control system was effective in finding not only optimal locations and numbers of actuators in structures but also minimum responses of the buildings. In the same line, **Figure 14**, which compares the dynamic behavior of the proposed approach with those of the benchmark control system in reducing displacements of the 20-storey building, clearly indicates the effectiveness of GA in minimizing the displacement/drift responses of the building structure.

3.6 Particle swarm optimization

PSO which was first proposed by Kennedy and Eberhart [76] is one of the population-based artificial intelligence optimization-based techniques. The approach was simulated by the social behavior of organisms such as bird flocking to be used as a suitable tool for global optimization [77]. In PSO, a particle represents

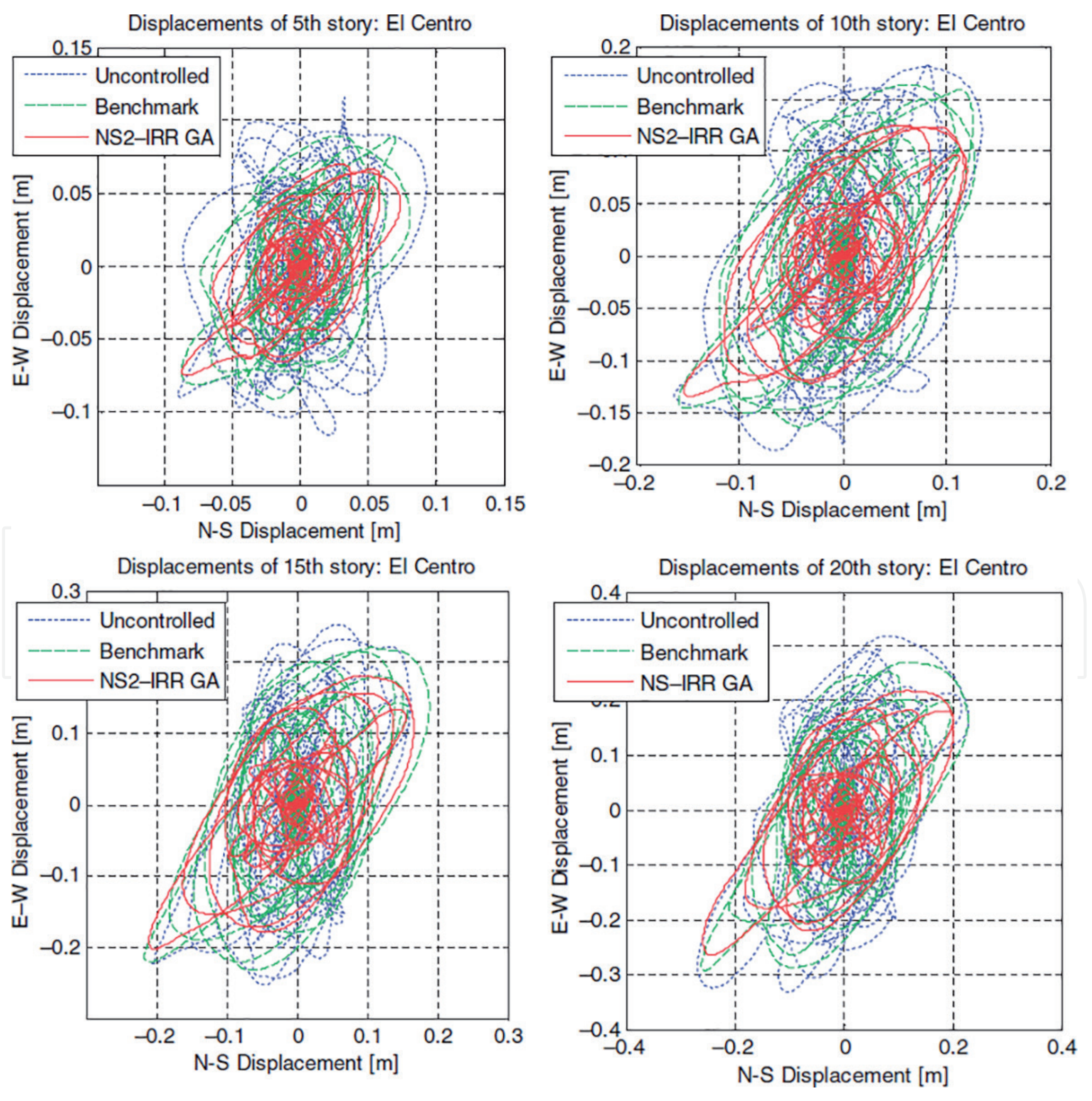

Figure 14.
Comparison of displacement responses of benchmark and NS2-IRR genetic algorithm approaches under the El Centro earthquake.

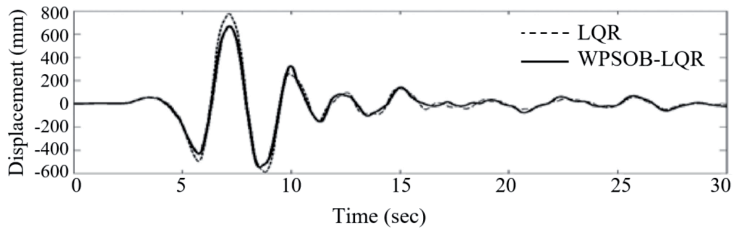

Figure 15.
Results for the 1981 Imperial Valley (El Centro-06): controlled displacement.

a potential solution where each particle has two updatable features: position and velocity. PSO is easy to apply and has a great computational capacity. In comparison with other optimization approaches, PSO is more efficient and requires a fewer numbers of function evaluations while giving better or the same quality of results. However, it has some weaknesses such as trapping into local optimum in a complex search space. Besides, the disability to implement a precise local search around a local optimum is another drawback in PSO [78, 79].

PSO was applied for optimization of the parameters of a TMD-viscously damped system in [80] including the optimum mass ratio, damper damping, and tuning frequency. The results were calculated by means of three numerical examples for different nonstationary ground acceleration systems to demonstrate the efficiency of the proposed method. To this end, the system was subjected to ground accelerations with different PSO-based power spectra in order to minimize either the maximum displacement or acceleration mean square responses. The authors of this research reported that it was quite easy to program the applications of PSO in practical engineering.

Another method called wavelet PSO-based linear quadratic regulator (WPSOB-LQR) was presented numerically by [81] to find the optimal control force of active TMD via PSO-based linear quadratic regulator (LQR) and wavelet analysis. To aid the aim, PSO was used to determine the gain matrices through the online update of the weighting matrices used in the controller while eliminating the trial and error. **Figure 15** shows the time history of displacement response by using pre-developed LQR control method and the proposed WPSOB-LQR approach. As it can be observed from this figure, the displacement was significantly reduced using their proposed method. Moreover, the authors stated that the proposed method was practicable and worthwhile for vibration control of structures.

4. Conclusion

In this chapter, a brief description of data mining has been made, the most applicable techniques were reviewed, and the applications of machine learning, artificial intelligence, and statistical algorithms in structural control systems have been stated. Furthermore, for each technique, an attempt has been made to present several examples to familiarize readers more in the corresponding field as well as presenting an overall background of the researches done by several investigators worldwide. The following are some of the important conclusions.

Fuzzy, GA, and ANN are the most applicable methods in structural control systems. Among all, fuzzy controllers were the most powerful techniques to solve numerous problems. As a matter of fact, fuzzy algorithm could present uncomplicated and strong solutions for control systems in order to modify uncertainty, such as selecting damping ratios and reducing the responses of structures. ANN was another self-organizing technique which has been used to control and predict the seismic responses of structures with energy dissipation systems. As far as the ANN was concerned, the local minimum point, overlearning, and the excessive dependence on experience in the choice of structures and types were its inevitable limitations, while SVM could get rid of these limitations and has been successfully applied to time series forecasting. Likewise, SVM could provide some special advantages in the fields of small sample issues and nonlinear and high-dimensional pattern recognition. MATLAB was the main program language which has been used to develop data mining techniques in this area.

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Author details

Meisam Gordan*, Zubaidah Ismail, Zainah Ibrahim and Huzaifa Hashim
Department of Civil Engineering, University of Malaya, Kuala Lumpur, Malaysia

*Address all correspondence to: meisam.gordan@gmail.com

References

[1] Hanif MU, Ibrahim Z, Jameel M, Ghaedi K, Aslam M. A new approach to estimate damage in concrete beams using non-linearity. Construction and Building Materials. 2016;**124**:1081-1089

[2] Hanif MU, Ibrahim Z, Jameel M, Ghaedi K, Hashim H. Simulation-based non-linear vibration model for damage detection in RC beams. European Journal of Environmental and Civil Engineering. March 2019:1-26. DOI: 10.1080/19648189.2019.1578270

[3] Filiatrault A. Principles of Passive Supplemental Damping and Seismic Isolation. Pavia: Iuss Press; 2006

[4] Ghayeb HH, Razak HA, Sulong NHR. Development and testing of hybrid precast concrete beam-to-column connections under cyclic loading. Construction and Building Materials. 2017;**151**:258-278. DOI: 10.1016/j.conbuildmat.2017.06.073

[5] Gordan M, Ismail Z, Razak HA, Ibrahim Z, Vibration-based structural damage identification using data mining. In: 24th International Congress on Sound and Vibration. London; 2017

[6] Gordan M, Ghaedi K. Experimental study on the effectiveness of tuned mass damper on a steel frame under harmonic load. In: 4th International Congress on Civil Engineering, Architecture & Urban Development, Shahid Beheshti University, Tehran. Tehran, Iran: Shahid Beheshti University; 2016

[7] Hanif MU, Ibrahim Z, Ghaedi K, Javanmardi A, Rehman SK. Finite element simulation of damage In RC beams. Journal of Civil Engineering, Science and Technology. 2018;**9**:50-57

[8] Ghaedi K, Ibrahim Z, Javanmardi A. A new metallic bar damper device for seismic energy dissipation of civil structures. IOP Conference Series: Materials Science and Engineering. 2018;**431**:1-7. DOI: 10.1088/1757-899X/431/12/122009

[9] Javanmardi A, Ibrahim Z, Ghaedi K, Jameel M, Khatibi H, Suhatril M. Seismic response characteristics of a base isolated cable-stayed bridge under moderate and strong ground motions. Archives of Civil and Mechanical Engineering. 2017;**17**:419-432. DOI: 10.1016/j.acme.2016.12.002

[10] Javanmardi A, Ibrahim Z, Ghaedi K, Khan NB, Ghadim HB. Seismic isolation retrofitting solution for an existing steel cable-stayed bridge. PLoS One. 2018;**13**:1-22. DOI: 10.1371/journal.pone.0200482

[11] Ghaedi K, Jameel M, Ibrahim Z, Khanzaei P. Seismic analysis of roller compacted concrete (RCC) dams considering effect of sizes and shapes of galleries. KSCE Journal of Civil Engineering. 2016;**20**:261:261-272. DOI: 10.1007/s12205-015-0538-2

[12] Ghaedi K, Hejazi F, Ibrahim Z, Khanzaei P. Flexible foundation effect on seismic analysis of roller compacted concrete (RCC) dams using finite element method. KSCE Journal of Civil Engineering. 2017;**22**:1-13

[13] Ghaedi K, Ibrahim Z, Adeli H. Invited review: Recent developments in vibration control of building and bridge structures. Journal of Vibroengineering. 2017;**19**:3564-3580

[14] Ghaedi K, Khanzaei P, Vaghei R, Fateh A, Javanmardi A, Gordan M, et al. Reservoir hydrostatic pressure effect on roller compacted concrete (RCC) dams. Malaysian Construction Research Journal. 2016;**19**:1-9

[15] Gordan M. Experimental Investigation of Passive Tuned Mass

Damper and Fluid Viscous Damper on a Slender Two Dimension Steel Frame. Johor, Malaysia: University Technology of Malaysia; 2014

[16] Gordan M, Haddadiasl A, Marsono AK, Md Tap M. Investigation the behavior of a four-storey steel frame using viscous damper. Applied Mechanics and Materials. 2015;**735**:149-153

[17] Gordan M, Izadifar M, Haddadiasl A, Ahad J, Abadi R, Mohammadhosseini H. Interaction of across-wind and along-wind with tall buildings. Australian Journal of Basic and Applied Sciences. 2014;**8**:96-101

[18] Ghaedi K, Javanmardi A, Gordan M, Hamed K, Abdollah M. Application of 2D and 3D finite element modelling of gravity dams under seismic loading. In: 3rd National Graduate. Conference, Universiti Tenaga Nasional, Kuala Lumpur, Putrajaya Campus; 2015. pp. 264-269

[19] Ghaedi K, Ibrahim Z, Jameel M, Javanmardi A, Khatibi H. Seismic response analysis of fully base-isolated adjacent buildings with segregated foundations. Advances in Civil Engineering. 2018;**2018**:1-21. DOI: 10.1155/2018/4517940

[20] Ghaedi K, Ibrahim Z, Javanmardi A, Rupakhety R. Experimental study of a new Bar damper device for vibration control of structures subjected to earthquake loads. Journal of Earthquake Engineering. 2018:1-19. DOI: 10.1080/13632469.2018.1515796

[21] Javanmardi A, Ibrahim Z, Ghaedi K, Benisi Ghadim H, Hanif MU. State-of-the-art review of metallic dampers: Testing, development and implementation. Archives of Computational Methods in Engineering. 2019:1-24. DOI: 10.1007/s11831-019-09329-9

[22] Miranda T, Correia AG, Santos M, Ribeiro L, Cortez P. New models for strength and deformability parameter calculation in rock masses using data-mining techniques. International Journal of Geomechanics. 2011;**11**:44-58

[23] Buchheit RB, Garrett JH Jr, Lee SR, Brahme R. A knowledge discovery case study for the intelligent workplace. Computing in Civil and Building Engineering. 2000:914-921. DOI: 10.1061/40513(279)119

[24] Gordan M, Razak HA, Ismail Z, Ghaedi K. Recent developments in damage identification of structures using data mining. Latin American Journal of Solids and Structures. 2017;**14**:2373-2401. DOI: 10.1590/1679-78254378

[25] Liao S-H, Chu P-H, Hsiao P-Y. Data mining techniques and applications – A decade review from 2000 to 2011. Expert Systems with Applications. 2012;**39**:11303-11311

[26] Alves V, Cremona C, Cury A. On the use of symbolic vibration data for robust structural health monitoring. Proceedings of the Institution of Civil Engineers. 2015;**169**:715-723

[27] Gordan M, Razak HA, Ismail Z, Ghaedi K. Data mining based damage identification using imperialist competitive algorithm and artificial neural network. Latin American Journal of Solids and Structures. 2018;**15**:1-14

[28] Vapnik V. The Nature of Statistical Learning Theory. New York: Springer-Verlag; 1995

[29] He H-X, Yan W. Structural damage detection with wavelet support vector machine: Introduction and applications. Structural Control and Health Monitoring. 2007;**14**:162-176

[30] Tinoco J, Gomes Correia A, Cortez P. Support vector machines

applied to uniaxial compressive strength prediction of jet grouting columns. Computers and Geotechnics. 2014;**55**:132-140

[31] Kishore B, Satyanarayana MRS, Sujatha K. Efficient fault detection using support vector machine based hybrid expert system. International Journal of Systems Assurance Engineering and Management. 2014:34-40. DOI: 10.1007/s13198-014-0281-y

[32] Li C, Liu Q. Support vector machine based semi-active control of structures: A new control strategy. Structural Design of Tall and Special Buildings. 2011;**20**:711-720

[33] Ahmed R, El Sayed M, Gadsden SA, Tjong J, Habibi S. Artificial neural network training utilizing the smooth variable structure filter estimation strategy. Neural Computing and Applications. 2015;**27**:537-548

[34] Ali A, Amin SE, Ramadan HH, Tolba MF. Enhancement of OMI aerosol optical depth data assimilation using artificial neural network. Neural Computing and Applications. 2013;**23**:2267-2279

[35] Azimzadegan T, Khoeini M, Etaat M, Khoshakhlagh A. An artificial neural-network model for impact properties in X70 pipeline steels. Neural Computing and Applications. 2012;**23**:1473-1480

[36] Suresh S, Narasimhan S, Nagarajaiah S. Direct adaptive neural controller for the active control of earthquake-excited nonlinear base-isolated buildings. Structural Control and Health Monitoring. 2012;**19**:370-384

[37] Mitchell R, Kim Y, El-Korchi T, Cha Y-J. Wavelet-neuro-fuzzy control of hybrid building-active tuned mass damper system under seismic excitations. Journal of Vibration and Control. 2012;**19**:1881-1894

[38] Jung H-J, Lee H-J, Yoon W-H, Oh J-W, Lee I-W. Semiactive neurocontrol for seismic response reduction using smart damping strategy. Journal of Computing in Civil Engineering. 2004;**18**:277-281

[39] Chen ZH, Ni YQ. On-board identification and control performance verification of an MR damper incorporated with structure. Journal of Intelligent Material Systems and Structures. 2011;**22**:1551-1565

[40] Vaidyanathan CV, Kamatchi P, Ravichandran R. Artificial neural networks for predicting the response of structural systems with viscoelastic dampers. Computer-Aided Civil and Infrastructure Engineering. 2005;**20**:294-302

[41] Lin T, Chang K, Chung L, Lin Y. Active control with optical fiber sensors and neural networks. I: Theoretical analysis. Journal of Structural Engineering. 2006;**132**:1293-1304

[42] Lin T, Chang K, Lin Y. Active control with optical fiber sensors and neural networks. II: experimental verification. Journal of Structural Engineering. 2006;**132**:1304-1314

[43] Weber F, Bhowmik S, Høgsberg J. Extended neural network-based scheme for real-time force tracking with magnetorheological dampers. Structural Control and Health Monitoring. 2014;**21**:225-247

[44] Rutkowski L. Flexible Neuro-Fuzzy Systems: Structures, Learning and Performance Evaluation. Poland: Technical University of Czestochowa, Springer Science & Business Media; 2004

[45] Nyongesa HO. Enhancing neural control systems by fuzzy logic and evolutionary reinforcement. Neural Computing and Applications. 1998;**7**:121-130

[46] Nerves AC, Krishnan R. Active control strategies for tall civil structures. Proceedings of IECON'95-21st Annual Conference on IEEE Industrial Electronics. 1995;**2**:962-967

[47] Zhou L, Chang C, Wang L. Adaptive fuzzy control for nonlinear building–Magnetorheological damper system. Journal of Structural Engineering. 2003;**129**:905-913

[48] Wongprasert N, Symans MD. Experimental evaluation of adaptive elastomeric Base-isolated structures using variable-orifice fluid dampers. 2005;**131**:867-877

[49] Ghaffarzadeh H, Dehrod EA, Talebian N. Semi-active fuzzy control for seismic response reduction of building frames using variable orifice dampers subjected to near-fault earthquakes. Journal of Vibration and Control. 2012;**19**:1980-1998

[50] Kim Y, Langari R, Hurlebaus S. Control of a seismically excited benchmark building nonlinear fuzzy control. Journal of Structural Engineering. 2010;**136**:1023-1026

[51] Ahlawat AS, Ramaswamy A. Multiobjective optimal fuzzy logic controller driven active and hybrid control systems for seismically excited nonlinear buildings. Journal of Engineering Mechanics. 2002;**130**:416-423

[52] Samali B, Al-dawod M, Kwok KCS, Naghdy F. Active control of cross wind response of 76-story tall building using a fuzzy controller. Journal of Engineering Mechanics. 2004;**130**: 492-498

[53] Soleymani M, Khodadadi M. Adaptive fuzzy controller for active tuned mass damper of a benchmark tall building subjected to seismic and wind loads. Structural Design of Tall and Special Buildings. 2014;**23**:781-800

[54] Lin C-J, Yau H-T, Lee C-Y, Tung K-H. System identification and semiactive control of a squeeze-mode magnetorheological damper. IEEE/ASME Transactions on Mechatronics. 2013;**18**:1691-1701

[55] Kim H, Roschke PN. Fuzzy control of base-isolation system using multi-objective genetic algorithm. Computer-Aided Civil and Infrastructure Engineering. 2006;**21**:436-449

[56] Reigles DG, Symans MD. Supervisory fuzzy control of a base-isolated benchmark building utilizing a neuro-fuzzy model of controllable fluid viscous dampers. Structural Control and Health Monitoring. 2006;**13**:724-747

[57] Shook DA, Roschke PN, Ozbulut OE. Superelastic semi-active damping of a base-isolated structure. Structural Control and Health Monitoring. 2008;**15**:746-768

[58] Mohtat A, Yousefi-Koma A, Dehghan-Niri E. Active vibration control of seismically excited structures by Atmds: Stability and performance robustness perspective. International Journal of Structural Stability and Dynamics. 2010;**10**:501-527

[59] Guo Y-Q, Fei S-M, Xu Z-D. Simulation analysis on intelligent structures with magnetorheological dampers. Journal of Intelligent Material Systems and Structures. 2007;**19**:715-726

[60] Pourzeynali S, Datta TK. Semiactive fuzzy logic control of suspension. Journal of Structural Engineering. 2005;**131**:900-912

[61] Gu ZQ, Oyadiji SO. Application of MR damper in structural control using ANFIS method. Computers and Structures. 2008;**86**:427-436. DOI: 10.1016/j.compstruc.2007.02.024

[62] Ghaedi K, Ibrahim Z. Earthquake prediction. In: Zouaghi T, editor. Earthquakes - Tectonics, Hazard Risk Mitig. Rijeka, Croatia: InTech; 2017. pp. 205-227. DOI: 10.5772/65511

[63] Symeonidis A, Mitkas P. Data mining and knowledge discovery: A brief overview. In: Agent Intelligence Through Data Mining. United States: Springer; 2005. pp. 11-40

[64] Chen TY, Huang JH. Application of data mining in a global optimization algorithm. Advances in Engineering Software. 2013;**66**:24-33

[65] Xiao F, Fan C. Data mining in building automation system for improving building operational performance. Energy and Buildings. 2014;**75**:109-118

[66] Kim Y, Langari R, Hurlebaus S. MIMO fuzzy identification of building-MR damper systems. Journal of Intelligent Fuzzy Systems. 2011;**22**:185-205

[67] Aghajanloo M, Sabziparvar A. Artificial neural network – Genetic algorithm for estimation of crop evapotranspiration in a semi-arid region of Iran. Neural Computing and Applications. 2012;**23**:1387-1393

[68] Pourzeynali S, Salimi S. Robust multi-objective optimization design of active tuned mass damper system to mitigate the vibrations of a high-rise building. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. 2014

[69] Singh MP, Singh S, Moreschi LM. Tuned mass dampers for response control of torsional buildings. Earthquake Engineering and Structural Dynamics. 2002;**31**:749-769

[70] Mohebbi M, Joghataie A. Designing optimal tuned mass dampers for nonlinear frames by distributed genetic algorithms. Structural Design of Tall and Special Buildings. 2012;**21**:57-76

[71] Ahadi P, Mohebbi M, Shakeri K. Using optimal multiple tuned liquid column dampers for mitigating the seismic response of structures. ISRN Civil Engineering. 2012;**2012**:1-6

[72] Hejazi F, Toloue I, Jaafar MS, Noorzaei J. Optimization of earthquake energy dissipation system by genetic algorithm. Computer-Aided Civil and Infrastructure Engineering. 2013;**28**:796-810

[73] Cha Y-J, Kim Y, Raich AM, Agrawal AK. Multi-objective optimization for actuator and sensor layouts of actively controlled 3D buildings. Journal of Vibration and Control. 2012;**19**:942-960

[74] Wongprasert N, Symans MD. Application of a genetic algorithm for optimal damper. Journal of Engineering Mechanics. 2004;**130**:401-406

[75] Lin T, Chu Y, Chang K, Chang C. Renovated controller designed by genetic algorithms. Earthquake Engineering and Structural Dynamics. 2009;**38**:457-475

[76] Kennedy J, Eberhart R. Particle swarm optimization. Proceedings of ICNN'95- International Conference on Neural Networks. 1995;**4**:1942-1948

[77] Ghayeb HH, Razak HA, Sulong NHR, Hanoon AN, Abutaha F, Ibrahim HA, et al. Predicting the mechanical properties of concrete using intelligent techniques to reduce CO2 emissions. Materiales de Construcción. 2019;**69**:1-20

[78] Gholizadeh S, Fattahi F. Design optimization of tall steel buildings by a modified particle. Structural Design of Tall and Special Buildings. 2014;**23**:285-301

[79] Gundogdu O, Egrioglu E, Aladag CH, Yolcu U. Multiplicative neuron model artificial neural network based on Gaussian activation function. Neural Computing and Applications. 2015;**27**:927-935

[80] Leung AYT, Zhang H, Cheng CC, Lee YY. Particle swarm optimization of TMD by non-stationary base excitation during earthquake. Earthquake Engineering and Structural Dynamics. 2008;**37**:1223-1246

[81] Amini F, Hazaveh NK, Rad AA. Wavelet PSO-based LQR algorithm for optimal structural control using active tuned mass dampers. Computer-Aided Civil and Infrastructure Engineering. 2013;**28**:542-557