Intelligent suspension system with two-degree-of-freedom hybrid mass dampers

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***Abstract*—The presented model discusses the advantages and drawbacks of combining three concepts in vibration suspension. Dual-Loop Controller (DLC) with two-degree-of-freedom Hybrid Mass Damper (HMD) attached to a single degree of freedom primary system is studied. The benefits of using the adaptive actuators instead of classical ones in terms of reducing the amount of energy required in active part are mentioned in this design by adding feed-forward Deep Neural Network (DNN) to the primary system. The proposed model aims to increase the performance of damping, reduce energy consumption with achieving the fail-safe behavior of dampers.**

***Index Terms*—Dynamic vibration absorber, active suspension system, hybrid vibration absorber, deep learning, deep neural network, dual loop controller.**

I. INTRODUCTION

In general, problems caused by vibration are basically related to structure resonances or important harmonic loads. When the frequency of a harmonic load matches the resonance frequency of a structure, huge amplitude vibration will be created by dynamic amplification which linked to the internal damping of the structure. To minimize these vibrations, structural damping can be increased by adding the vibration absorbers. Passive and active vibration dampers are used widely to reduce the effects of structure oscillations. The Tuned Mass Damper (TMD) as a traditional Passive device is an auxiliary mass–spring–damper system which correctly tuned to a target mode, or a well-known harmonic perturbation, then the device is called Dynamic Vibration Absorber (DVA) [1]. The main benefits of the passive approach are the inherent stability of the overall set-up and no energy needs to be exerted to damp the oscillations. The design of a single-degree-of-freedom (SDOF) tuned-mass-damper (TMD) to attenuate the vibration of a single mode of the main structure under various conditions is studied e.g., [2]–[6]. Multiple SDOF TMDs with frequencies tuned in the neighborhood of a mode of the main structure is proposed in [7] to enhance the robustness and effectiveness of TMDs performance. Using a multiple SDOF TMDs to absorb more than one mode of main structure is studied in [8] and [9] by tuning each TMD to an individual mode of interest in the primary system. The problem with DVA is that in practice, the resonant frequency of the primary structure or the disturbance frequency may change during the time but the traditional DVA has no ability to automatically adjust its passive parameters or absorption frequency .So, to overcome this problem, a lot of attempts were made to improve the vibration suppression performance of a TMDs and create an adaptive DVA, which has a self-adjusting ability on its absorption frequency. The adaptive DVA can adjust its absorption frequency by modifying its passive parameters. However, the effect of adaptive DVA can only perform well on vibration control with slow time-varying disturbances frequency. Adding an actuator controls the force that the reaction mass applies to the structure gives more efficient method to treat several resonances and improves the efficiency of the vibration absorber on controlling the structural vibration excited by forces of random disturbance. The resulted proposed device is called Active Mass Damper (AMD) which can be efficient on all the controllable modes and usually an absolute velocity (or acceleration) measurement is required as an input of AMD [10]. Active Mass Damper uses the active element to generate a force to reduce the effects of the exciting forces acting on a vibrating structure in order to minimize the vibration of the controlled structure [11]. However, the drawback of traditional AMD design is that all counter forces are created by the active element and therefore the power consumption and the size of the active actuator become very large in case dealing with large structural vibration [12]–[14]. Consequently, some suggestions are proposed. An electromagnetic actuator or piezoelectric actuator is integrated with a passive DVA as an active element to reduce the large counter-acting force requirement from the actuator [15], [16]. The absorber in this design uses the inertial force generated by the passive components as part of the counter-acting force to the excitations of the structure of the vibration. Therefore, with this feature, the control effort and the power requirement of the counterforce actuator can be reduced [14]. In the same context, the experimental results of some researches showed that the developed Neural Network (NN) as controller also gives a great performance and better results than the optimal controller under uncertainties in terms of reducing actuator energy consumption [17]. Attaching a lightweight mass damper to minimizing oscillating motions of structures like ships or buildings has been discussed in the late 1980s and early 1990s. In [18], different types of controller designs are reported. The authors in the research proposed a new concept of active vibration absorption, "Delayed Resonator" where a controlled time delay has been used in a feedback loop. In fact, the main difference between this new generation damper and TMD is that this device is mainly developed for harmonic perturbation rejection and thus cannot be considered as a fail-safe, i.e. that the damper is not still efficient when the controller is turned off. Also, some attempts to enhance the suspension technology by transition traditional passive suspension systems to active suspension systems are reported in [19]. Combination of an actuator with spring and dampers is discussed to generate a force that controls suspensions' dynamics behavior in order to achieve a higher level of performance [20].improving the classical resonator setting with lumped delay introducing a distributed delay structure into the control law with modification of delayed resonator concept for vibration suppression using both delayed and non-delayed acceleration feedback control laws together taking into account both the stability and implementation constraints is discussed in [**?**]. A robust alternative of the delayed resonator using a spectral approach is proposed in [**?**]. Because of the nonlinearities and time-varying characteristics of the suspension system, it is difficult to design and tune the parameters of Active Suspension System (ASS) or to establish an appropriate dynamic model for model-based controller design, many researchers focused on ASS. Sliding mode is one of the common examples of control systems [21]. Also with advances in technology, more complex controllers are developed. Some researches discussed simple solutions to design controllers able to deal with uncertainties such as the use of a self-tuning pole assignment and fuzzy logic to adjust the gains of the controller [22]. Using linear-quadratic (LQ) control and pole placement techniques for a linearized model is developed in [23]; however, the results were not satisfying with respect to sprung acceleration suspension.

Recently, a new definition appeared to refer to the new generation of dampers which combining the behavior of an optimal TMD and the active damping devices. These dampers are named Hybrid Mass Damper (HMD), or Hybrid Vibration Absorber (HVA). The HMD over the last decade is used widely and many control laws have been proposed. The researches attempted to prove that using HMD will enhance the dynamic systems by increasing the performance, reducing the stroke of the moving mass, decreasing the energy consumption, reducing the embedded mass and to ensure fail-safe behavior. Optimal control is used to combine structural damping with a restricted stroke of the actuator to create a HMD in [24]. In summary, the hybrid controllers attempt to combine the features of optimal TMD with AMD with robust and simple control law, while maintaining the basic goals of increasing the performance and/or decreasing the control effort of the actuator.

More recently, Neural Network (NN) is used in vibration suspension to enhance the controller performance. In [25], the author proposed a novel neural network-based sliding mode control by combining the advantages of the adaptive, radial basis function neural network and sliding mode control strategies to decide the dynamical model requirement. So, by tuning the neural network weightings and/or radial basis function parameters, NN can learn online to deal with the system time-varying and non-linear uncertainty behaviors. Development of a Recurrent Neural Network (RNN) is discussed in [26]. RNN here is based on inverse dynamics derived from the Bouc–Wen model of a semi-ASS with magnetic damper as well as an actual damper fitted in a hardware-in-the-loop simulation (HILS) showed that the RNN offered improved actuator voltage signal which ensures extended service life and lower power requirement. In [27], back propagation neural network (BPN) has been used to determine the gain parameters of a PID controller by using NN trained with a Levenberg–Marquardt algorithm and the outputs were compared with the results of other algorithms. In fact, almost all the previous NN which used in the control of ASSs were combined with sliding mode, LQR, PID, neuro-fuzzy or similar model to adjust their parameters either offline or in real-time. In [17], [26] RNN and DNN are reported where RNN is used with a semi-ASS utilizing a magnetic damper in [26], while the author substituted the conventional controller with a DNN controller in [17] which is the closest to our proposed design. In the present model, we will discuss using DNN controller added to Dual-Loop Controller (DLC) with Two-Degree-Of-Freedom hyperstable HMD to:

- reduce the actuator energy consumption and the sprung mass acceleration.
- provide stable and efficient control.
- increase the damping performance.
- achieve fail-safe behavior based on optimally tuned passive device.

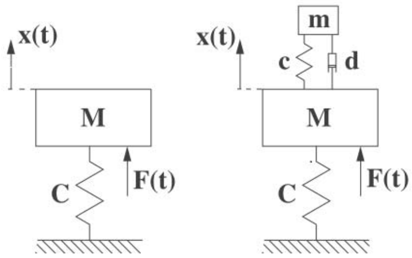
II. Review of passive tuned mass damper

The passive devices do not require an external power supply to control its operation and use the internal motion of the structure to enhance the absorption forces and dissipate the vibration energy of a specific resonance. For the ideal passive devices, the control forces applied to the structure are only dependent to the structural motion [28]. Vibration absorber systems such as Tuned Mass Damper (TMD) has been widely used for vibration control in mechanical systems. Basically, a TMD is a device consisting of a mass attached to a structure through a spring-dashpot system in parallel [29], see the Fig. 1 where a simple mechanical model for TMD is shown. In Fig. 1(a), Mass M represents the main structural mass and m represents the added mass of the TMD which is usually about 10% of the main structure mass and mounted on a spring and a damper. The equations for stiffness and damping can be found in [30]. The feature of this kind of dampers is that the same design rules can be used to damp nanometer vibrations or meter vibrations. The most popular is the so-called Den Hartog's method [1], [30]. The optimal design of a dynamic absorber can be classified into time-domain optimization and frequency domain optimization. In [31], four optimum design methods for a dynamic absorber are compared when they are applied to a single-degree-of-freedom system with primary damping. Furthermore, they can be used on another complex systems, including continuous systems. The undamped natural frequency of the TMD depends on the mass and stiffness of the

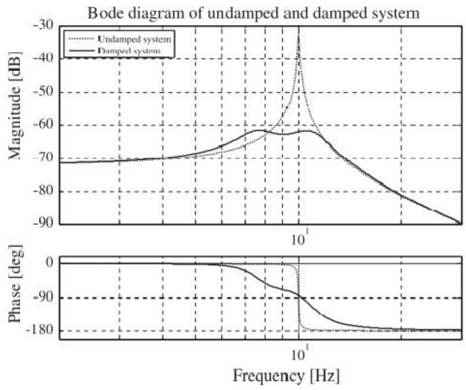
TMD and has to be tuned close to the natural frequency of the main structure, therefore, reducing the amplitude of the main structure is achieved at the resonance frequency by adjusting TMD parameters damping correctly [32]–[34]. In Fig. 1(b), TMD oscillates at the same frequency of the structure, but with a phase-shift. The challenge in designing TMD is hard tuning correctly the parameters of stiffness and damping of the absorber because of the large sensitivity of the suppression amplitude to parameter variations of stiffness and damping of TMD which consider a drawback in passive devices, in addition to another drawback in DVAs work which is that they are tuned to damp only one specific resonance. This problem was addressed by adding an actuator which controls the force that the reaction mass applies to the structure, we mention it in section III and section IV. In fact, overall performance of designed systems is affected by parameter variations of the dynamics and natural frequency variations of the main structure. Some methods designed to deal with this sensitivity. One of them is represented in [35]. TMD devices have proven as a useful concept in a lot of fields and were used in the widespread field of applications. For example, In buildings and structures, automotive industry, airplanes, space structures and so on. in Fig. 2(a) you can notice many types of passive devices with the vibration performance according to each dynamical components. One thing should be noticed that during the work of TMD, the main advantage is that these structures do not make reaction forces in the dynamical systems. A semi-active tuned mass damper (STMD) with variable damping under harmonic excitation is studied in [36], [37]. A study about the comparison between passive and active dampers is presented in [38]. In [39], the designed model is closed to our proposed model in this research where a complex TMD tuned optimally with two degrees of freedom (displacement and rotational movements) is achieved to increase the efficiency of the damper.

III. Review of semi-active mass dampers

The controllers must be designed so as to achieve an acceptable trade-off between control effectiveness and energy consumption. From this point of view, the control strategies can be grouped into two main categories: active and semi-active. When the controller requires a small external power source for its operation by utilizing the motion of the structure to develop control force, it is called Semi-active controller. Where the magnitude of the force can be adjusted by an external power source [40]. Since its introduction [41] these systems somewhat trying to use the advantages of both passive and active devices by filling the gap between purely passive and purely active suspensions. However, the benefits of semi-active devices over active devices are their fewer power requirements. And moreover, that semi-active devices cannot inject the mechanical energy into the controlled structural system, but has properties that can be controlled to optimally reduce the response of the system. Therefore, in contrast to active control devices, semi-active control devices do not have the potential to destabilize the structural system [42].



(a) a



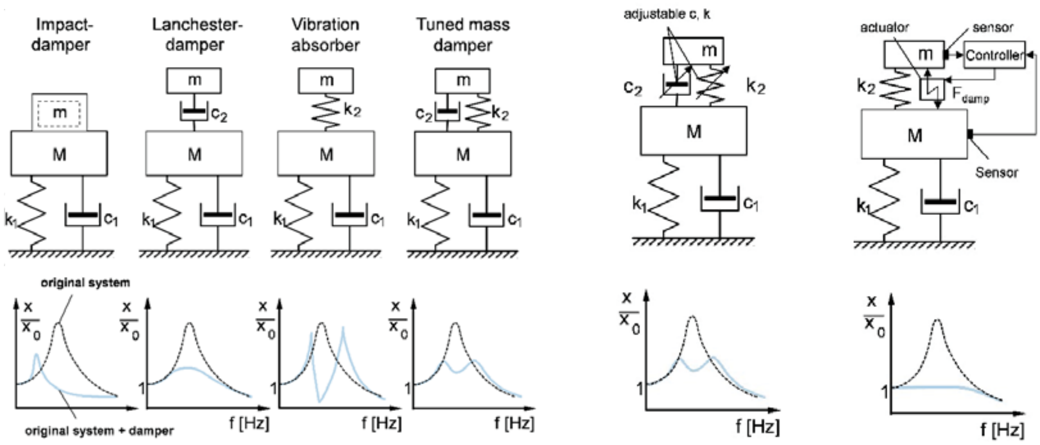
(b) b

Fig. 1. (a) Main structural mass with TMD added to reduce the vibration amplitude with force F(t) and positions measurements X(t) (b) Bode diagrams of the undamped and the damped system.

The design of semi-active damper with its performance is shown in Fig. 2.b . In fact, the semi-active concept has been applied to many applications in vibration isolation problems. One of these applications used the concept to high-speed ground transportation vehicles [43]. In [44], a two-degree-of-freedom model of a semi-actively suspended vehicle is used as a starting point in the design of an optimal suspension. Using semi-active dampers for structural control application is proposed in [45]. Semi-active controllable fluid damper is studied in [46]. These devices have some special fluid, where applying external energy gives the ability to adjust their property. The electric and magnetic fields are mainly used to control these devices. Electro Rheological (ER) and Magneto-Rheological (MR) dampers are proposed in [40]. In [47], design and analysis of a control strategy, for semi-active suspensions in road vehicles, based on model-predictive control (MPC) strategies is studied.

IV. Review of active mass dampers

The Active Mass Damper (AMD) is a mechanical device that attenuates the vibrations of a structural system. It uses reaction forces generated by moving the auxiliary mass with an actuator connected between the structure and the auxiliary mass. An AMD concept is shown in Fig. 2.c and the equations of motion can be found in [48]. In fact, many applications used the AMD concept in the last decades. For



(a) a (b) b (c) c

Fig. 2. (a) Passive Auxiliary System (b) Semi-active system (c) Active system

examples, in buildings, Moving a relatively small mass with a limited amplitude is required to suppress the vibrations of the structures. This is the reason why AMDs do not have a great ability to absorb the large earthquake excitations. However, the goal of absorption energy of structural vibrations under small earthquake excitations or under strong wind is achieved. Usually, The auxiliary mass of an AMD for a building structure is less than 0.4% of the total mass of the structure. In [49], some switching between passive and active vibration control methods in buildings are proposed. Where behaves as an AMD to suppress the vibrations caused by small earthquakes, and as a tuned mass damper to suppress the vibrations of a targeted mode excited by a big earthquake. The response motion of the auxiliary system is ordinarily increased as a result of active control. Hence, it is desired not only to increase the control efficiency but also to restrict the auxiliary mass motion as much as possible. Generally, the size of AMD or the installations space decides the allowable amplitude of the AMD with strong restrictions. These restrictions of the amplitude of the auxiliary mass are one of the main reasons for the limited performance of AMDs. In [24], a control law for AMD that effectively suppress the vibrations of a one-degree-of-freedom structural system under the amplitude constraint of the auxiliary mass is studied. Optimal control is used to combine structural damping with a restricted stroke of the actuator. Active Suspension Systems (ASS) also have used widely in the automotive industry [50], [51]. The research [52] discussed the advantages of ASS compared with Passive Suspension Systems (PSS) where the parameters of PSS are normally chosen based on the vehicle's design requirements and are fixed generally, therefore do not have the ability to improve both the passenger comfort and the vehicle handling at the same time. Force actuators, such as pneumatic, linear motor, hydraulic actuators, or so on can provide the required forces between the sprung mass and the main structure to control the attitude of the vehicles in [53]. Many attempts and methods have been used and proposed to improve the performance of ASS from simple on-off control to highly advanced linear and non-linear control techniques, including linear- quadratic-Gaussian control [54], linear parameter-varying control (LPV) control [55], adaptive control [56], a multi-objective control method with wheelbase preview for active vehicle suspension. A four-degree-of-freedom half-car model with active suspension is studied [57], and quantitative feedback theory [58].

Recently with self-driving vehicles, the suspension of the vertical vibration amplitude of the cameras which mounted on the vehicles is needed to reduce the unwanted motion effects. In this context, a new assisted technologies started to emerge. A novel adaptive neural network based on sliding mode control strategy to stabilize the image captured area of the camera, therefore, suppress vertical displacement of sprung mass with the application of active suspension system is proposed in [59]. In [60], an adaptive fuzzy optimal control design is addressed for a class of unknown. The control objective is to design a controller not only to guarantee the stability of the systems but also to achieve the optimal control performance as well.

In fact, with the many uses of ASS in the automotive industry, a problem has appeared. It is the parametric uncertainties and changing the road disturbances during the time which in turn will adversely affect vibration mitigation. To solve this problem, many methods have been used. For instance, sliding mode control [61]. a velocity-dependent multi-objective control method to solve the problem of preview control with velocity uncertainty is presented in [62]. Neural network showed great potential for solving non-linear state observation problems when the system model has uncertain parameters. Wherein practical terms, the state variables are usually not available for direct online measurement so, an observer is needed. A stable neural network NN-based observer for general multi-variable non-linear systems is proposed in [63] which uses a back-propagation algorithm with a modification

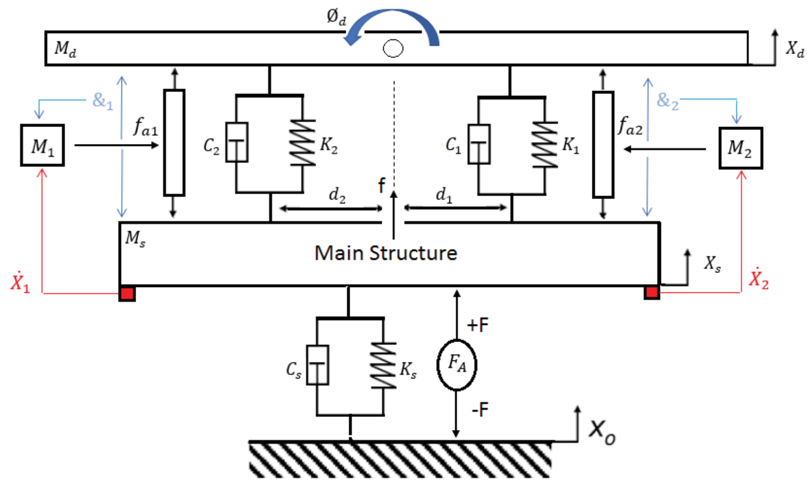


Fig. 3. intelligent suspension system with two degree of freedom hybrid mass damper

term. Adaptive neural network (NN) state feedback control and robust observation for an active suspension system that considers parametric uncertainties, road disturbances and actuator saturation is studied in [64]. Since an ASS actuator only provides a limited control force, input saturation with a nonlinear factor may adversely affect system performance and can destabilize the system [65]–[67].

V. Review of hybrid mass damper

After many studies in the last decades, a novel class of dampers has appeared that are trying to combine several objectives and features at the same time. These devices are gathered under the common name of Hybrid Mass Dampers (HMDs), or Hybrid Vibration Absorbers (HVAs) which combine passive and active vibration control. Combining passive and active elements the system is fail-safe that the damper will behave as a passive device even when the feedback control is turned off. The goal of using HMD may differ from one to other. For example, in [68], H_∞ optimal design of HMD is used for the minimization of the resonant vibration amplitude of a single-degree-of-freedom (sdof) vibrating structure.

In [69], [70], a pole placement technique is proposed to ensure performance and stability where the proposed hybrid absorber design could provide a simple alternative to adjust the conventional TMD as a higher performance HVA [69]. And a special pole placement controller is designed such that all vibration modes of the flexible structures become critically damped in [70]. In [71], a dual loop approach is preferred to increase the stability margins.

Improving the performance and stability of hybrid mass dampers by creating a hyperstable controller is studied in [72]–[74]. Where two zeros are added to interact with the poles of the system so as to reduce the resonant vibration amplitude of a multiple degree-of-freedom structure [72]. In [74], a compensator is introduced in the control loop to correct the phase of the actuator in order to be stable at low frequency. A hybrid fuzzy logic approach which combines fuzzy logic and PID controllers is designed in the automotive industry [75]. In [76], a hybrid self-organizing fuzzy radial basis-function neural-network controller has been proposed by manipulating an ASS to reduce the power spectral density of the vehicle body acceleration. A fail-safe and unconditionally stable controller with a simple control law which is extremely efficient under harmonic excitation and required a low consumption are proposed in [72]. In [72], Small active forces are required when hypersatble controller is applied to three degrees of freedom.

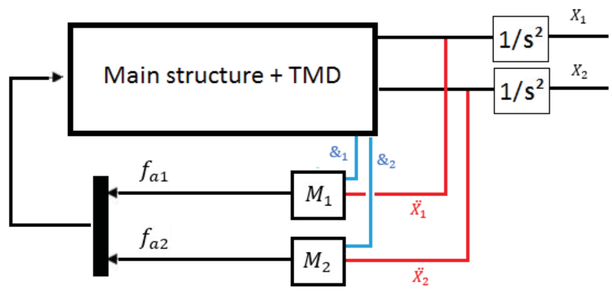


Fig. 4. Controller loops.

VI. Proposed model

More than one mode of vibration of an absorber body relative to a primary system be tuned to suppress single-mode vibration of a primary system with developing an algorithm to enhance the connection of multi-degree-of-freedom between the absorber body and primary structure, therefore, mitigation the response to random and harmonic excitations is proposed in the present model. The model simulates two-degree of freedom HMD attached to a single degree of freedom primary system Fig. 3. Vertical displacement movement and rotational movement around the center of the auxiliary mass are proposed where the results proved that an optimal two-degree of freedom TMD performs better than a traditional single degree of freedom or two separate TMDs with optimal mass distribution, even for the case where the rotary inertia of the absorber tends to zero. [39]. We will use this prove and continue to convert the TMDs to HMDs.

When we use a HMD to attenuate the vibration; the passive part has a positive impact where mitigate the amplitudes of the vibrations i.e. damping the oscillations is occurring without the need for any external power. On the other hand, the frequency band where the absorber suppresses the vibrations efficiently is relatively narrow, being centered at the natural frequency of the absorber. Practically, the damper cannot absorb the vibration entirely even if the vibration frequency is identical with the natural frequency of the absorber because of fact that the physical absorber is never ideal, i.e. it features nonzero damping. Solving this problem is presented in section II. The proposed model tries to achieve three main objectives: (1) increase the performance of the suspension system, (2) reduce energy consumption, and (3) ensure fail-safe behavior. We consider passive absorbers are supplemented by dual transducer loops in the model Fig.3. The passive parts are a TMDs optimally tuned using Den Hartog's law [1], and the active control forces (f_{a1}) and (f_{a2}) are introduced between the two masses. The auxiliary mass is the moving part of the actuator. In fact, the general concept of dual-loop controller is started in [10] and is used precisely as parallel dual loops and act on the same transducer in [77] which is the closest to our model with the difference that in the previous research a dual loop controller (DLC) is used with single degree of freedom. The proposed controller combines two control laws using two inputs (i) the relative displacement between the inertial mass and the main structure, and (ii) the absolute velocity of the main structure. Subsequently, dual loops in each side of the damper are used. One to detune the HMD (negative stiffness feedback), and the second one to damp the main structure (direct velocity feedback). Since the relative velocity or absolute acceleration will be measured, so integration has to be added to the control laws M1 and M2 Fig 4. The proposed controller will be designed to increase the margins and reduce the stiffness of the TMD by develop the controller to hyperstable controller because it is known that direct velocity feedback associated with a TMD results in very poor stability margins [72]–[74]. The rotational movement of the damper gives ability to absorb not only vertical disturbances but also disturbances with angles. Also, as long as we use an active impact in our design, we have to keep in mind the necessity of restriction the amount of energy required for absorption operation. Where as we mentioned in section I, one of the drawback of AMD design that all counter forces are created by the active element, therefore, required forces of the actuator become very large in a case dealing with large structural vibration. In this context, we proposed using feed-forward DNN as a controller to decrease the actuator energy consumption. The network will be trained through supervised learning using the back-propagation algorithm. We relied on this type of network because experimental results showed that the developed DNN controller outperforms the optimal controller under uncertainties in terms of reducing the sprung mass acceleration and actuator energy consumption, with a 4% and 14% reduction, respectively [17].

VII. Conclusion

Combining many concepts in vibration absorption will be achieved in this study to attain an optimal absorber over a relatively wide frequency band. A fail-safe behaviour will be guaranteed by taking advantage of the features of combining between active and passive elements in one absorber which called a hybrid mass damper. We cast the problem of optimization of the multi-degree-of-freedom connection between the absorber body and primary structure. Developing optimization algorithms based on the H2 and H-infinity norms will be discussed to reduce the response to random and harmonic excitations with attaining better performance in vibration by using an optimal 2DOF HMD instead of traditional SDOF HMD. Finally, actuator energy consumption was taken into consideration by using a back-propagation algorithm with deep neural network DNN to reduce the sprung mass acceleration.

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TABLE I
Nomenclature

Abbreviation	Definition
AMD	Active Mass Damper
ASS	Active Suspension System
BPN	Back-Propagation Neural Network
DLC	Dual-Loop-Controller
DNN	Deep Neural Network
DVA	Dynamic Vibration Absorber
HILS	Hardware-In-the-Loop-Simulation
HMD	Hybrid Mass Damper
HVA	Hybrid Vibration Absorber
NN	Neural Network
PSS	Passive Suspention System
RNN	Recurrent Neural Network
STMD	Semi active Tuned Mass Damper
SDOF	Single-Degree-Of-Freedom
TMD	Tuned Mass Damper

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