*actuators*

*Review*

# A Review on Vibration Control Strategies Using Magnetorheological Materials Actuators: Application Perspective

**Aji Masa'id [1], Bhre Wangsa Lenggana [1], U. Ubaidillah [1,*], Didik Djoko Susilo [1] and Seung-Bok Choi [2,3,*]**

[1] Department of Mechanical Engineering, Faculty of Engineering, Universitas Sebelas Maret, Surakarta 57126, Indonesia
[2] Department of Mechanical Engineering, Industrial University of Ho Chi Minh City (IUH), Ho Chi Minh City 70000, Vietnam
[3] Department of Mechanical Engineering, The State University of New York, Korea (SUNY Korea), Incheon 21985, Republic of Korea
* Correspondence: ubaidillah_ft@staff.uns.ac.id (U.U.); seungbok.choi@sunykorea.ac.kr (S.-B.C.); Tel.: +62-857-9952-7552 (U.U.)

**Abstract:** Magnetorheological (MR) materials are a group of smart materials used in new technologies with controlled reliability. The development of these materials is expanding, starting from MR fluids, elastomers, grease, and gel. This large number of material types further expands the various applications of MR materials as a creative technology to support performance enhancement. For example, MR fluid is used to improve the performance of shock absorbers such as vehicle suspension, the damping of building structures, and polishing of the workpiece. MR elastomers are used for engine mounting, insulation base, and many other applications with intelligent material properties such as stiffness controllability. However, there are still complexities in the practical implementation of the control system beyond reliability. Many previous studies have focused on the performance improvement and reliability of MR materials as smart materials for application devices and systems. In this review article, the specific discussion related to vibration control strategies in MR material-based systems was thoroughly investigated. To discuss this point, many MR applications including transportation system and vibration isolation were adopted using different types of control strategies. Many different control strategies that have been used for MR applications such as fuzzy logic control, optimal control, and skyhook control are discussed in-depth in terms of the inherent control characteristics of merits and demerits.

**Keywords:** magnetorheological materials; control strategies; vibration control; adaptive control; fuzzy control

check for updates

**Citation:** Masa'id, A.; Lenggana, B.W.; Ubaidillah, U.; Susilo, D.D.; Choi, S.-B. A Review on Vibration Control Strategies Using Magnetorheological Materials Actuators: Application Perspective. *Actuators* **2023**, *12*, 113. https://doi.org/10.3390/act12030113

Academic Editor: Ramin Sedaghati

Received: 20 January 2023
Revised: 15 February 2023
Accepted: 18 February 2023
Published: 3 March 2023



## 1. Introduction

Since material technology is known to have had a major impact on human advancement, materialists have defined different periods in human history based on the main materials used during those periods. The term smart material is one of them, and it initially arose in the late 1980s. This has prompted many research activities on smart materials to have been carried out in various industrial fields. The capacity to perceive, actuate, and control the external inputs that regulate system responses is one of the numerous features inherent in intelligent materials, which is crucial in obtaining a high performance in application devices and systems. More than 100 intelligent materials have been presented with these qualities thus far, and their adaptability has been confirmed as an intelligent property. Sensitive material qualities can be identified as sensors, electricity can be produced as actuators, and control reactions can be carried out as controllers. Due to their distinct actuator properties and utility in several engineering applications, several classes of intelligent materials have drawn a lot of interest during the past 20 years. Electro-viscosity materials, magnetic rheological (MR) materials, shape memory alloys, piezoelectric materials, and electroactive polymers are examples of potential intelligent materials. A magnetic field quickly changes the rheological properties of MR materials, which are a significant subset in the area of smart materials. These substances typically contain micrometer-sized (about 35 mm) iron or iron particles dispersed in a variety of carrier media including liquids, foams, elastomers, lipids, polymer gels, and plastomers [1–4]. Depending on the composition of the mixture, MR materials are referred to as magnetic rheological fluids (MRF), magnetorheological elastomers (MRE), magnetic rheological fats (MRG), magnetic rheological polymer gels (MRPGs), and magnetic rheological plastomers. Numerous MR intelligent materials still exist as novel materials that are in the exploratory stages of development.

MR fluid is the most popular type of MR material used and discussed. This is related to the response of MR fluid, which tends to be faster than other types. MR fluid is usually used as a working fluid in shock-absorbing devices such as transportation suspensions: passenger vehicles, heavy vehicles, earthquake-resistant structures, bridges, landing gear, and trains. Although, in general, the use of MR is used in the same application, MR fluid has shown its effectiveness in responding to a magnetic field as a modifier of the viscosity of the fluid [5]. However, behind its advantages, MR fluid has weaknesses that are still an interesting discussion such as magnetic particle deposits that often occur when the device is not working. In contrast to MR fluids that can settle, MR elastomers cover this weakness because in general, the magnetic particles used are bound by a carrier matrix such as rubber. MR elastomers also have their own advantages in the flexibility of its application to a device. MR elastomers are often used as engine mounts because they do not take up much space and have a controllable performance. The use of MR elastomers is also widespread in the field of civil engineering such as base isolation for bridge structures. Several studies have also discussed MR elastomers as damping applications for the base isolation of bridge structures.

In addition to the two types of MR materials, there are other MR materials that are still in the early stages of development, and further studies, namely, MR grease and MR gel. Recently, gel and grease type MR materials have received a lot of attention because of their considered application possibilities. MR grease was originally created because of a weakness found in MR fluids, namely, the deposition that occurs in MR fluids that results in a high probability of decreasing performance. Therefore, MR grease was created to replace the existing weaknesses in MR fluids. The low MR effect on magnetorheological elastomers can be mitigated by MR grease, in addition to being able to address sedimentation issues that develop in MRF. Grease, a non-Newtonian fluid, is used in MRG as a medium to enable suspended magnetic particles to defy gravity and prevent particle sedimentation [6]. Additionally, grease is categorized as a transitional state between a liquid and a solid, giving magnetic particles some mobility to form columnar chains when subjected to a magnetic field [7]. In contrast to MRF, MRG possesses self-sealing properties because of its thick viscosity, which negates the need for extra sealing to stop device leakage. This characteristic can keep the machinery stable over time, cutting down on production expenses [8,9]. MRG is a possible contender for engineering applications such as seismic dampers, brakes, and clutches due to the benefits indicated above [6]. Due to the fact that grease is used as a MR material medium, MR grease has a shortcoming in that it has a high off-state viscosity, which restricts the expansion of the yield stress under on-state circumstances. As a result, MRG performs poorly on metrics such as torque output.

MR gel is the following class of magnetorheological substance. A type of intelligent material called MR gel may be quickly and irreversibly altered by manipulating an excited magnetic field. Its rheological properties are similar to those of MR fluids [10,11]. Soft magnetic particles are typically dispersed into a cross-linked polymer matrix to create MR gels. The presence of a viscoelastic polymer matrix allows MR gels to partially overcome several of the drawbacks of MR fluids including the problems with sealing and sedimentation [12]. Additionally, the restrictions of the hard rubber matrix on the magnetic particles in the MR elastomer prevent them from moving freely, resulting in a much weaker MR effect than the MR gel [9]. With the advantages listed above, MR gel and MR grease are comparable in nature. Of course, this sort of material's high viscosity value in off-state situations must be regarded as a weakness. However, MR gels show promise for usage in engineering devices such MR actuators, MR insulators, and MR absorbers [13–16].

In addition to the four types of MR materials, there are other types of MR materials such as MR dust, which is still in the early stages of study. However, in this article, we examined vibration control strategies using magnetorheological materials including MR fluids, elastomers, greases, and gels in various applications. Each of these materials has its advantages and disadvantages, but some of them can be applied in the same field. The study of magnetorheological actuator material as a vibration control strategy is focused on transportation systems (automotive, military, railway, aerospace, and ship), machine vibration, civil engineering, flexible structures, and offshore plants. With this aim, this review article will provide a good contribution to the full discussion of the control strategy section in various applications. This is due to the fact that only a few discussions have been carried out in the field of the control of a magnetorheological actuator material strategy in various fields that have been completely studied. In addition, the article can also be used as material for research studies in the field of magnetorheological actuator material strategy control.

Smart materials, as is generally known, can be employed as sensors or actuators in application systems [17]. As a result, for effective deployment, a suitable control mechanism for a given application is necessary. More attention to controller design is required, especially when smart materials are utilized as actuators. To support the review, in this paper, various applications and control strategies with the use of magnetorheological materials are discussed in a structured manner based on their field of use. In this case, for each field of use, we present four possible types of magnetorheological materials used (MR fluids, elastomers, greases, and gels) with the type of strategic control used. The field of land transportation (automotive) is said to be the most popular study of applying magnetorheological intelligent materials based on the findings of many studies that have discussed related cases. In contrast to the field of transportation, the discussion of magnetorheological materials in the field of shipping and aircraft tends to be less. This is presumably because the level of complexity in the discussion of the shipping and aircraft sector still tends to be higher than land transportation. The performance of the controlled device is optimized by the application of a strategy control. Strategic control is closely related to automated control, which typically compares the generator's actual output with a reference input (the desired value), and generates a control signal to bring the difference between the two values as close to zero or as little as possible. Figure 1 shows a block diagram of a typical control system featuring MR actuator devices combined with a magnetorheological (MR) device to help with an overview of automatic control.

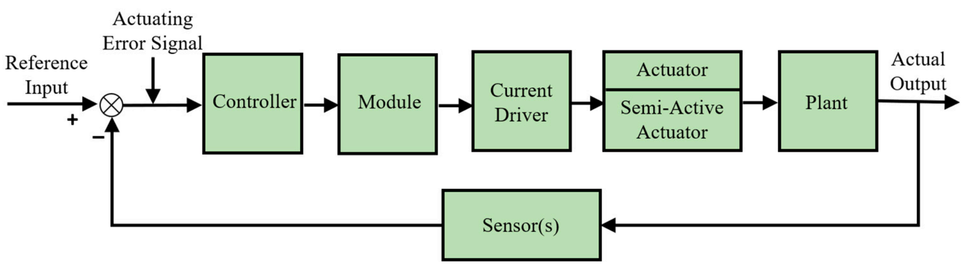


**Figure 1.** Block diagram of a typical control system featuring MR actuator devices [18]. Reproduced with permission from Choi, S.-B. and Han, Y.-M., Magnetorheological Fluid Technology: Applications in Vehicle Systems; published by CRC Press, 2013.

The driving fault signal, which is typically very low power level, is detected by the controller, and then the module computes the desired MR damper current based on the desired semi-active control force. Furthermore, the MR damper current was amplified by a current driver to a high enough level for the MR device. The control box also includes the clipping of the active desired control force to obtain the semi-active desired control force since MR dampers can only exert dissipative (=semi-active) forces. An actuator is a power tool that generates an input in response to a control signal. Active control systems frequently employ conventional actuators such as electric motors. However, semi-active control systems frequently employ actuators based on MR fluids. Control energy can be taken and injected into the plant when using an active type of actuator, but it can only be done when using a semi-active type. Through a pump-related hydraulic servo valve mechanism, the MR device can be used as an active actuator. The majority of today's sensors including accelerometers can be modified to measure the dynamic control system reaction connected to MR devices. In the case of using magnetorheological materials, several control methodologies can be used, some of which are often used, namely, semi-active control, proportional-integral-derivative (PID) control, linear quadratic (LQ) control, and sliding mode control, and there are other types of strategic control. Some studies selected the control used based on its application, but there were also those who choose it because of the level of convenience and simplicity without compromising its performance. In this paper, this kind of discussion will be discussed in more detail. However, before reviewing the control strategy on the use of magnetorheological actuators, a brief overview of the types of controls commonly used in the study of magnetorheological materials is briefly discussed as a reminder and to simplify the course of the review that will be discussed. Typically, an active control device can be used to extract or input the control energy into the controlled system. However, the control energy can only be dissipated using semi-active devices [18]. As a result, the control system's level of stability is raised. The applied field's intensity can be adjusted using the MR device to continually manage the system attenuation. There are three alternative semi-active control techniques that can be used including controller skyhook, groundhook, and sky–groundhook to produce the necessary damping force in the controlled domain. Karnopp et al. [19] introduced the skyhook controller. The skyhook controller logic is acknowledged to be straightforward and simple to apply in the real world.

The PID control is a second common type of controller that is employed in numerous investigations. In industrial control systems, the PID (proportional integral derivative) controller is a control approach with a feedback mechanism. The error value is essentially calculated continually by a PID as the difference between the desired set-point and the measured process variable. In this instance, PID sets the control variable in an effort to reduce the error value in any given time unit. Position, force, and power are often the control factors. The next control method is linear quadratic (LQ) control, which is among the most widely used since it can be used in a variety of applications including MR actuator-based control systems. The key benefit of the LQ control approach is that it produces linear control principles that are simple to use and comprehend. PID and LQ controls tend to be more adapted to vehicle actuator-based MR control systems. However, several uses of this method can be found in the fields of civil engineering, flexible structures, machine vibration, and offshore. Other types of control are also often used for magnetorheological actuators in various applications such as adaptive controller, fuzzy logic control, neural networks, h-infinity, sliding mode control, and hybrid control, as shown in Table 1. The use of control strategies in this study was classified into various application areas that are described below. In general, magnetorheological actuators are widely used in transportation systems such as cars, trains, ships, and planes. However, other applications have also been developed for various other needs such as rehabilitation robots, offshore, and sound systems.

## 2. State-of-the-Art

In 1974, the development of a control strategy for a semi-active damping system intended as a means of supporting vehicle comfort levels was carried out by Karnopp et al. [20]. In their study, the skyhook controller was introduced because the controller logic is simple and easy to implement in real conditions. The skyhook controller system is described as shown in Figure 2.

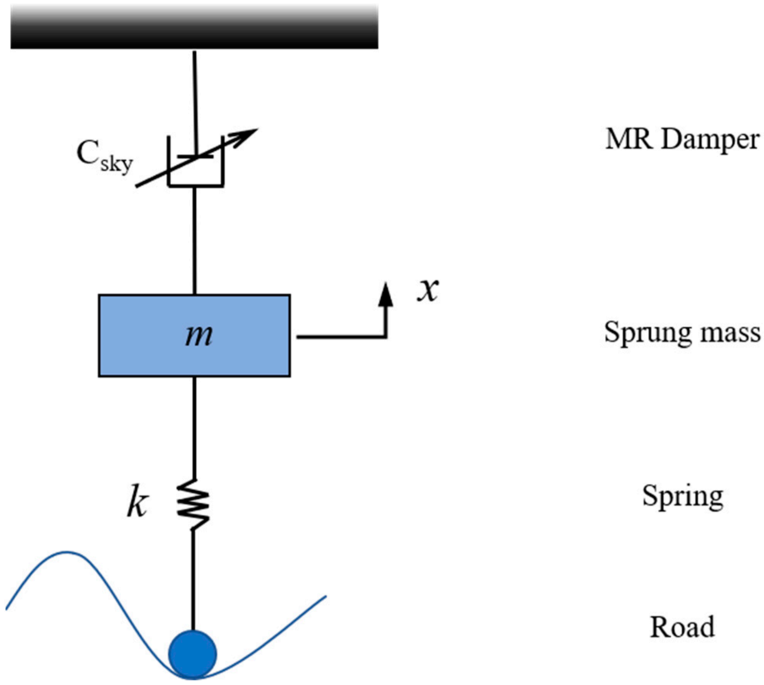


**Figure 2.** Semi-active system with a skyhook controller [18]. Reproduced with permission from Choi, S.-B. and Han, Y.-M., Magnetorheological Fluid Technology: Applications in Vehicle Systems; published by CRC Press, 2013.

The study of skyhook control strategies was also studied by Choi et al. [18]. In their study, they discuss the skyhook controller method where the desired force is formulated in an equation. The desired damping force can be set by $F_d = C_{sky}(E)\dot{x}$, where Csky is a control gain that physically indicates the damping. The gain on this skyhook controller is adjusted by the magnetic field to meet the desired damping force. This logic is a skyhook on–off control logic that is very often adopted in vehicle suspensions. The development carried out in the study was conducted by Choi et al. by combining the damping system used for driving comfort with the stability of the steering system. To achieve this, a sky–groundhook control was used. This controller was a combination of the skyhook controller that is used for vehicle suspension in controlling body comfort, and the groundhook controller was used to maintain/control the stability of the steering system while driving. The schematic drawing of the sky–groundhook control system is shown in Figure 3. The sky–groundhook controller consists of two ideal dampers: one is fixed to the ceiling, while the other is fixed to the ground. The one fixed to the ceiling produces a damping force to control the vibration of the vehicle body (sprung mass, $m_s$), while the one fixed to the ground generates a damping force to control the vibration of the wheel (unsprung mass, $m_{us}$). Therefore, we may improve both the ride quality and the steering stability by properly adjusting each component of the damping forces associated with MR dampers. The desired damping force can be set by $F_d = \sigma C_{sky}\dot{x}_1 + (1-\sigma)C_{ground}\dot{x}_2$, where $C_{sky}$ is the skyhook control gain, $C_{ground}$ is the groundhook control gain, and $\sigma$ ($0 \leq \sigma \leq 1$) is the weighting parameter between two control inputs.

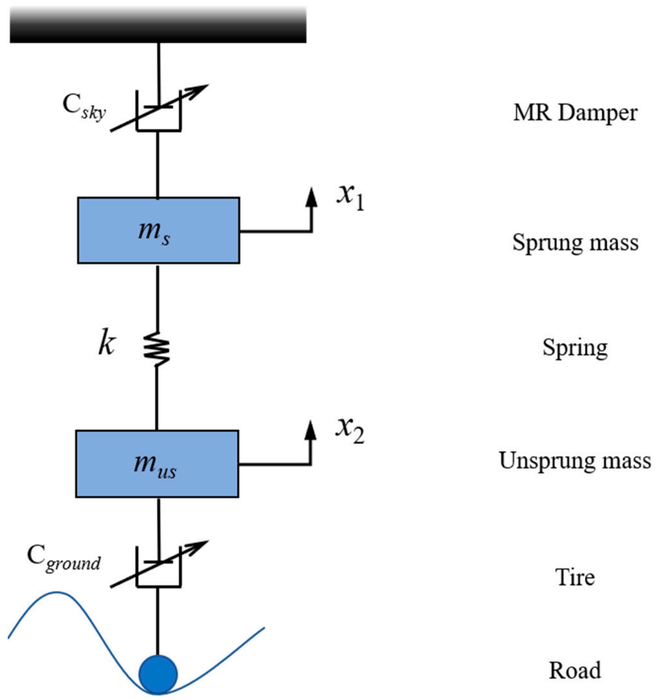


**Figure 3.** A semi-active system with the sky–groundhook controller [18]. Reproduced with permission from Choi, S.-B. and Han, Y.-M., Magnetorheological Fluid Technology: Applications in Vehicle Systems; published by CRC Press, 2013.

The skyhook controller is not only used as a control strategy in the application of an MR damper with an MRF base as the working fluid, but it can also be used in the case of MR elastomers. The study conducted by Opie et al. discussed the design and control strategy of vibration isolators on magnetorheological elastomers [21]. In their study, the approach used for MRE cases used the approach used in MR damper cases in general, which is because the MRE's adjustable property can be used to emulate a passive skyhook dampening system. Their idea was to show that the physical properties of the MRE can be described as a function of the flux density passing through the MRE. The study conducted by Opie et al. not only discussed one type of control used, but they also used other types of controllers and compared them. In the control skyhook used, two other types were used, namely, continuous and on/off skyhook controllers. Several other controllers were also mentioned in the study, but these controllers are alternatives and may be used in MRE applications. In fact, controllers applied to MRE are still rarely discussed, in contrast to controllers applied to MR fluids, MR grease, and MR gel. Studies related to the strategic control of MR materials have also been carried out by Bucchi et al. [22]. In this study, Bucchi et al. carried out an MR clutch optimization strategy using a neural network control strategy. The MR material used in the proposed clutch was MR fluid. In their study, they performed an analysis of the dependence of the magnetorheological coupling torque characteristics on several working parameters using a feed-forward neural network. The data collected during all tests were utilized to train a neural network with five input components and one output element based on the study outcomes. They claimed that the created neural network successfully reproduced the genuine coupling features.

In addition to MR fluids, in the clutch case study, MR grease was also often used as a clutch working material. Unfortunately, MR grease and MR gel had higher initial viscosity values than MR fluids. This makes the use of MR grease and MR gel not widely used in the automotive sector. However, MR grease and MR gel are widely studied in other fields of application. In addition to the discussion in other application areas, because this material is still in the early stages of development, the most common studies related to MR grease and MR gel are the selection and composition of the constituent materials. The use of control strategies for these two materials will be found in the discussion of other applications. Several control strategies have been discussed and used in individual case studies. In addition to the control strategies mentioned, there are other types of controls, which are summarized in Table 1. In fact, studies conducted on the development of MR materials in terms of control strategies in the automotive sector are still dominated by the use of MR fluid as a viscous reducing working material. Many studies have suggested that this is due to the low initial viscosity of MR fluids and their excellent response rate. Thus, the frequency range achieved by MR fluids as damping working fluids is high enough to meet the damping requirements. However, this may be different in other applications, where this MR fluid material still has weaknesses despite the optimization of the control strategy.

Military vehicles can also be included in the automotive category in the field of transportation systems. The use of MR materials and the control strategies used also tend to be the same as in the automotive sector. In this case, the difference is due to the damping character that is generated because of its need for uncertain terrain. However, in this case, it is not the character that is discussed, but the use of control strategies and what MR materials have been used in the development of military vehicle applications. The difference in the results of the required devices is what makes this discussion worthy of being separated from applications in the automotive field. A study on the MR damper in the military was conducted by Ha et al. in 2013 [23]. Ha et al. proposed a new type of suspension system based on MR fluid as a vibration control for military vehicles. MR fluids are indeed more popular in vehicle applications as in the previous discussion. In their study, Ha et al. used a suspension system consisting of a gas spring, a passive damper using a disc spring, and an MR damper while the optimization strategy used on this device used a skyhook controller. However, in this case study, Ha et al. demonstrated this by simulating the proposed suspension system to see the level of effectiveness in dealing with vibrations such as roads that have steep slope angles and bumpy roads [23].

In the same field, which is related to the application of MR materials in military vehicles, another study applied MR elastomers as damping devices for mounting a wheel loader cabin. Yang et al. conducted this research in 2017 [24] and developed a semi-active magnetorheological (MR) mount to reduce undesirable vibrations in heavy vehicles such as military vehicles. It seeks to improve the performance of the stand in fields where the frequency is not fixed. According to their results, the application of MR is a good solution considering that the viscosity of the MR fluid can be adjusted. In this scenario, an on–off controller linked to a fast Fourier transform (FFT) was employed to manage the damping force. As the results showed, the semi-active mount with the MR device was better than the passive device. In regard of the review in the previous discussion above, the control strategy used by Yang et al. provides new insights. As discussed above, the skyhook control strategy is used more often. In addition, this can be an idea for study in the field of MR materials for automotive applications, where it is still very rare to find the use of controls applied to MRE materials. This controller could also be used on MR elastomers as engine mounts on public or private vehicles. It turns out that a similar study was conducted by Kim et al. in 2021 [25]. However, what makes the difference is the material used, as Kim et al. used MR fluids as the working fluid of the damping device in the wheel loader cabin. The control strategy used by Kim et al. was an on–off controller. This study is similar to that conducted by Yang et al. in the previous discussion, but in this study, it can be seen that the use of mounting devices as vibration dampers did not only use rubber, and vice versa. Furthermore, in this study, it could be seen that there is a possibility that the controller used in damping devices based on MR fluids can also be used in damping devices based on MR elastomers.

Several other control strategies used in previous studies related to their application to the transportation system are summarized in Table 1 and the specific equation form of each controller is given in Table 2. Based on Table 1, it can be seen that the use of strategic control, which is quite popular in transportation systems in the form of the adaptive control strategy and fuzzy control strategy, has become widely used because the simplicity presented is quite promising as a control system. Although quite simple compared to other control strategies, the controller is able to show a good level of accuracy and can compete with other types. Meanwhile, the most popular MR material used in transportation systems is MRF. This is because MRF has an inherently fast response compared to other MR materials such as MRE, MR gel, and MR grease. In the use of transportation systems, they are often used as a vehicle damping device (shock absorber), so the use of MRF is very suitable for this application. If interest is that no other MR materials such as grease and elastomers have been found in transportation system applications. In fact, studies related to magnetorheological grades have been carried out at an early stage. This application is used in suspension systems replacing MR fluids. Meanwhile, MR elastomers are widely used for engine mounting. Figures 4–9 illustrate the concept of control in magnetorheological applications.

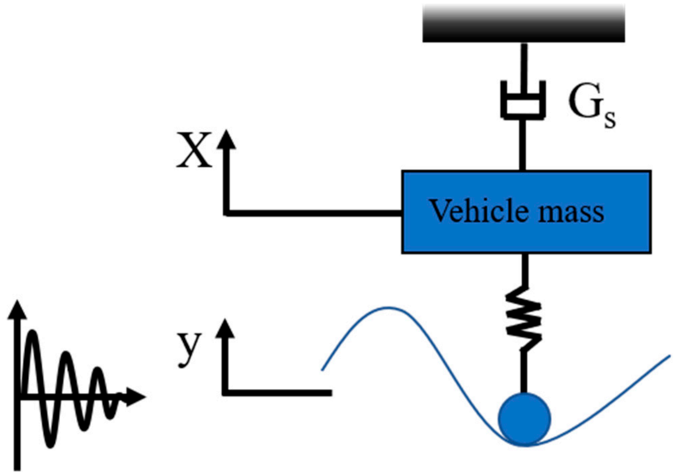


**Figure 4.** Skyhook controller concept [26]. Reproduced with permission from Choi, S.-B. et al. State of the art of control schemes for smart systems featuring magnetorheological materials; published by Smart Materials and Structures, 2016.

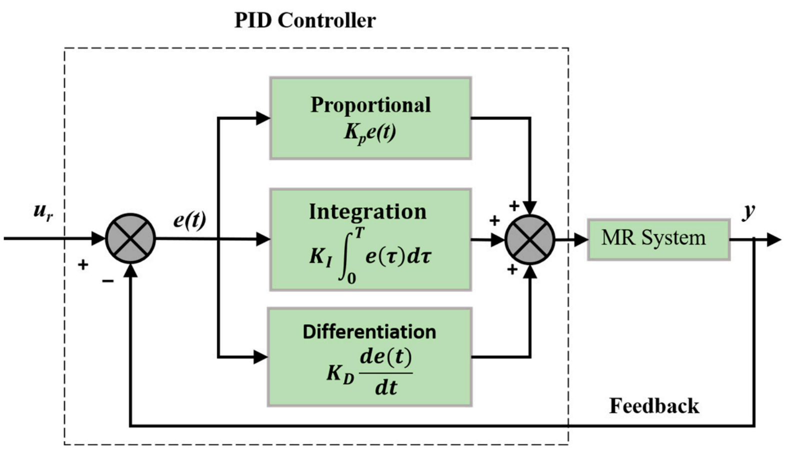


**Figure 5.** Block diagram of a PID controller [26]. Reproduced with permission from Choi, S.-B. et al. State of the art of control schemes for smart systems featuring magnetorheological materials; published by Smart Materials and Structures, 2016.

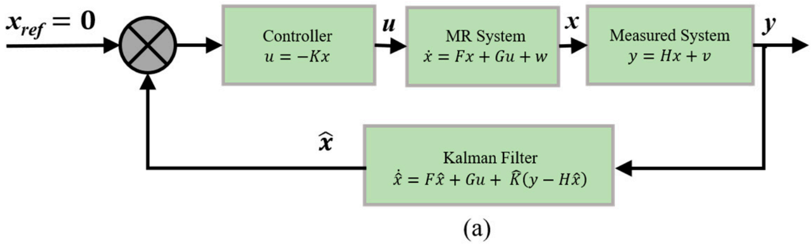


**Figure 6.** Block diagram of (**a**) LQG and (**b**) LQR [26]. Reproduced with permission from Choi, S.-B. et al. State of the art of control schemes for smart systems featuring magnetorheological materials; published by Smart Materials and Structures, 2016.

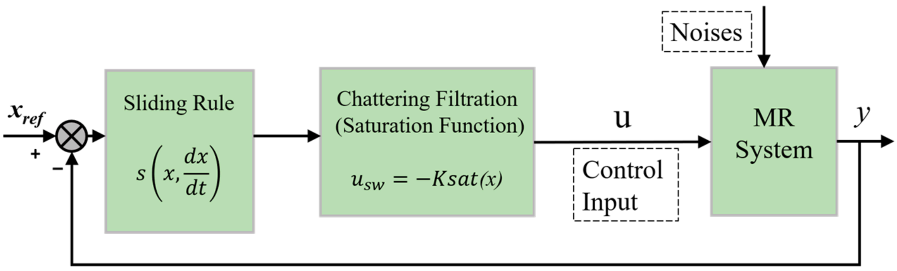


**Figure 7.** Sliding mode controller block diagram [26]. Reproduced with permission from Choi, S.-B. et al. State of the art of control schemes for smart systems featuring magnetorheological materials; published by Smart Materials and Structures, 2016.

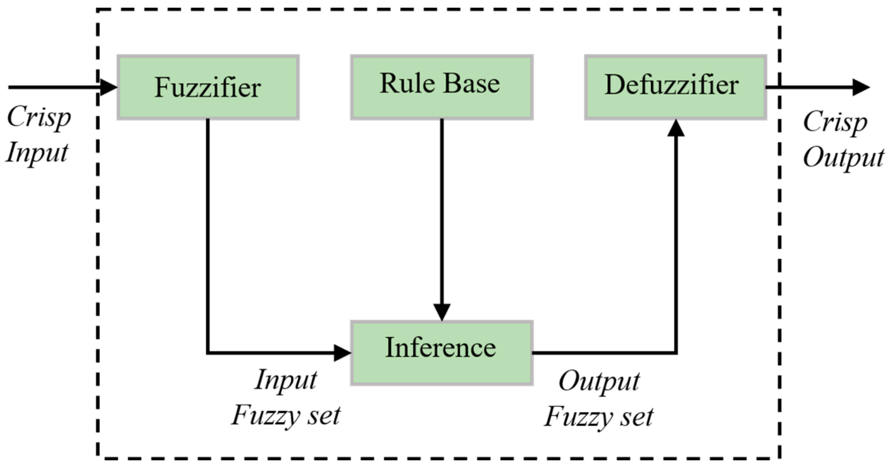


**Figure 8.** Fuzzy control system block diagram [26]. Reproduced with permission from Choi, S.-B. et al. State of the art of control schemes for smart systems featuring magnetorheological materials; published by Smart Materials and Structures, 2016.

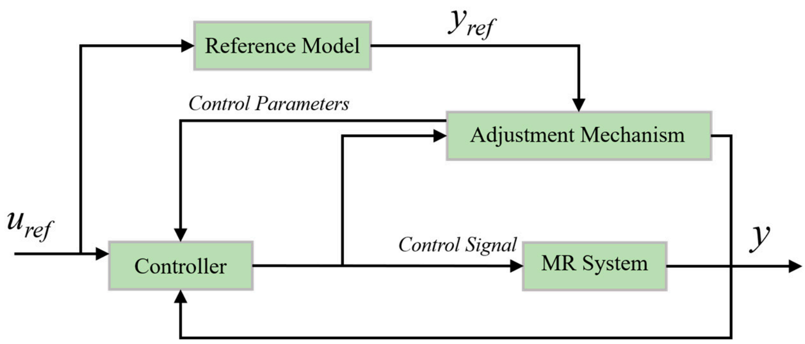


**Figure 9.** Model reference of an adaptive control system block diagram [26]. Reproduced with permission from Choi, S.-B. et al. State of the art of control schemes for smart systems featuring magnetorheological materials; published by Smart Materials and Structures, 2016.

The control input of the skyhook controller ($u$) is defined as follows: $u = G_s\dot{x}$, where $G_s$ is the control gain and $\dot{x}$ is the velocity of the system. The control gain of $G_s$ for this controller is normally determined on the basis of a trial-and-error method by considering the magnitude of the required damping force. This parameter is the main factor in achieving a high performance of the control system. The definition of PID control is: $u_{PID} = K_P e(t) + K_I \int_0^t e(\tau)d\tau + K_D\frac{de(t)}{dt}$, where $u_{PID}$ is the control variable, $e$ is the error defined as $e = u_r - y$, where $u_r$ is the reference value and $y$ is the process output. $K_P$, $K_I$, $K_D$ are the control gains for the proportional, integral, and derivative control action, respectively. The optimal control strategy can be divided into two schemes: the LQG control method and the LQR control method as shown in Figure 6a,b, respectively. The main difference between LQG and LGR is that the state estimator (Kalman filter) is integrated with the controller in the LQG controller. It is noted that when using active control methods such as LQG, we need to impose a so called "a semi-active condition". Under the semi-active condition, damping force can be controlled in certain quadrants only in the damping force versus velocity plot. Therefore, the semi-active actuating system associated with an MR damper cannot track the arbitrary desired damping force in a whole control domain. In the block-diagram, the sliding rule is the existing condition of the sliding mode that guarantees the system stability. In the figure, $u$ is the sliding surface function, $u_{sw}$ is the switching input function, and *sat* is the saturation function for preventing the chattering phenomenon. It was noted that the control $u$ was synthesized from the main control function of the system and switching function. There are four main components of a fuzzy controller, as shown in Figure 8: (1) fuzzification; (2) inference mechanism; (3) rule-base; and (4) defuzzification. It was noted that the rule base is normally determined from the experience of the control system. The critical parameters in designing the fuzzy controller are the membership functions, the inference mechanism and algorithm, and the defuzzification algorithm. An adaptive control system has two loops: one is a normal feedback with the plant and the controller, and the other is a parameter adjustment loop. The model reference adaptive system consists of four parts: a plant that contains unknown parameters; a model that characterizes the desired command–response behavior of the system; a controller that contains adjustable parameters; and an adjustment mechanism that updates these parameters.

**Table 1.** Vibration control strategies using magnetorheological materials actuators: application perspective.

| Control Types | Application on Transportation Systems | | Related References | Refs. |
|---|---|---|---|---|
| Skyhook | Automotive | MRF | Yi and Song (1999) | [27] |
| | | | Ahmadian and Pare. (2000) | [28] |
| | | | Choi SB et al. (2000) | [29] |
| | | | Choi SB et al. (2003) | [30] |
| | | | Ahmadian et al. (2004) | [31] |
| | | | Batterbee and Sims. (2004) | [32] |
| | | | Choi SB et al. (2005) | [33] |
| | | | Shen et al. (2006) | [34] |
| | | | Eslaminasab and Golnaraghi (2007) | [35] |
| | | | Nguyen QH and Choi SB (2009) | [36] |
| | | | Yao et al. (2013) | [37] |
| | | | Balamurugan L et al. (2014) | [38] |
| | | | Ramalingam et al. (2020) | [39] |
| | | | Lee AS et al. (2020) | [40] |
| | | | Chen et al. (2021) | [41,42] |
| | | MR Grease | Shiraishi et al. (2022) | [43] |
| | Railway | MRF | Fotoohi et al. (2006) | [44] |
| | | | Oh JS et al. (2016) | [45] |
| | | MRE | Jin T et al. (2020) | [46] |
| | Building structure | MR Grease | Shiraishi et al. (2022) | [47] |
| PID | Automotive | MRF | Choi SB et al. (2000) | [48] |
| | | | Ciocanel et al. (2008) | [49] |
| | | | Rashid et al. (2011) | [50] |
| | | | Gad et al. (2015) | [51] |
| | | | Muthalif et al. (2017) | [52] |
| | | MR Gel | Kim et al. (2016) | [53] |
| | Building structure | MRE | Guo YQ et al. (2020) | [54] |
| LQR/LQG | Automotive | MRF | Zhang CW et al. (2006) | [55] |
| | | | Lee DY et al. (2009) | [56] |
| | | | Nagarkar et al. (2011) | [57] |
| | | | Sibielak et al. (2011) | [58] |
| | | | Bégin MA et al. (2018) | [59] |
| | Railway | | Wang DH and Liao WH (2003) | [60] |
| | Aerofoil | | Sivrioglu et al. (2020) | [61] |
| | | | Weber F et al. (2003) | [62] |
| | | | Nagarajaiah and Narasimhan (2006) | [63] |
| | | | Swartz RA et al. (2007) | [64] |
| | Building structure | | Tan P et al. (2009) | [65] |
| | | | Winter BD et al. (2015) | [66] |
| | | | Afshari V et al. (2020) | [67] |
| | | MRE | Tariq MA et al. (2021) | [68] |
| Sliding mode control | Automotive | MRF | Lai CY et al. (2002) | [69] |
| | | | Chen, Y and Zhao Q (2012) | [70] |
| | | | Jeon J et al. (2013) | [71] |
| | | | Yusop MAM et al. (2016) | [72] |
| | | | Zhang H et al. (2015) | [73] |
| | | | Ning et al. (2017) | [74] |
| | | | Yoon DS et al. (2021) | [75] |
| | | | Zhu M et al. (2022) | [76] |
| | Railway | | Nguyen SD et al. (2015) | [77] |
| | | | Lee TY et al. (2011) | [78] |
| | Building structure | | Ha QP et al. (2013) | [79] |
| | | MRE | Balamonica K et al. (2019) | [80] |
| | | | Altabey WA et al. (2021) | [81] |
| Fuzzy logic control | Automotive | MRF | Devdutt and Aggarwal (2011) | [82] |
| | | | Félix-Herrán LC et al. (2014) | [83] |
| | | | Nguyen et al. (2015) | [84] |
| | | | Tang X et al. (2017) | [85] |
| | | MRE | Qian LJ et al. (2017) | [86] |
| | Military | MRF | Li Z et al. (2018) | [87] |
| | | | Amini F et al. (2015) | [88] |
| | | | Bathaei et al. (2017) | [89] |
| | Building structure | | Braz-César MT et al. (2018) | [90] |
| | | | Hormozabad et al. (2020) | [91] |

**Table 1.** *Cont.*

| Control Types | Application on Transportation Systems | | Related References | Refs. |
|---|---|---|---|---|
| | | MRE | Jung HJ et al. (2011) | [92] |
| | | | Yang J et al. (2016) | [93] |
| | | | Nguyen XB et al. (2017) | [94] |
| | | | Nguyen XB et al. (2018) | [95] |
| | | MR Grease | Ma YQ and Qiu HX (2015) | [96] |
| Adaptive control | Automotive | MRF | Song X et al. (2004) | [97] |
| | | | Krauze and Kasprzyk (2014) | [98] |
| | | | Phu D et al. (2015) | [99] |
| | | | Phu D et al. (2017) | [100] |
| | | | Yıldız AS et al. (2021) | [101] |
| | | | Basargan H et al. (2022) | [102] |
| | | | Truong HT et al. (2022) | [103] |
| | | MR Gel | Kim HK et al. (2017) | [53] |
| | Railway | MRF | Nguyen SD et al. (2015) | [104] |
| | | | Sakai et al. (2003) | [105] |
| | | | Terasawa et al. (2004) | [106] |
| | | | Chen C et al. (2009) | [107] |
| | | | Tu JY et al. (2009) | [108] |
| | Building structure | | Chen C et al. (2010) | [109] |
| | | | Karimi HR et al. (2010) | [110] |
| | | | Bitaraf M et al. (2012) | [111] |
| | | | Chen PC et al. (2015) | [112] |
| | | | Chen X et al. (2016) | [113] |
| | | MRE | Nguyen XB et al. (2018) | [114] |
| | | | Susheelkumar GN et al. (2019) | [115] |
| Neural network control | Automotive | MRF | Zapateiro M. et al. (2009) | [116,117] |
| | | | Metered et al. (2010) | [118,119] |
| | | | Ubaidillah et al. (2014) | [120] |
| | | | Guo et al. (2016) | [121] |
| | | MRE | Liu C et al. (2020) | [122] |
| | | | Nguyen XB et al. (2020) | [123] |
| | | | Yu Y et al. (2015) | [124] |
| | | | Fu J et al. (2016) | [125] |
| | | | Gu X et al. (2017) | [126] |
| | Building structure | | Yu Y et al. (2019) | [127] |
| | | | Gu X et al. (2019) | [128] |
| | | | Brancati R et al. (2020) | [129] |
| | | | Perez-Ramírez CA et al. (2020) | [130] |
| H-infinity control | Automotive | MRF | Choi SB and Sung KG (2008) | [131] |
| | | | Prabakar et al. (2009) | [132] |
| | | | Fallah MS et al. (2013) | [133] |
| | | | Félix-Herrán LC et al. (2012) | [134] |
| | | | Yao et al. (2013) | [37] |
| | | | Wu J et al. (2019) | [135] |
| | | | Félix-Herrán LC et al. (2019) | [136] |
| | | | Hosseini et al. (2020) | [137] |
| | Airfoil | | Bolat FC et al. (2018) | [138,139] |
| | | | Sivrioglu S et al. (2018) | [140] |
| | Building structure | | Zapateiro M. et al. (2009) | [141] |
| | | | Gao X et al. (2014) | [142] |
| Hybrid control | Automotive | | Ahmadian et al. (2000) | [28] |
| | | | Félix-Herrán et al. (2008) | [143] |
| | | | Ding et al. (2021) | [144] |
| | Aircraft | | Luong QV et al. (2020) | [145] |
| | | | Park KS et al. (2003) | [146] |
| | Building structure | | Fisco NR and Adeli H (2011) | [147] |
| | | | Chen B and Zheng B (2012) | [148] |
| | | | Kemerli M et al. (2022) | [149] |

**Table 2.** Defining equation of the controllers.

| | |
|---|---|
| Skyhook | $u = G_s \dot{x}$ |
| PID | $u_{PID} = K_P e(t) + K_I \int_0^t e(\tau) d\tau + K_D \frac{de(t)}{dt}$ |
| LQG/LQR | LQR<br>$u^*(t) = -R^{-1} G'(t) P(t, T) x(t)$<br>LQG<br>$u(t) = -R^{-1} G'(t) P(t, T) \hat{x}(t)$ |
| Sliding mode control | $s_g \dot{s}_g = (a - a_0) x_1 s_g - (k + \lvert a_m \rvert \lvert x_1 \rvert) \lvert s_g \rvert < 0$ |
| Fuzzy logic | Fuzzifier<br>$u(x) = exp\left(-\left(\frac{x-a}{\sigma}\right)^2\right)$<br>Rule Base<br>$if\ x_1\ is\ A_i^k\ and\ x_2\ is\ B_i^k\ then\ y\ is\ C_i^k\ (K = 1, 2, \ldots, q)$<br>$U_R\ (x_1,\ x_2,\ y) = \vee_{i=1,\ j=1}^{i=k, j=l} \mu_{xli}\ (a) \wedge\ \mu_{x2j}(b) \wedge \mu_{ij}(c),$<br>Defuzzification<br>$y = \frac{\sum_{i=1}^{R} c_i^q \int_y \mu_{\tilde{c}_i^l}(y) dy}{\sum_{i=1}^{R} \int_y \mu_{\tilde{c}_i^l}(y) dy}$ |
| Adaptive | $u(t) = k_f(t) r(t) + k_b(t) y_p(t)$ |
| Neural network | $y_k = g\left(\sum_{i=1}^{p} w_{ki} x_i - \theta_k\right)$ |
| H-infinity control | $\lVert F_1(P, K) \rVert_\infty = sup\ sup\ \underline{\sigma}(F_1(P, K)(jw))$ |
| Hybrid | $F_{hybrid} = \eta F_{sky} + (1 - \eta) F_{ground}$ |

### 2.1. Automotive

The development of MR damping device studies has generally been dominated by the automotive field and the establishment of an MR damper as an actuator in this field is quite popular. This is related to the level of need for the use of public transportation modes. Vehicle comfort is of high concern for researchers in developing damping devices [150]. These developments include passive, active, and semi-active damping devices. The MR damper as a semi-active damping device has become popular since the introduction of MR fluid materials. For the purpose of optimizing the device and the comfort level of the vehicle, a device support control strategy was also developed. As a result, the researcher introduced various types of control strategies for semi-active systems with an MR damper as an actuator. New forms of controllers to regulate steering motion such as shimmy vibrations were also developed and their control performance was tested [151]. The study proposed a novel sort of adaptive sliding mode control using a moving sliding surface to improve ride comfort and decrease undesired vibrations. Furthermore, Phu et al. [152,153] suggested a new adaptive fuzzy controller for automobile seat suspension based on the H-infinity approach, as shown in Figure 10, and claimed that utilizing an adaptive controller improved the vibration control performance substantially more than using a fuzzy controller.

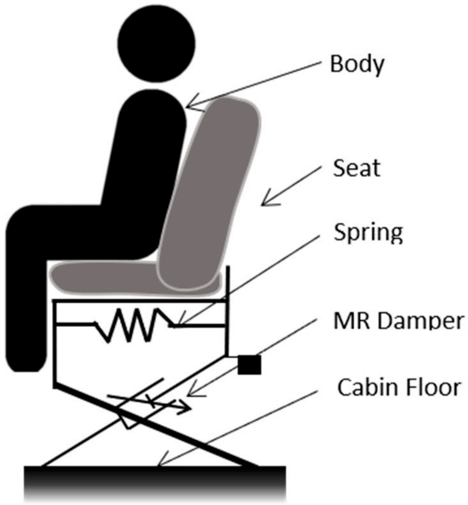


**Figure 10.** Physical model of the semi-active seat suspension with an MR damper [37]. Reproduced with permission from Yao, H. J. et al. Semi-active H∞ control of seat suspension with MR damper; published by Journal of Physics: Conference Series, 2013.

### 2.2. Military (Tracked) Vehicle

In addition to the previously mentioned applications, MR dampers are also used in various military sectors as seen in the research on the use of damping in ship and car parts in the military field, which was carried out by Oh et al. [154]. According to Oh et al., shock waves from non-contact underwater explosions (UNDEX) regularly damage components of submarines and navy vessels during combat conditions. In general, impact tests are performed to assess the resistance and shockability of an explosion using the MIL-S-901D formulation, which was established by the U.S. in 1989. Light and medium impacts were tested using a shock engine, whereas large impacts were tested using a large-scale floating shock platform and UNDEX. However, some parties recommend that the tests be carried out especially in heavy tests that are recommended using a shock machine. Therefore, several test methods have been proposed in the research, as proposed by Zhaodong et al. Another method was also proposed by Oh et al., who created a heavyweight impact test device equipped with a controlled magnetorheological damper [155]. This proposal is an interesting one, because in their research, they stated that by applying the MR damper to the proposed impact test apparatus, the resulting acceleration profile could be adjusted and the impact energy could be effectively removed. However, this research is limited under certain conditions such as low frequency and low speed while at high impact speeds and frequencies, the proposed MR damper may not work optimally. In this case, Oh et al. proved that the MR actuator applied with the MR damper model could be used in the military field. Unfortunately, in this study, they did not explain in detail the control strategy used and only explained that used the Bingham model. In the research by Oh et al., they stated that the simple use of MR dampers as actuators in the military, railways and heavy equipment fields has something in common, which indicates that MR actuators have also been investigated by several parties in the railway and heavy equipment sector. The research conducted by Oh et al. also suggests that the proposed MR damper is used for two fields at once, namely, military and shipping [154,156].

In general, as shown in Figure 11, military vehicles are vehicles that can be categorized as heavyweight vehicles that require good speed, stability, and strength [156]. To support this, damping device technology has been developed. Although there have not been many studies discussing MR damping devices in the military field, this technology deserves to be evaluated and researched further. One related studies conducted by Hiemenz et al. implemented an MR damping device on a helicopter seat [157] in a study carried out to improve passenger comfort. The MR damping device was implemented in series with the existing fixed load energy damper so that the seat capability was not compromised.

Semi-active controls were applied and performance was evaluated both analytically and experimentally. In their study, they used a skyhook control strategy. In addition to implementing MR damping devices for helicopters, the military sector also usually uses MR damping devices on other vehicles such as military cars, ships, and landing gear on aircraft.

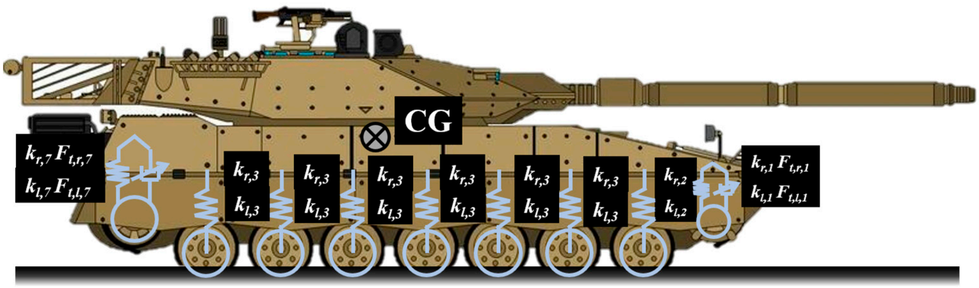


**Figure 11.** Model of the 2S1 military vehicle [156].

*2.3. Railway*

The needs of modern society in fulfilling mass transportation modes are increasing, which has meant that better public transportation systems need to be developed worldwide, one being a high-speed rail vehicle. However, in this case, the vibrations of the vehicle body due to high speed are significantly felt. The vibration certainly reduces the quality of the ride and also affects the stability of the ride. Thus, one option to manage this scenario is to design a more advanced rail vehicle suspension system, which is necessary when considering the comfort and safety of the vehicle and passengers. Railroad vehicle suspensions are divided into two types: primary and secondary, as shown in Figure 12 [158]. The main suspension is positioned between the wheel set and the bogie frame and is made up of four distinct nonlinear axle box dampers per bogie. The secondary suspension is positioned between the bogie and the vehicle body. When the train vehicle turns, both types of suspension are used to hold the body and allow the bogie to revolve. Because the vibration of the vehicle body is directly related to the secondary suspension, many studies on the secondary suspension have been conducted in order to improve the vehicle's quality and stability.

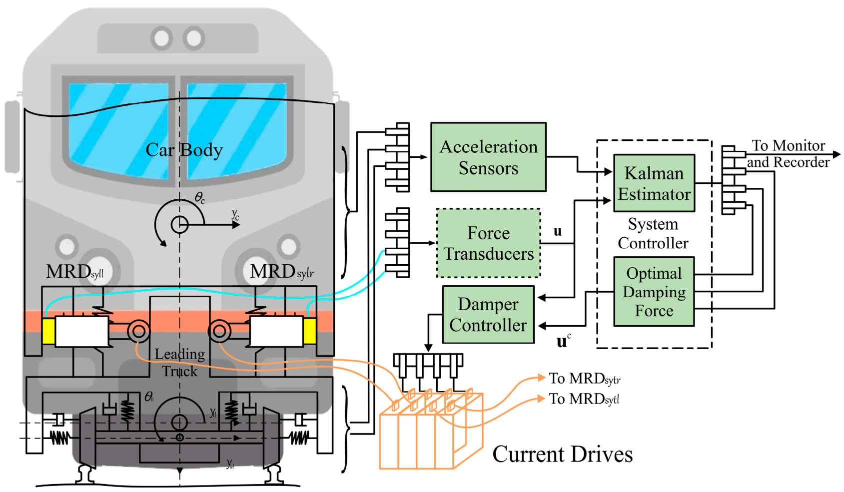


**Figure 12.** Schematic of a railway vehicle integrated with the semi-active controlled secondary suspension system based on magnetorheological dampers [158].

The secondary suspension commonly used in railroad vehicles is a passive suspension consisting of springs and hydraulic dampers. Passive suspension provides various advantages such as compactness, cost-effectiveness, and easy maintenance. However, this form of passive hydraulic damper cannot simultaneously meet the requirements of vehicle quality and stability at high speeds. On the other hand, active suspension is generally more capable of guaranteeing reasonable performance under various running conditions including high speeds. However, there are various disadvantages or complexities in constructing an active suspension such as the need for enormous resources and complex control algorithms at a high cost. Furthermore, when a sensor fails, the active suspension system might induce instability. As a result, a semi-active suspension system for railroad trucks has been designed to anticipate failures while still providing the benefits of active suspension. The semi-active suspension system can increase the isolation performance without requiring a large amount of resources by regulating the damping of the system, and this good performance can be achieved by utilizing simple control methods such as a skyhook controller.

One adjustable semi-active suspension system with magnetorheological (MR) fluids has been documented, each with its own set of advantages. Depending on the terrain, a semi-active suspension system with an MR damper offers numerous advantages such as high stability, smooth movement, and vibration control performance. Sun et al. conducted experiments on rail vehicles using MR dampers [159]. Lau and Liao combined an MR damper with a rail vehicle suspension system to test the suspension performance of the unit components [160]. They assessed the suspension performance of the on–off control technique using numerical simulations of a railroad vehicle model and discovered that the vibration of the car body could be decreased to a maximum of 38.9%. Liao and Wang suggested a 9-DOF rail vehicle system and used numerical analysis to assess the performance of the dynamic model. It has been proven that it performs very effectively to regulate the rail system along the vertical direction. Ha et al. studied the ride quality of a rail vehicle system fitted with MR dampers [161] and employed the ride index approach to analyze suspension performance and gauge the ride quality. Using numerical simulations, they also demonstrated that ride quality could be greatly enhanced by changing the terrain-dependent dampening force of the MR damper.

Wei et al. conducted a study on a train vehicle with a magnetorheological damper [162]. In their study, they focused on the control strategy of a semi-active suspension system. First, they measured the angular velocity of the bogie and the angular velocity of the wheelset for the purpose of feedback control. The use of one wheelset was considered because the control methods for the others were similar. The control moment needed to be generated by increasing the damping coefficient MR to minimize the angle of attack. For each MR damper, excitation current adjustment was carried out as a controller to change the damping force. In addition, Nguyen et al. also conducted a study on control strategies for damping devices used on railways [77]. Their studies focused on the manufacture of controllers for the active suspension systems of train cars and relied on the assumption that the spring mass and model error were uncertainty parameters. The controller was designed based on adaptive neuro-fuzzy inference system (ANFIS), sliding mode control, and uncertainty observer (NFSmUoC). Identification of the MR damping device using ANFIS and the scalable MR damper-dynamic response dataset was carried out. The ANFIS-I damping device was then used to estimate the current applied to the damper device and created an active control force that was calculated to control the vertical vibration status of the train carriage. In the same year, Nguyen et al. conducted similar research with different types of control strategies [104]. A new adaptive type 2 fuzzy sliding control (AT2FC) for the vibration control of a magnetorheological damper based rail suspension subject to uncertainty and disturbance was proposed. This type of control consists of four main parts. The first is the sliding mode controller (SMC) to determine the main damping force that supports the suspension. Next is an interpolation model based on a type 2 interval fuzzy logic system to determine the optimal parameters of the SMC. The third is a nonlinear UAD observer to compensate for external disturbances. The last controller used is the inverse MRD model (T2F-I-MRD) to determine the input current. The results of their study indicate that the survey results obtained reflect the excellent performance of the AT2FC's vibration control compared to other controllers. There has not been not much strategic control applied to the railway sector. In the published Scopus database, the number of articles can be said to be very small, in contrast to other fields such as cars and buildings. Fuzzy control strategies tend to be used more in the railway sector. However, other control strategies can also be used, as shown by Nguyen et al., who conducted a study with four types of control strategies. The type of control developed by Nguyen et al. also has the potential to be adapted for other fields with customized development. Not unlike the railway sector, the discussion of control strategies in the aerospace sector has also been rarely discussed, especially with regard to MR damping actuators.

### *2.4. Aircraft/Aerospace*

Magnetorheological dampers as actuators have also been introduced in several aerospace applications. The application most often proposed in this field is the use of an MR damper on the landing gear. MR dampers are said to be quite reliable in landing gear applications, which are known to experience high vibrations and speeds, so good shock energy absorption is needed during the landing process. Several studies on the application of MR dampers as actuators for landing gear have been reported. Wereley and Batterbee investigated the design methodology for the MR landing gear. As a result, a basic landing gear model was proposed, and the mathematical equations for the governing dynamics were derived [163,164]. Skorupka [165] and Holnicki-Szulc et al. [166] designed the manufactured MR shock absorbers for the landing gear system. The absorber was experimentally tested according to the input current, and a displacement that could be reduced by increasing the damping force was identified. Mikułowski and Jankowski designed an optimal controller for the MR landing gear, and the high performance of the MR landing gear system was verified through a comparison between the passive, semi-active, and active dampers [167]. Han et al. also reported research on a landing gear with a new type of MR damper, as shown in Figure 13 [168]. Han et al. used oleo-pneumatic dampers, which are used for small aircraft landing gear systems. In their research, a simple but effective skyhook controller was formulated with the safety conditions in mind. Through computer simulations, it was demonstrated that the proposed MR damper could provide the best vibration control and highest efficiency, showing the shock absorber capability during the landing stage.

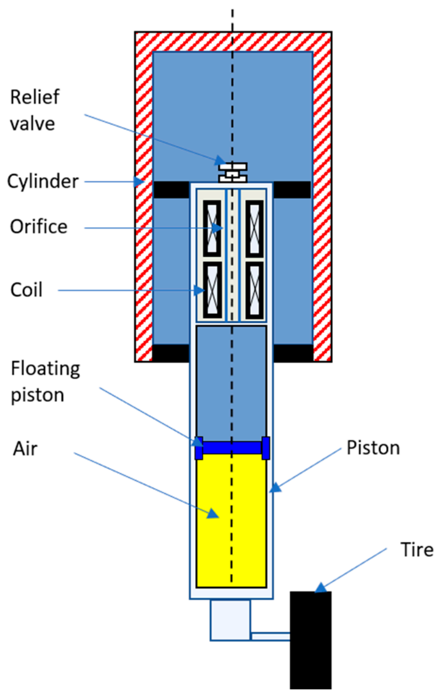


**Figure 13.** Schematic of the MR damper for the landing gear [169]. Reproduced with permission from Luong, Q. V. et al. Semi-Active Control for a Helicopter with Multiple Landing Gears Equipped with Magnetorheological Dampers; published by Applied Sciences, 2021.

### 2.5. Ship

MR materials are becoming increasingly used in a variety of applications to fulfill the force/torque requirements, one of which is in the shipping industry. As shown in Figure 14, the use of MR materials in the maritime area include engine mounting, propeller shaft mounting, and as a mast damper of warships. The use of MR for engine mounting has been researched by numerous researchers including studies on the unique configurations of a small and high damping force engine mount utilizing magnetorheological fluid (MRF), as suggested by Nguyen in 2013 [170]. Other engine mount research was undertaken by Phu D in 2015, who utilized a new modified indirect fuzzy sliding mode controller and a combination of an MR mount and MR brake [171]. The usage of MR materials on ship shafts was researched by Yang in 2014 and Lu in 2017 [172,173]. MR materials are required to reduce the vibrations on ships generated by unexpected saltwater waves, in addition to dampening the ship engines and the need for shaft propulsion damping. Seawater waves generate vibrations on the ship's radar mast, so the ship's radar mast needs a damper. Zhong and Cheng conducted research on the ship's radar mast in 2008 by utilizing the fuzzy control method [174].

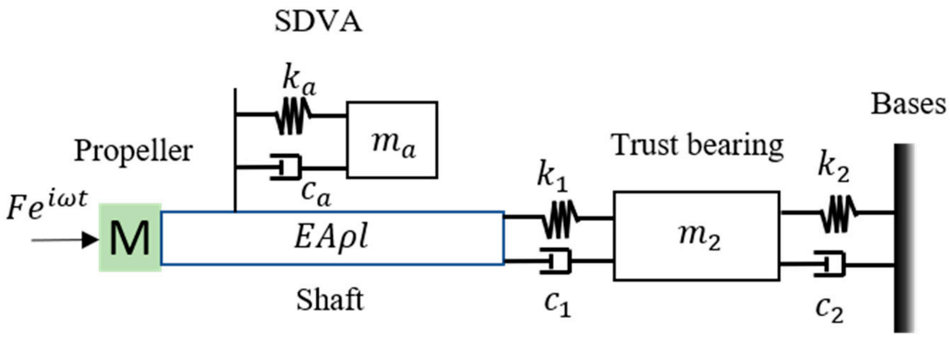


**Figure 14.** Simplified physical model of the propulsion shaft system with a semi-active dynamic vibration absorber [172].

### 2.6. Vibration Isolation for Machinery

In the realm of equipment, the need for vibration isolation systems has increased in recent years. In many circumstances, vibration is inevitable, but it may be minimized to manageable levels. Vibration isolators are required to minimize vibration when it becomes excessive or unbearable. As a result, more research efforts have been directed toward the development of vibration isolation technologies. Researchers have recently researched magnetorheological materials in vibration isolation for machinery given their advantages of linearity of transfer characteristics, low excitation voltage, high efficiency, compact size, and low transmission noise. In 2014, Li, Yancheng published *A highly adjustable magnetorheological elastomer base insulator for real-time adaptive control applications*, as shown in Figure 15 [175]. The experimental results revealed that under a modest magnetic field, this new MRE base isolator could significantly affect the lateral stiffness of the isolator by up to 1630%. Sun studied the control strategy simulation analysis of a novel micro-cultivator MR elastomer vibration isolation system in 2020. To validate the control effect from the simulation findings, simulation analysis was performed using PID control, on/off control, and no control techniques [176].

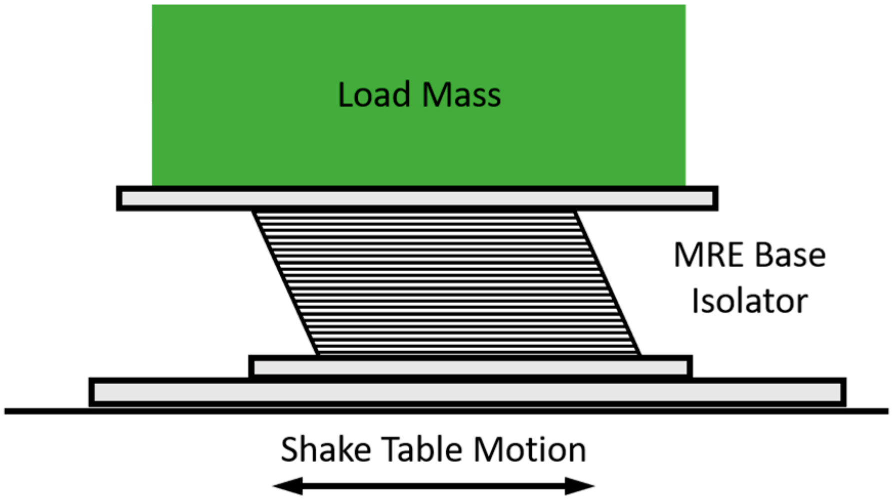


**Figure 15.** MRE base isolator schematic illustration [175].

*2.7. Civil Engineering*

In addition to the use of MR technology in the transportation sector, MR materials have also penetrated the civil sector. The inclusion of MR materials in this field can be said to be in accordance with their ability to be controlled. One of the purposes of using MR materials in this field is disaster mitigation [177]. In fact, mitigation technology in the civil sector has made a lot of progress. Starting from the development of a friction damper, a mass damper that can be controlled (tuned mass damper), until now, viscous dampers have also followed the development of controlled technology through technology based on MR materials. Not only as a viscous damper, but MR materials are also used as a base isolation damper in several studies. Similar to the use of MR materials in transportation systems, the field of civil engineering has also used MRF a lot in the study of the development of MR technology in civil engineering. However, some studies have presented a different view, because in this field, MR technology will certainly consume a lot of MR fluid. As a result, some of this study examined the development of other suitable materials in civil engineering cases such as MR grease and MR gel for viscous damping applications. Although it has several weaknesses, this type of MR material is quite good at handling sedimentation and large excitation forces. To optimize all of these performances, of course, a good control system is also required in civil engineering applications. Nonlinear behavior caused by earthquakes requires an actuator and control method for structural nonlinear vibrations. Sliding-mode and fuzzy type controls have been proposed by Li et al. [178] and numerical simulations were used to evaluate the performance of the proposed controls on a 3-story steel building model (Figure 16). As a result, the controls (Figure 17) revealed the effectiveness of the proposed method. In the following control system, $f(x, \dot{x})$ will be replaced by a fuzzy system $\hat{f}\left(x \middle| \theta_f\right)$, and $g(x, \dot{x})$ will be replaced by a fuzzy system $\hat{g}(x|\theta_g)$. For the fuzzy system $\hat{f}\left(x \middle| \theta_f\right)$, the fuzzy output will be the nonlinear force (restoring and damping force) of the structure, and the fuzzy input will be the interstory displacement and velocity. For the fuzzy system $\hat{g}(x|\theta_g)$, the fuzzy output will be the nonlinear coefficient, and the fuzzy input will be the interstory displacement and velocity. For the fuzzy system, $\hat{f}(s|\theta_s)$ is the approximation of the sliding mode control. The sliding mode surface can be defined as $s = c_1 x + \dot{x}$. The adaptive laws of a fuzzy system obtained from the Lyapunov function is $\dot{\theta}_f = \gamma_1 s \zeta(x)$, $\dot{\theta}_s = \gamma_2 s \psi(s)$, and $\dot{\theta}_g = \gamma_3 s \chi(x) u$.

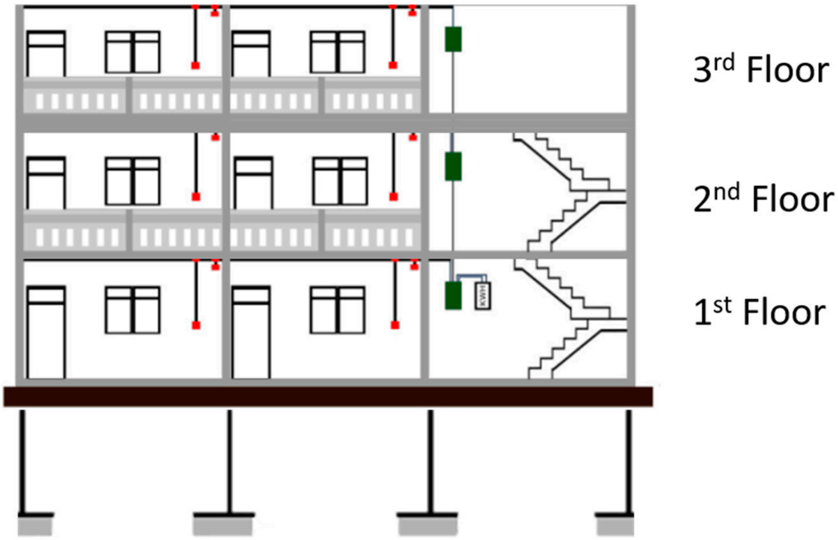


**Figure 16.** A 3-story steel building model [179].

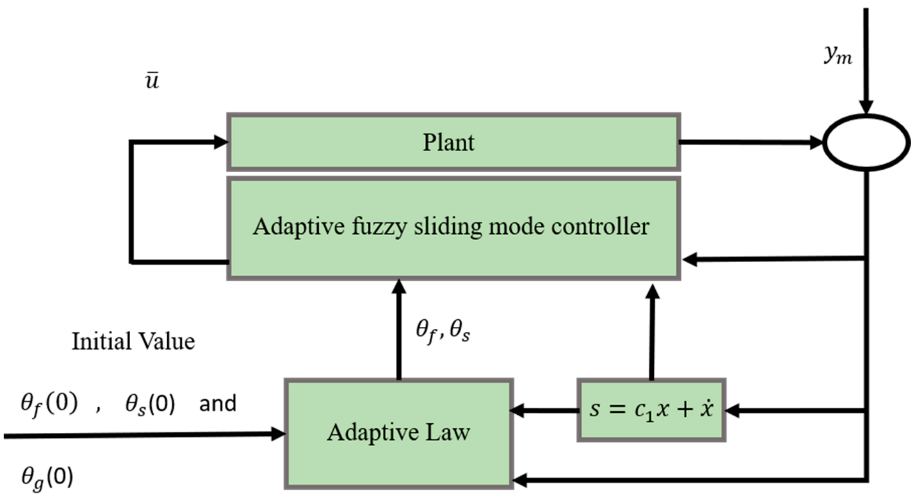


**Figure 17.** Block diagram of the control system proposed by Li et al. [178].

Fuzzy type control for the field of civil structures was also applied and proposed in another study by Mahdi et al. [180]. They reported the fuzzy control performance of a 3-story building. The results of the study conducted showed that the displacement of the building was reduced compared to the uncontrolled building. In addition to fuzzy control, adaptive control is also a popular type of controller used for building structures such as the study conducted by Omar et al. [181]. Omar et al. investigated the seismic response of high-rise buildings with MR dampers. Adaptive controllers can handle changes in structural features that occur during an earthquake well [181,182]. Types of control other than fuzzy and adaptive controls are also known to have been used for MR dampers in buildings such as LQR and the type of fuzzy control developed.

The application of MR dampers in buildings has indeed been widely reported, but the type of material used is still dominated by MR fluids. In fact, the use of MR fluid for building damping still has some drawbacks. Some of these include leaks due to large excitation forces, problems with the deposition of iron particles in fluids, and performance ranges that are not high enough to overcome the earthquake loads. Therefore, other magnetorheological materials such as elastomers and greases have also been developed for the MR damping technology of buildings. One of the studies that reported on MR grease damping devices for buildings was conducted by Shiraishi et al. [2] where the dynamic range and dispersion stability of the shear type MR grease damping device were investigated. They tested an MR grease damping device that was applied to a small single-degree-of-freedom model structure that was subjected to seismic excitation. The skyhook type control was adapted in their research and the results of the damper performance test showed that the dynamic range obtained was much higher than that of the conventional MR damper. In addition, the high level of the dispersion stability of MR grease indicates that its performance can be maintained for 9 days longer compared to similar reducers using MR liquid. The study conducted by Shiraishi et al. showed good results at the beginning of the development of damper technology by using MR grease as its working material. Other types of damping devices such as MR elastomers have also been developed for building applications in earthquake disaster management efforts. In general, the use of MR elastomers as damping devices is a basic insulation system. This is a new discussion that is still in the early stages of developing intelligent materials whose modulus of elasticity or stiffness can be adjusted depending on the magnitude of the applied magnetic field. Jung et al. [92] reported MR elastomers as an intelligent ground insulation system for scalable buildings under earthquake loads. The results of the research showed that the proposed MR elastomeric base isolation system with the fuzzy logic control algorithm was superior to the conventional passive type-based isolation system in reducing the response of the building structure to seismic excitation.

### *2.8. Flexible Structures*

A flexible structure system consists of two components: one is a vibrating machine and the other is a supporting structure. In order to eliminate unwanted vibration of the flexible structure system, various types of mounts are utilized in the passive or active control method. MR damping devices are widely installed on bridge structures and civil structures [183]. In the early 20th century, Heo et al. [184] conducted an experimental study on the vibration control of bridge structures using a semi-active vibration control method in real-time. A laboratory-scale model of a cable-stayed bridge was constructed, and a shear-type MR damper and a semi-active vibration control algorithm (Lyapunov and clipped optimal) were applied for the real-time control of the model bridge's harmful vibration. The Lyapunov and clipped-optimal control methods were found to be more effective than the passive-on and passive-off control methods in reducing displacement and acceleration relative to the uncontrolled state. In particular, compared to the passive-on control state, their input voltage consumption was reduced by approximately 50%, proving that these two semi-active control methods are more cost-effective than passive control methods. Due to the fact that this research was based on indoor experiments on a model structure, it should be noted that additional research is required to find adequate criteria to calculate the capacity of the control devices, suitable installation positions, appropriate numbers of control devices, the development of control devices of various shapes and forms, design procedure of the systematic control algorithm, etc., and to conduct semi-active vibration control with MR dampers in real-time. In 2014, Weber et al. [183] conducted research by installing decentralized real-time controllers on Sutong Bridge, China with pulse width modulation installed next to each MR damper. Duan et al. (2014) [185] utilized the linear quadratic regulator (LQR) control technique to develop a state-derivative feedback control law and derive the feedback and estimator gains for the real-time control of cable vibration using MR dampers. The real-time control test conducted on a prototype cable at the Dongting Lake Bridge site demonstrates that the damping capacity obtained from the semiactive control test corresponded well to the simulation results.

In the theoretical complex mode analysis of cable, Xu YW et al. (2022) investigated the effect of the damping coefficient and negative stiffness coefficient on stay cable vibration active control (Figure 18) [186]. It was demonstrated that the MR damper-based pseudo-negative stiffness force, which had a coupled equivalent negative stiffness coefficient and damping coefficient, could provide a superior control effect compared to the optimal passive control. The results indicate that the intelligent devices proposed and installed at

3% of cable length could still provide an additional 2.28% modal damping ratio, which had 1.63 times the damping effect of the optimal passive-on MR method.

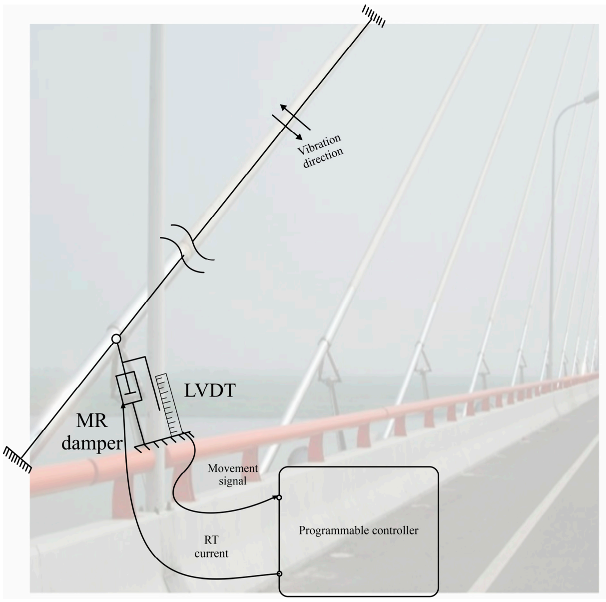


**Figure 18.** MR damper based programmable stay cable vibration control system [186].

In another study conducted by Weber F. in 2014 [187], a semi-active vibration absorber with a real-time controlled magnetorheological damper (MR-SVA) for the reduction of harmonic structure vibrations was built. When the natural frequency of the MR-passive SVA's mass spring system was correctly tuned to the intended structural resonance frequency and de-tuning was present, the MR-SVA was mathematically and experimentally verified for harmonic excitation of the primary structure. An adaptive damping control was proposed, and the findings showed that at the structural resonance frequency, the MR-SVA outperformed the passive TMD by at least 12.4% and up to 60.0%. Zhang X.Z. et al. [188] conducted research and presented the invention of a novel adaptive tuned dynamic vibration absorber (ATDVA) using magnetorheological elastomers a year before (MREs). Carbonyl iron particles were mixed with silicone rubber and hardened in a high magnetic field to create the MRE materials. An ATDVA prototype was conceived and built utilizing MRE as an adaptable spring. The MRE ATDVA operated in shear mode, with the magnetic field produced by a magnetic circuit and regulated by a DC power source. Vibration testing equipment was used to assess the dynamic performances or system transmissibility of the absorber at varied magnetic fields. According to the experimental results, this absorber could vary its natural frequency from 35 Hz to 90 Hz, or 150% of its fundamental natural frequency. To assess the control impact, a real-time control logic was provided. The simulation findings showed that the control effect of MRE ATDVA could be greatly enhanced. In a magnetic field of 0.44 T, Li Y et al. [175] developed and produced a soft MRE material with a 1300% shear modulus increase, which was then incorporated into the laminated structure of the base isolator design. To increase the magnetic field in the laminated MRE isolator, a novel production procedure for the MRE base isolators was also created. A prototype of this novel highly adjustable MRE base isolator was then submitted to a thorough experimental analysis to better understand its features and performance. The results of the testing and subsequent analysis revealed that the novel MRE base isolator had an exceptional adaptation ability, capable of producing up to a 1479% force increase and a 1630% stiffness increase when the applied current was shifted from 0.0 to 3.0 A.

Seung-Bok Choi invented a new form of MR mount in 2007 by combining the flow and shear modes to reduce vibration in a structural system composed of a vibrating mass and flexible beam, as shown in Figure 19 [189]. A linear quadratic Gaussian (LQG) controller was then constructed to dampen the vibration of the structural system. The experiment demonstrated that activating the proposed MR mount associated with the optimal controller reduced the imposed vibrations of the structural system such as acceleration and displacement. Hong and Choi conducted another experiment with linear quadratic Gaussian (LQG) control in 2005 [190]. Another study was conducted by Xu Z. et al. in 2010 [191]. The frequency shift property test showed that the resonant frequency of the created active-damping-compensated magnetorheological elastomer adaptive tuned vibration absorber (MRE ATVA) ranged from 28.75 Hz at 0 A to 44.56 Hz at 0.8 A, and the average damping ratio was lowered from 0.16 to 0.06 by the active force. The vibration attenuation performance of the active-damping-compensated MRE ATVA on a clamped–clamped beam was evaluated experimentally. The results revealed that the active-damping-compensated MRE ATVA outperformed the traditional MRE ATVA in terms of vibration attenuation.

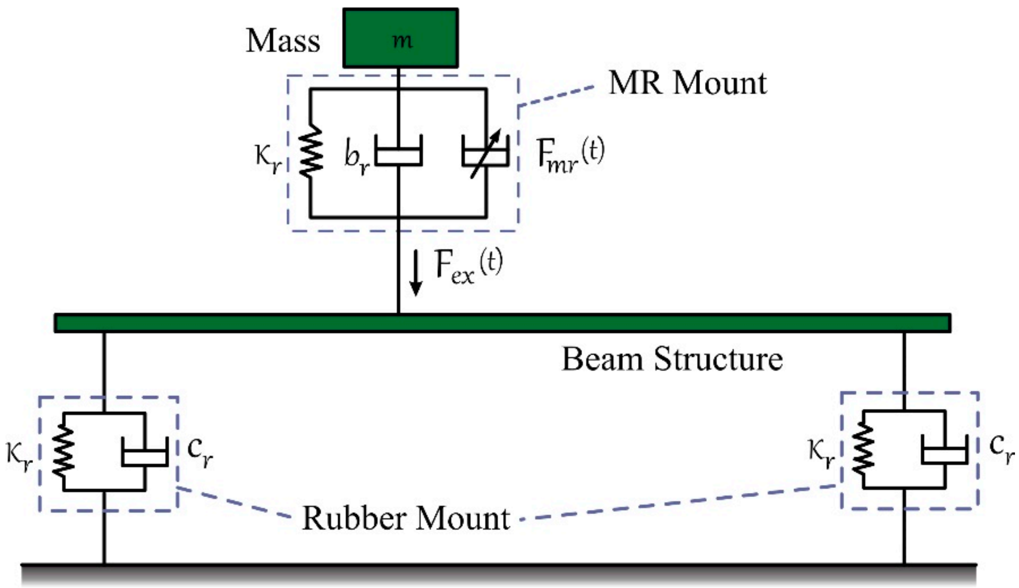


**Figure 19.** Configuration of the structural system with the MR mount [189].

## 3. Results and Discussion

The skyhook controller was introduced by Karnopp et al. [20]. It is known that the skyhook controller logic is simple, cost effective, and easy to implement into the real field. However, the disadvantage of the skyhook controller is the lack of robust stability in the presence of external disturbances and parameter variations. The second type of controller that is well-known and used in various studies is PID control. A PID (proportional integral derivative) controller is a control strategy with a feedback mechanism that is usually used in industrial control systems. Basically, a PID continuously calculates the error value as the difference between the desired setpoint and the measured process variable. In this case, PID tries to minimize the error value in any given time unit by setting the control variable. The control variables are usually position, force, and power. Next, is linear quadratic (LQ) control, which can be said to be one of the most popular control techniques because it can be applied in various applications including MR actuator-based control systems. The salient advantage of the LQ control method is that it leads to linear control laws that are easy to apply and analyze. PID and LQ controls tend to be more adapted to vehicle actuator-based MR control systems; however, several uses of this method have been found in the fields of civil engineering, flexible structures, machine vibration, and offshore.

Next is sliding mode control. SMC is well-known for its ability to ensure control robustness in the face of system insecurity and external disruption. Under the sliding mode motion, sliding mode control systems have invariance qualities to parameter fluctuations and external disturbances. Because of its advantages, the SMC system is still being developed further, particularly in automotive and building structures. It is commonly known that fuzzy logic (FL) has intrinsic robustness, the capacity to handle nonlinearities and uncertainties, and does not require a precise mathematical model, and thus it has piqued the interest of researchers and engineers in recent years. The membership functions, inference mechanism and algorithm, and defuzzification method are key components in the design of the fuzzy controller. Fuzzy logic control is used mostly in automotive and building structure control systems.

Several control methods have been used in MRF and MRE application systems. However, system uncertainties caused by modeling errors, material property variations, component nonlinearity, and changing load situations can induce controller instability or performance loss. To provide appropriate control, an adaptive controller with parameters that can be modified or customized to the unknown or variable properties of the MRF and MRE systems was developed. McCulloch and Pitts proposed a model for biological neurons and biological NNs in the 1940s [192]. NNs learn to approximate sampled functions even when their form cannot be described precisely, and so NN models represent a potentially robust new approach to systems engineering. Next is $H\infty$, which was first developed in the frequency domain to generate controllers with guaranteed performance. Adaptive control, NNs control, and $H\infty$ devices have been designed and widely used in automotive and building structure applications. Last but not least, is hybrid control. Hybrid control systems are those that incorporate two or more traditional control methodologies. The system performance can be considerably improved by combining several tactics. The overall reason for hybrid approaches is the strong interaction between the multiple optimization targets. In addition, hybrid solutions are required for the hierarchical control structure in many of today's complicated technical systems. Hybrid control systems are mostly used in the fields of automotives and building structures.

In this study, mapping analysis was also carried out to help map the research that has been conducted related to the control strategy used in the magnetorheological actuator. By using topic trend mapping and keyword usage in scientific studies that have been reported in the Scopus database related to strategic control for magnetorheological actuators, adaptive control was seen to have the most records. This is shown in Figure 20, which shows the use of keywords and the titles of scientific articles in the Scopus database. Figure 20 shows that the use of adaptive controls was often used in various studies, with a recorded number of 31. This number is not an accurate number, but was compared to other types of control that were not recorded in the 100 sample treemaps. Based on a Scopus search with keyword selection arranged according to each type of control, adaptive control was used in 109 articles related to magnetorheological actuators. This number was the largest number compared to the others such as a neural network control type with a total of 102 articles, and sliding mode control with a total of 101 articles. In addition to the treemaps, the trend mapping of topics with the same settings was also carried out. The search results are shown in Figure 21 (the size of the bubble indicates how often the keyword is used on Scopus), which also showed that adaptive control entered the trend topic in the discussion of this field, especially in 2013. In accordance with the keyword search conducted on Scopus, control neural networks also entered the trend topic in 2009.

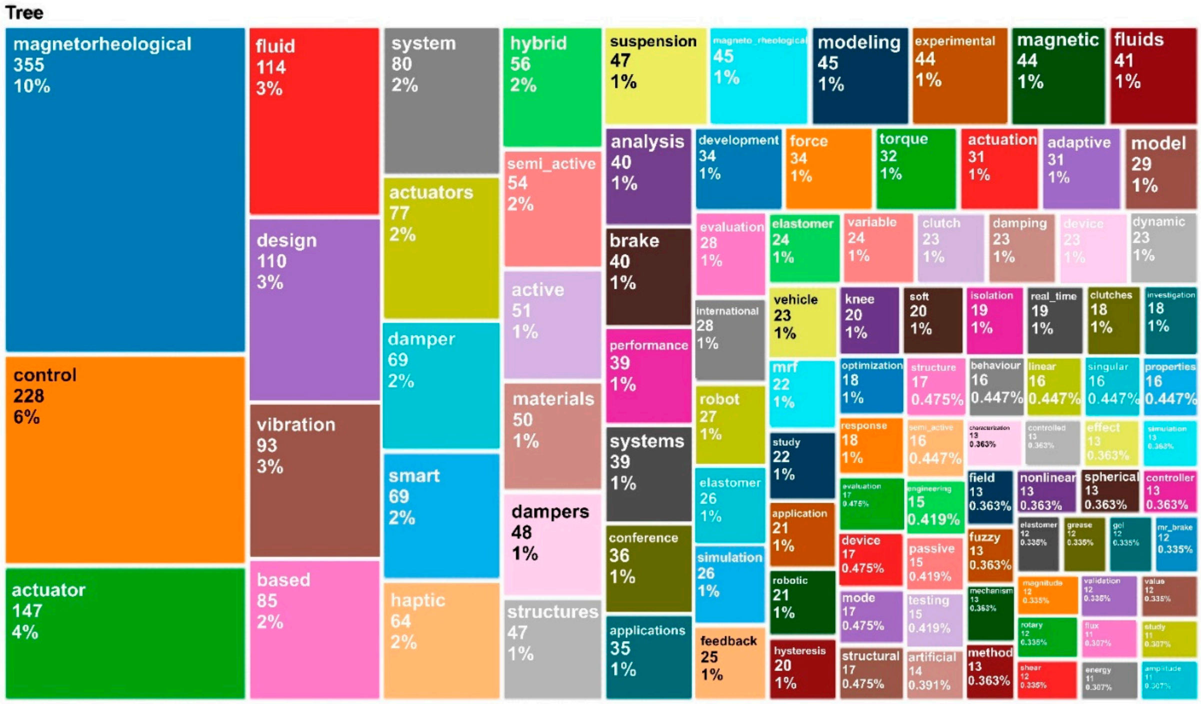


**Figure 20.** Treemaps of the keywords and scientific article titles used in the Scopus database.

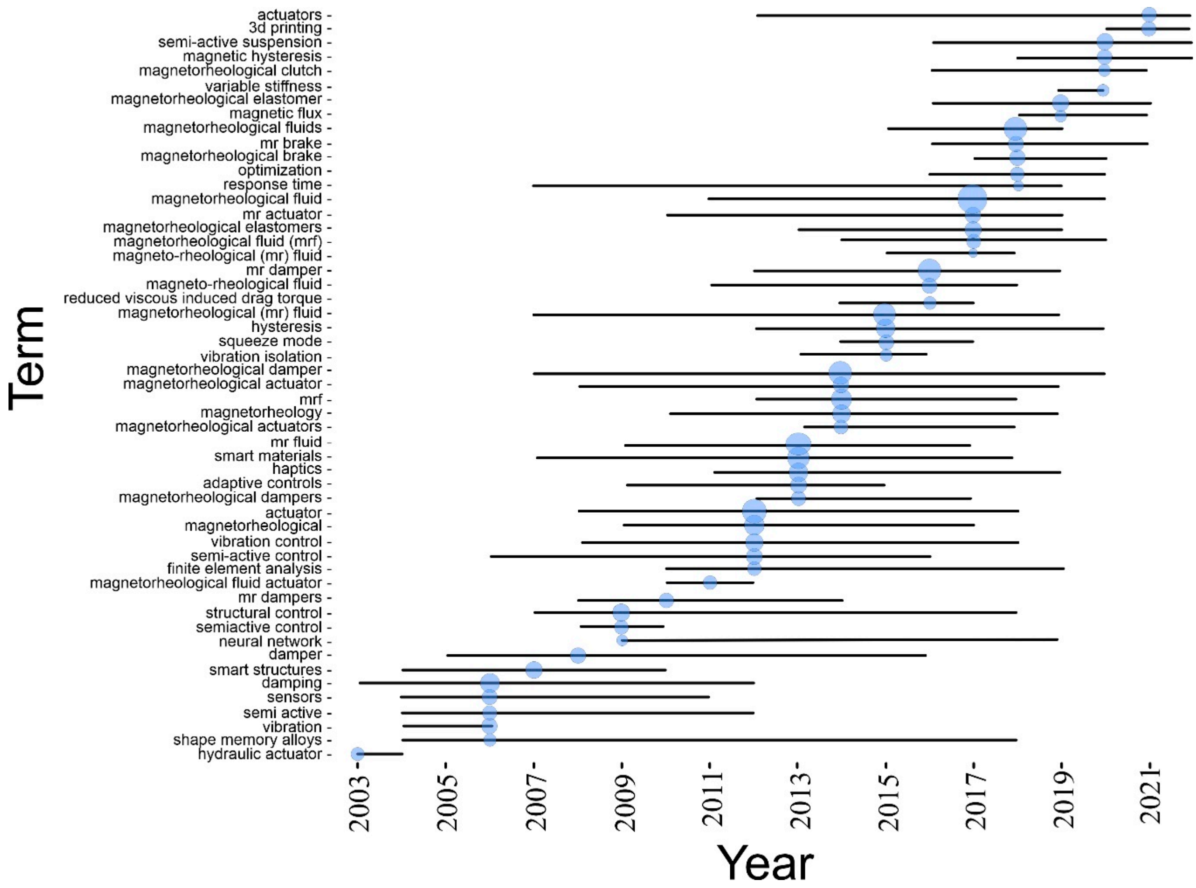


**Figure 21.** Trend topic of the control strategy used in the magnetorheological actuator.

Based on the control strategies that have been summarized, nine different vibration control strategies were reviewed from the perspective of application. The review study discovered that the control techniques connected with various actuators are comparable, despite the fact that the intrinsic characteristics of each actuator varies greatly. The skyhook control, PID control, LQR/LQG control, sliding mode control, fuzzy logic control, adaptive control, neural network control, H-infinity control, and hybrid control are all commonly used controllers for actuators. MRF and MRE are the most commonly used types of MR, with applications in automotive and building structures. The application of MR grease and gel has not been developed much in most fields. Therefore, the development of MR types of grease and gel, especially in the control system, is suggested for future works. It will be worthwhile developing a novel control method that combines the composite controller with a deep learning approach that has incredibly powerful calculation capabilities, allowing for the hysteresis fluctuation to be addressed in real-time. This approach has the potential to provide more precise control performance than the hysteresis model compensating method.

## 4. Conclusions

In this review article, the literature analysis of control strategies related to the use of a magnetorheological actuator was carried out by adopting various application systems. The literature study shows that magnetorheological actuators using MR fluid materials, elastomers, gels, greases, and foams can be used as effective actuators in various fields with their respective advantages. As a viscosity modifier, MR fluids demonstrate their effectiveness in responding to a magnetic field. However, in addition to their benefits, MR fluids have drawbacks, one of which is magnetic particle deposits, which frequently arise when the device is not in use. Unlike MR fluids, which can settle, MR elastomers overcome this limitation since the magnetic particles utilized are bound by a carrier matrix such as rubber in general. The flexibility of its application to a device is another advantage of MR elastomers. MR grease was initially developed to alleviate the low MR effect on magnetorheological elastomers as well as to address sedimentation concerns that arise in MRF. Grease, a non-Newtonian fluid, has been applied as a medium in MRG to allow suspended magnetic particles to resist gravity and avoid particle sedimentation. To make MR gels, soft magnetic particles are typically distributed in a cross-linked polymer matrix. The presence of a viscoelastic polymer matrix allows MR gels to overcome some of the limitations of MR fluids such as sealing and sedimentation issues. Furthermore, the magnetic particles in the MR elastomer are restricted by the hard rubber matrix, resulting in a significantly weaker MR effect than the MR gel. However, the high viscosity value of this type of material in off-state settings must be recognized as a weakness.

In addition, many control strategies in the use of actuators aimed at optimizing semi-active damping devices have also been introduced such as skyhook, LQR, sliding mode control, fuzzy logic control, H-infinity control, adaptive control, neural networks, and hybrid control. Of the various control strategies, the adaptive control strategy is the most popular. This is because the adaptive control strategy has advantages in its adaptive ability and ease of use for various fields of application. The next popular control strategy is the sliding mode control and neural networks. The use of popular adaptive control strategies is also evidenced by the mapping trend topics and the use of keywords based on the Scopus database. There have been no reviews or journals that have discussed control strategies in detail, so this paper contributes to mapping the control strategies used in MR materials in various applications. Based on previous research, research on MR grease and MR gel has at least been carried out, but only several studies have been made, namely, on automotive applications with skyhook, PID, and adaptive control strategies, and in building structure applications with skyhook, LQR/LQG, fuzzy, and neural network control strategies. It is finally remarked that other research needs to be conducted, especially in optimizing the control strategies for grease and gel type MR materials in possible practical applications because they have high opportunities, which was shown from the mapping that was elaborated in this review article.

**Author Contributions:** Conceptualization, U.U. and S.-B.C.; Methodology, B.W.L. and D.D.S.; Supervision, U.U., D.D.S. and S.-B.C.; Resources, A.M.; Writing—original draft preparation, A.M.;

Writing—review and editing B.W.L.; Validation, U.U. and S.-B.C.; Investigation, A.M. and B.W.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Hibah Non APBN UNS—International Collaboration 2023 (Kolaborasi Internasional).

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The authors wish to thank Universitas Sebelas Maret for the financial support through Hibah Non APBN UNS 2023 (Kolaborasi Internasional).

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Carlson, J.D.; Jolly, M.R. MR fluid, foam and elastomer devices. *Mechatronics* **2000**, *10*, 555–569. [CrossRef]
2. Shiraishi, T.; Misaki, H. Vibration Control by a Shear Type Semi-active Damper Using Magnetorheological Grease. *J. Phys. Conf. Ser.* **2016**, *744*, 012012. [CrossRef]
3. Yu, M.; Ju, B.; Fu, J.; Liu, S.; Choi, S.-B. Magnetoresistance characteristics of magnetorheological gel under a magnetic field. *Ind. Eng. Chem. Res.* **2014**, *53*, 4704–4710. [CrossRef]
4. Zhang, W.; Gong, X.; Xuan, S.; Jiang, W. Temperature-dependent mechanical properties and model of magnetorheological elastomers. *Ind. Eng. Chem. Res.* **2011**, *50*, 6704–6712. [CrossRef]
5. Ubaidillah, U.; Lenggana, B.W.; Son, L.; Imaduddin, F.; Widodo, P.J.; Harjana, H.; Doewes, R.I. A New Magnetorheological Fluids Damper for Unmanned Aerial Vehicles. *J. Adv. Res. Fluid Mech. Therm. Sci.* **2020**, *73*, 35–45. [CrossRef]
6. Mohamad, N.; Ubaidillah; Mazlan, S.; Choi, S.; Abdul Aziz, S.; Sugimoto, M. The Effect of Particle Shapes on the Field-Dependent Rheological Properties of Magnetorheological Greases. *Int. J. Mol. Sci.* **2019**, *20*, 1525. [CrossRef]
7. Mohamad, N.; Mazlan, S.A.; Ubaidillah; Choi, S.-B.; Nordin, M.F.M. The Field-Dependent Rheological Properties of Magnetorheological Grease Based on Carbonyl-Iron-Particles. *Smart Mater. Struct.* **2016**, *25*, 095043. [CrossRef]
8. Sahin, H.; Wang, X.; Gordaninejad, F. Temperature Dependence of Magneto-rheological Materials. *J. Intell. Mater. Syst. Struct.* **2009**, *20*, 2215–2222. [CrossRef]
9. Xu, Y.; Gong, X.; Xuan, S.; Zhang, W.; Fan, Y. A high-performance magnetorheological material: Preparation, characterization and magnetic-mechanic coupling properties. *Soft Matter* **2011**, *7*, 5246–5254. [CrossRef]
10. Xu, Y.; Liu, T.; Liao, G.; Lubineau, G. Magneto-dependent stress relaxation of magnetorheological gels. *Smart Mater. Struct.* **2017**, *26*, 115005. [CrossRef]
11. Meharthaj, H.; Sivakumar, S.M.; Arockiarajan, A. Significance of particle size on the improved performance of magnetorheological gels. *J. Magn. Magn. Mater.* **2019**, *490*, 165483. [CrossRef]
12. Ashtiani, M.; Hashemabadi, S.H.; Ghaffari, A. A review on the magnetorheological fluid preparation and stabilization. *J. Magn. Magn. Mater.* **2015**, *374*, 716–730. [CrossRef]
13. Li, W.; Sun, L.; Sun, J.; Chen, W.; Ma, F.; Leng, D. Experimental and numerical investigation on damping properties and energy dissipation mechanisms of magnetosensitive rubber. *J. Phys. Conf. Ser.* **2013**, *412*, 012030. [CrossRef]
14. Rahman, M.; Ong, Z.C.; Julai, S.; Ferdaus, M.M.; Ahamed, R. A review of advances in magnetorheological dampers: Their design optimization and applications. *J. Zhejiang Univ. Sci. A* **2017**, *18*, 991–1010. [CrossRef]
15. Rossi, A.; Orsini, F.; Scorza, A.; Botta, F.; Belfiore, N.P.; Sciuto, S.A. A review on parametric dynamic models of magnetorheological dampers and their characterization methods. *Actuators* **2018**, *7*, 16. [CrossRef]
16. Khazoom, C.; Caillouette, P.; Girard, A.; Plante, J.-S. A Supernumerary Robotic Leg Powered by Magnetorheological Actuators to Assist Human Locomotion. *IEEE Robot. Autom. Lett.* **2020**, *5*, 5143–5150. [CrossRef]
17. Do, X.P.; Choi, S.B. A state-of-the-art on smart materials actuators over the last decade: Control aspects for diverse applications. *Smart Mater. Struct.* **2022**, *31*, 053001. [CrossRef]
18. Choi, S.-B.; Han, Y.-M. *Magnetorheological Fluid Technology: Applications in Vehicle Systems*; RSC Publishing: Cambridge, UK, 2012; p. 301.
19. Karnopp, D. *Active and Semi-Active Vibration Isolation*; Springer: Berlin/Heidelberg, Germany, 1995.
20. Karnopp, D.; Crosby, M.J.; Harwood, R.A. Vibration Control Using Semi-Active Force Generators. *J. Eng. Ind.* **1974**, *96*, 619–626. [CrossRef]
21. Opie, S.; Yim, W. Design and control of a real-time variable modulus vibration isolator. *J. Intell. Mater. Syst. Struct.* **2011**, *22*, 113–125. [CrossRef]
22. Bucchi, F.; Forte, P.; Frendo, F. Analysis of the torque characteristic of a magnetorheological clutch using neural networks. *J. Intell. Mater. Syst. Struct.* **2015**, *26*, 680–689. [CrossRef]
23. Ha, S.H.; Seong, M.S.; Choi, S.B. Design and vibration control of military vehicle suspension system using magnetorheological damper and disc spring. *Smart Mater. Struct.* **2013**, *22*, 065022. [CrossRef]
24. Yang, S.-Y.; Han, C.; Shin, S.-U.; Choi, S.-B. Design and evaluation of a semi-active magneto-rheological mount for a wheel loader cabin. *Actuators* **2017**, *6*, 16. [CrossRef]

25. Kim, S.-H.; Yoon, D.-S.; Kim, G.-W.; Choi, S.-B.; Jeong, J.-Y.; Kim, J.-H.; Kim, S.-J.; Kim, I.-D. Road traveling test for vibration control of a wheel loader cabin installed with magnetorheological mounts. *J. Intell. Mater. Syst. Struct.* **2021**, *32*, 1336–1348. [CrossRef]
26. Choi, S.-B.; Li, W.; Yu, M.; Du, H.; Fu, J.; Do, P.X. State of the art of control schemes for smart systems featuring magneto-rheological materials. *Smart Mater. Struct.* **2016**, *25*, 043001. [CrossRef]
27. Yi, K.; Song, B.S. A new adaptive sky-hook control of vehicle semi-active suspensions. *Proc. Inst. Mech. Eng. Part J. Automob. Eng.* **1999**, *213*, 293–303. [CrossRef]
28. Ahmadian, M.; Pare, C.A. A Quarter-Car Experimental Analysis of Alternative Semiactive Control Methods. *J. Intell. Mater. Syst. Struct.* **2000**, *11*, 604–612. [CrossRef]
29. Choi, S.-B.; Nam, M.-H.; Lee, B.-K. Vibration Control of a MR Seat Damper for Commercial Vehicles. *J. Intell. Mater. Syst. Struct.* **2000**, *11*, 936–944. [CrossRef]
30. Choi, S.B.; Song, H.J.; Lee, H.H.; Lim, S.C.; Kim, J.H.; Choi, H.J. Vibration control of a passénger vehicle featuring magnetorheological engine mounts. *Int. J. Veh. Des.* **2003**, *33*, 2–16. [CrossRef]
31. Ahmadian, M.; Song, X.; Southward, S.C. No-Jerk Skyhook Control Methods for Semiactive Suspensions. *J. Vib. Acoust.* **2004**, *126*, 580–584. [CrossRef]
32. Batterbee, D.C.; Sims, N.D. Skyhook damping with linearized magnetorheological dampers. *Smart Struct. Mater.* **2004**, *5386*, 72–82. [CrossRef]
33. Choi, Y.-T.; Wereley, N.M.; Jeon, Y.-S. Semi-active vibration isolation using magnetorheological isolators. *J. Aircr.* **2005**, *42*, 1244–1251. [CrossRef]
34. Shen, Y.; Golnaraghi, M.F.; Heppler, G.R. Semi-active vibration control schemes for suspension systems using magnetorheological dampers. *JVC J. Vib. Control* **2006**, *12*, 3–24. [CrossRef]
35. Eslaminasab, N.; Golnaraghi, M.F. The Effect of Time Delay of the Semi-Active Dampers on the Performance of On-Off Control Schemes. In Proceedings of the Volume 9: Mechanical Systems and Control, Parts A, B, and C, Seattle, WA, USA, 1 January 2007; ASMEDC: Seattle, WA, USA, 2007; pp. 1911–1918.
36. Nguyen, Q.-H.; Choi, S.-B. Optimal design of MR shock absorber and application to vehicle suspension. *Smart Mater. Struct.* **2009**, *18*, 015013. [CrossRef]
37. Yao, H.J.; Fu, J.; Yu, M.; Peng, Y.X. Semi-active H∞ control of seat suspension with MR damper. *J. Phys. Conf. Ser.* **2013**, *412*, 012054. [CrossRef]
38. Balamurugan, L.; Jancirani, J.; Eltantawie, M.A. Generalized magnetorheological (MR) damper model and its application in semi-active control of vehicle suspension system. *Int. J. Automot. Technol.* **2014**, *15*, 419–427. [CrossRef]
39. Ramalingam, M.; Thirumurugan, M.A.; Kumar, T.A.; Jebaseelan, D.D.; Jebaraj, C. Response characteristics of car seat suspension using intelligent control policies under small and large bump excitations. *Int. J. Dyn. Control* **2020**, *8*, 545–557. [CrossRef]
40. Lee, A.S.; Andrew Gadsden, S.; Al-Shabi, M. Application of Nonlinear Estimation Strategies on a Magnetorheological Suspension System with Skyhook Control. In Proceedings of the 2020 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS), Vancouver, BC, Canada, 9–12 September 2020; IEEE: Vancouver, BC, Canada, 2020; pp. 1–6.
41. Chen, Q.; Zhang, Y.; Zhu, C.; Wu, J.; Zhuang, Y. A sky-hook sliding mode semiactive control for commercial truck seat suspension. *JVC J. Vib. Control* **2021**, *27*, 1201–1211. [CrossRef]
42. Chen, Z.-W.; Zhu, G. Semi-active control of metro vehicle based on flexible multi-body dynamics. *Jiaotong Yunshu Gongcheng Xuebao J. Traffic Transp. Eng.* **2021**, *21*, 298–309. [CrossRef]
43. Shiraishi, T.; Miida, Y.; Sugiyama, S.; Morishita, S. Typical characteristics of magnetorheological grease and its application to a controllable damper. *Nihon Kikai Gakkai Ronbunshu C Hen Trans. Jpn. Soc. Mech. Eng. Part C* **2011**, *77*, 2193–2200. [CrossRef]
44. Fotoohi, A.; Yousefi-Koma, A.; Yasrebi, N. Active control of train bogies with MR dampers. In *Smart Structures and Materials 2006: Industrial and Commercial Applications of Smart Structures Technologies*; SPIE: Bangkok, Thailand, 2006; Volume 6171, pp. 169–177. [CrossRef]
45. Oh, J.-S.; Shin, Y.-J.; Koo, H.-W.; Kim, H.-C.; Park, J.; Choi, S.-B. Vibration control of a semi-active railway vehicle suspension with magneto-rheological dampers. *Adv. Mech. Eng.* **2016**, *8*, 1687814016643638. [CrossRef]
46. Jin, T.; Liu, Z.; Sun, S.; Ren, Z.; Deng, L.; Yang, B.; Christie, M.D.; Li, W. Development and evaluation of a versatile semi-active suspension system for high-speed railway vehicles. *Mech. Syst. Signal Process.* **2020**, *135*, 106338. [CrossRef]
47. Shiraishi, T.; Nagamatsu, S.; Misaki, H. High dynamic range and high dispersion stability of a magnetorheological grease damper for semi-active vibration suppression. *J. Intell. Mater. Syst. Struct.* **2022**, *33*, 419–431. [CrossRef]
48. Choi, S.-B.; Lee, H.; Hong, S.-R.; Cheong, C. Control and response characteristics of a magnetorheological fluid damper for passenger vehicles. In Proceedings of the Smart Structures and Materials 2000: Smart Structures and Integrated Systems, Newport Beach, CA, USA, 6–9 March 2000; SPIE: Bangkok, Thailand, 2000; Volume 3985, pp. 438–443.
49. Ciocanel, C.; Elahinia, M.H.; Molyet, K.E.; Naganathan, N.G. Design Analysis and Control of a Magnetorheological Fluid Based Torque Transfer Device. *Int. J. Fluid Power* **2008**, *9*, 19–24. [CrossRef]
50. Rashid, M.M.; Rahim, N.A.; Hussain, M.A.; Rahman, M.A. Analysis and experimental study of magnetorheological-based damper for semiactive suspension system using fuzzy hybrids. *IEEE Trans. Ind. Appl.* **2011**, *47*, 1051–1059. [CrossRef]
51. Gad, S.; Metered, H.; Bassuiny, A.; Ghany, A.M.A. Vibration control of semi-active MR seat suspension for commercial vehicles using genetic PID controller. *Mech. Mach. Sci.* **2015**, *23*, 721–732. [CrossRef]

52. Muthalif, A.G.A.; Kasemi, H.B.; Nordin, N.H.D.; Rashid, M.M.; Razali, M.K.M. Semi-active vibration control using experimental model of magnetorheological damper with adaptive F-PID controller. *Smart Struct. Syst.* **2017**, *20*, 085–097.
53. Kim, H.K.; Kim, H.S.; Kim, Y.-K. Stiffness control of magnetorheological gels for adaptive tunable vibration absorber. *Smart Mater. Struct.* **2016**, *26*, 015016. [CrossRef]
54. Guo, Y.Q.; Zhang, J.; He, D.Q.; Li, J.B. Magnetorheological Elastomer Precision Platform Control Using OFFO-PID Algorithm. *Adv. Mater. Sci. Eng.* **2020**, *2020*, 1–9. [CrossRef]
55. Zhang, C.W.; Ou, J.P.; Zhang, J.Q. Parameter optimization and analysis of a vehicle suspension system controlled by magnetorheological fluid dampers. *Struct. Control Health Monit.* **2006**, *13*, 885–896. [CrossRef]
56. Lee, D.Y.; Park, Y.K.; Choi, S.B.; Lee, H.G. Design and vibration control of vehicle engine mount activated by MR fluid and piezoelectric actuator. *Second Int. Conf. Smart Mater. Nanotechnol. Eng.* **2009**, *7493*, 74936T. [CrossRef]
57. Nagarkar, M.P.; Vikhe, G.J.; Borole, K.R.; Nandedkar, V.M. Active control of quarter-car suspension system using linear quadratic regulator. *Int. J. Automot. Mech. Eng.* **2011**, *3*, 364–372. [CrossRef]
58. Sibielak, M.; Raczka, W.; Konieczny, J. Modified Clipped-LQR Method for Semi-Active Vibration Reduction Systems with Hysteresis. *Solid State Phenom.* **2011**, *177*, 10–22. [CrossRef]
59. Begin, M.-A.; Chouinard, P.; Lebel, L.-P.; Masson, P.; Pasco, Y.; Plante, J.-S.; Berry, A. Experimental Assessment of a Controlled Slippage Magnetorheological Actuator for Active Seat Suspensions. *IEEEASME Trans. Mechatron.* **2018**, *23*, 1800–1810. [CrossRef]
60. Wang, D.-H.; Liao, W.-H. Ride quality improvement ability of semi-active, active, and passive suspension systems for railway vehicles. *Smart Struct. Mater.* **2003**, *5056*, 201.
61. Sivrioglu, S.; Bolat, F.C. Switching linear quadratic Gaussian control of a flexible blade structure containing magnetorheological fluid. *Trans. Inst. Meas. Control* **2020**, *42*, 618–627. [CrossRef]
62. Weber, F.; Feltrin, G. Theoretical comparison of different controlled damping devices for cable vibration mitigation. *Smart Struct. Mater.* **2003**, *5056*, 412. [CrossRef]
63. Nagarajaiah, S.; Narasimhan, S. Smart base-isolated benchmark building. Part II: Phase I sample controllers for linear isolation systems. *Struct. Control Health Monit.* **2006**, *13*, 589–604. [CrossRef]
64. Swartz, R.A.; Lynch, J.P. Partial Decentralized Wireless Control Through Distributed Computing for Seismically Excited Civil Structures: Theory and Validation. In Proceedings of the 2007 American Control Conference, New York, NY, USA, 9–13 July 2007; IEEE: New York, NY, USA, 2007; pp. 2684–2689.
65. Tan, P.; Agrawal, A.K. Benchmark structural control problem for a seismically excited highway bridge-Part II: Phase I Sample control designs. *Struct. Control Health Monit.* **2009**, *16*, 530–548. [CrossRef]
66. Winter, B.D.; Velazquez, A.; Swartz, R.A. Low-force magneto-rheological damper design for small-scale structural control experimentation. *Sens. Smart Struct. Technol. Civ. Mech. Aerosp. Syst. 2015* **2015**, *9435*, 943511. [CrossRef]
67. Afshari, V.; Niri, M.F.; Kalamian, N. Robust fault detection and isolation in semi-actively controlled building structures using a set of unknown input observers. In Proceedings of the 2020 28th Iranian Conference on Electrical Engineering (ICEE), Tabriz, Iran, 26–28 May 2020; IEEE: Tabriz, Iran, 2020; pp. 1–6.
68. Tariq, M.A.; Usman, M.; Farooq, S.H.; Ullah, I.; Hanif, A. Investigation of the structural response of the mre-based mdof isolated structure under historic near- and far-fault earthquake loadings. *Appl. Sci.* **2021**, *11*, 2876. [CrossRef]
69. Lai, C.Y.; Liao, W.H. Vibration control of a suspension system via a magnetorheological fluid damper. *JVC J. Vib. Control* **2002**, *8*, 527–547. [CrossRef]
70. Chen, Y.; Zhao, Q. Sliding mode variable structure control for semi-active seat suspension in vehicles. *Harbin Gongcheng Daxue Xuebao J. Harbin Eng. Univ.* **2012**, *33*, 775–781. [CrossRef]
71. Jeon, J.; Han, Y.-M.; Lee, D.-Y.; Choi, S.-B. Vibration control of the engine body of a vehicle utilizing the magnetorheological roll mount and the piezostack right-hand mount. *Proc. Inst. Mech. Eng. Part J. Automob. Eng.* **2013**, *227*, 1562–1577. [CrossRef]
72. Yusop, M.A.M.; Ariff, M.H.M.; Zamzuri, H.; Mazlan, S.A. Longitudinal slip control using Magnetorheological brake via Second Order Sliding Mode Controller. In Proceedings of the 5th IEEE International Conference on Control System, Computing and Engineering, ICCSCE 2015, Penang, Malaysia, 25–27 November 2016; pp. 563–568. [CrossRef]
73. Zhang, H.; Wang, E.; Zhang, N.; Min, F.; Subash, R.; Su, C. Semi-active sliding mode control of vehicle suspension with magneto-rheological damper. *Chin. J. Mech. Eng. Engl. Ed.* **2015**, *28*, 63–75. [CrossRef]
74. Ning, D.; Sun, S.; Wei, L.; Zhang, B.; Du, H.; Li, W. Vibration reduction of seat suspension using observer based terminal sliding mode control with acceleration data fusion. *Mechatronics* **2017**, *44*, 71–83. [CrossRef]
75. Yoon, D.-S.; Kim, G.-W.; Choi, S.-B. Response time of magnetorheological dampers to current inputs in a semi-active suspension system: Modeling, control and sensitivity analysis. *Mech. Syst. Signal Process.* **2021**, *146*, 106999. [CrossRef]
76. Zhu, M.; Lv, G.; Zhang, C.; Jiang, J.; Wang, H. Delay-Dependent Sliding Mode Variable Structure Control of Vehicle Magneto-Rheological Semi-Active Suspension. *IEEE Access* **2022**, *10*, 51128–51141. [CrossRef]
77. Nguyen, S.D.; Nguyen, Q.H. Design of active suspension controller for train cars based on sliding mode control, uncertainty observer and neuro-fuzzy system. *J. Vib. Control* **2015**, *23*, 1334–1353. [CrossRef]
78. Lee, T.Y.; Chen, P.C. Experimental and Analytical Study of Sliding Mode Control for Isolated Bridges with MR Dampers. *J. Earthq. Eng.* **2011**, *15*, 564–581. [CrossRef]
79. Ha, Q.P.; Nguyen, M.T.; Li, J.; Kwok, N.M. Smart structures with current-driven MR dampers: Modeling and second-order sliding mode control. *IEEEASME Trans. Mechatron.* **2013**, *18*, 1702–1712. [CrossRef]

80. Balamonica, K.; Kumar, K.S.; Gopalakrishnan, N. *Semi-Active Control of Structures Using Magnetorheological Elastomer-Based Seismic Isolators and Sliding Mode Control*; Springer: Singapore, 2019; Volume 12, ISBN 9789811303654.
81. Altabey, W.A.; Noori, M.; Li, Z.; Zhao, Y.; Aval, S.B.B.; Farsangi, E.N.; Ghiasi, R.; Silik, A. A novel MRE adaptive seismic isolator using curvelet transform identification. *Appl. Sci. Switz.* **2021**, *11*, 11409. [CrossRef]
82. Devdutt; Aggarwal, M.L. Fuzzy control of passenger ride performance using MR shock absorber suspension in quarter car model. *Int. J. Dyn. Control* **2014**, *3*, 463–469. [CrossRef]
83. Felix-Herran, L.C.; Soto, R.; Rodriguez-Ortiz, J.D.J.; Ramirez-Mendoza, R.A. Fuzzy control for a semi-active vehicle suspension with a magnetorheological damper. In Proceedings of the 2009 European Control Conference, ECC 2009, Budapest, Hungary, 23–26 August 2009; pp. 4398–4403. [CrossRef]
84. Nguyen, S.D.; Nguyen, Q.H.; Choi, S.-B. A hybrid clustering based fuzzy structure for vibration control—Part 2: An application to semi-active vehicle seat-suspension system. *Mech. Syst. Signal Process.* **2015**, *56*, 288–301. [CrossRef]
85. Tang, X.; Du, H.; Sun, S.; Ning, D.; Xing, Z.; Li, W. Takagi-Sugeno Fuzzy Control for Semi-Active Vehicle Suspension with a Magnetorheological Damper and Experimental Validation. *IEEEASME Trans. Mechatron.* **2017**, *22*, 291–300. [CrossRef]
86. Qian, L.J.; Xin, F.L.; Bai, X.X.; Wereley, N.M. State observation–based control algorithm for dynamic vibration absorbing systems featuring magnetorheological elastomers: Principle and analysis. *J. Intell. Mater. Syst. Struct.* **2017**, *28*, 2539–2556. [CrossRef]
87. Li, Z.; Gong, Y.; Wang, J. Optimal control with fuzzy compensation for a magnetorheological fluid damper employed in a gun recoil system. *J. Intell. Mater. Syst. Struct.* **2018**, *30*, 677–688. [CrossRef]
88. Amini, F.; Mohajeri, S.A.; Javanbakht, M. Semi-active control of isolated and damaged structures using online damage detection. *Smart Mater. Struct.* **2015**, *24*, 105002. [CrossRef]
89. Bathaei, A.; Ramezani, M.; Ghorbani-Tanha, A.K. Type-1 and Type-2 Fuzzy Logic Control Algorithms for Semi-Active Seismic Vibration Control of the College Urban Bridge Using MR Dampers. *Civ. Eng. Infrastruct. J.* **2017**, *50*, 333–351. [CrossRef]
90. Braz-César, M.T.; Folhento, P.L.P.; Barros, R.C. Fuzzy controller optimization using a genetic algorithm for non-collocated semi-active MR based control of a three-DOF framed struture. In Proceedings of the 13th APCA International Conference on Control and Soft Computing, CONTROLO 2018—Proceedings, Ponta Delgada, Portugal, 4–6 June 2018; pp. 364–367. [CrossRef]
91. Hormozabad, S.J.; Ghorbani-Tanha, A.K. Semi-active fuzzy control of Lali Cable-Stayed Bridge using MR dampers under seismic excitation. *Front. Struct. Civ. Eng.* **2020**, *14*, 706–721. [CrossRef]
92. Jung, H.J.; Eem, S.H.; Jang, D.D.; Koo, J.H. Seismic performance analysis of a smart base-isolation system considering dynamics of MR elastomers. *J. Intell. Mater. Syst. Struct.* **2011**, *22*, 1439–1450. [CrossRef]
93. Yang, J.; Sun, S.; Tian, T.; Li, W.; Du, H.; Alici, G.; Nakano, M. Development of a novel multi-layer MRE isolator for suppression of building vibrations under seismic events. *Mech. Syst. Signal Process.* **2016**, *70*, 811–820. [CrossRef]
94. Nguyen, X.B.; Komatsuzaki, T.; Iwata, Y.; Asanuma, H. Fuzzy Semiactive Vibration Control of Structures Using Magnetorheological Elastomer. *Shock Vib.* **2017**, *2017*, 1–15. [CrossRef]
95. Nguyen, X.B.; Komatsuzaki, T.; Iwata, Y.; Asanuma, H. Modeling and semi-active fuzzy control of magnetorheological elastomer-based isolator for seismic response reduction. *Mech. Syst. Signal Process.* **2018**, *101*, 449–466. [CrossRef]
96. Ma, Y.-Q.; Qiu, H.-X. Fuzzy neural network control to suppress seismic responses of continuous girder railway bridges using new magneto rheological grease damper. *Zhendong Yu Chongji J. Vib. Shock* **2015**, *34*, 66–73. [CrossRef]
97. Song, X.; Ahmadian, M. Study of Semiactive Adaptive Control Algorithms with Magneto-Rheological Seat Suspension. *SAE Tech. Pap.* **2004**, *1*, 1–14. [CrossRef]
98. Krauze, P.; Kasprzyk, J. Vibration control in quarter-car model with magnetorheological dampers using FxLMS algorithm with preview. In Proceedings of the 2014 European Control Conference (ECC), Strasbourg, France, 24–27 June 2014; IEEE: Strasbourg, France, 2014; pp. 1005–1010.
99. Phu, D.X.; Shin, D.K.; Choi, S.B. Design of a new adaptive fuzzy controller and its application to vibration control of a vehicle seat installed with an MR damper. *Smart Mater. Struct.* **2015**, *24*, 85012. [CrossRef]
100. Phu, D.X.; Huy, T.D.; Choi, S.B. Robust Adaptive Controls of a Vehicle Seat Suspension System. *Adapt. Robust Control Syst.* **2017**. [CrossRef]
101. Yıldız, A.S.; Sivrioğlu, S. Constrained adaptive backstepping control of a semi-active suspension considering suspension travel limits. *Asian J. Control* **2021**, *23*, 1380–1393. [CrossRef]
102. Basargan, H.; Mihály, A.; Gáspár, P.; Sename, O. An LPV-Based Online Reconfigurable Adaptive Semi-Active Suspension Control with MR Damper. *Energies* **2022**, *15*, 3648. [CrossRef]
103. Truong, H.T.; Nguyen, X.B.; Bui, C.M. Singularity-Free Adaptive Controller for Uncertain Hysteresis Suspension Using Magnetorheological Elastomer-Based Absorber. *Shock Vib.* **2022**, *2022*, 1–17. [CrossRef]
104. Nguyen, S.D.; Jung, D.; Choi, S.-B. A Robust Vibration Control of a Magnetorheological Damper Based Railway Suspension Using a Novel Adaptive Type 2 Fuzzy Sliding Mode Controller. *Shock Vib.* **2017**, *2017*, e7306109. [CrossRef]
105. Sakai, C.; Ohmori, H.; Sano, A. Modeling of MR Damper with Hysteresis for Adaptive Vibration Control. In Proceedings of the 42nd IEEE International Conference on Decision and Control, Maui, HI, USA, 9 December 2003; Volume 4, pp. 3840–3845.
106. Terasawa, T.; Sakai, C.; Ohmori, H.; Sano, A. Adaptive identification of MR damper for vibration control. In Proceedings of the 2004 43rd IEEE Conference on Decision and Control (CDC), Paradise Island, Bahamas, 14 December 2004; Volume 3, pp. 2297–2303.

107. Chen, C.; Ricles, J.M. Experimental Evaluation of an Adaptive Actuator Control Scheme for Real-Time Tests of Large-Scale Magneto-Rheological Damper Under Variable Current Inputs. In Proceedings of the Volume 1: Active Materials, Mechanics and Behavior, Modeling, Simulation and Control, Oxnard, CA, USA, 1 January 2009; ASMEDC: Oxnard, CA, USA, 2009; pp. 457–462.
108. Tu, J.Y.; Lin, P.Y.; Stoten, D.P.; Li, G. Testing of dynamically substructured, base-isolated systems using adaptive control techniques. *Earthq. Eng. Struct. Dyn.* **2009**, *39*, 661–681. [CrossRef]
109. Chen, C.; Ricles, J.M.; Sause, R.; Christenson, R. Experimental evaluation of an adaptive inverse compensation technique for real-time simulation of a large-scale magneto-rheological fluid damper. *Smart Mater. Struct.* **2010**, *19*, 025017. [CrossRef]
110. Karimi, H.R.; Zapateiro, M.; Luo, N. Application of adaptive wavelet networks for vibration control of base isolated structures. *Int. J. Wavelets Multiresolution Inf. Process.* **2010**, *8*, 773–791. [CrossRef]
111. Bitaraf, M.; Hurlebaus, S.; Barroso, L.R. Active and Semi-active Adaptive Control for Undamaged and Damaged Building Structures Under Seismic Load: Active and semi-active adaptive control for building. *Comput.-Aided Civ. Infrastruct. Eng.* **2012**, *27*, 48–64. [CrossRef]
112. Chen, P.-C.; Chang, C.-M.; Spencer, B.F.; Tsai, K.-C. Adaptive model-based tracking control for real-time hybrid simulation. *Bull. Earthq. Eng.* **2015**, *13*, 1633–1653. [CrossRef]
113. Chen, X.; Li, J.; Li, Y.; Gu, X. Lyapunov-based semi-active control of adaptive base isolation system employing magnetorheological elastomer base isolators. *Earthq. Struct.* **2016**, *11*, 1077–1099. [CrossRef]
114. Nguyen, X.B.; Komatsuzaki, T.; Iwata, Y.; Asanuma, H. Robust adaptive controller for semi-active control of uncertain structures using a magnetorheological elastomer-based isolator. *J. Sound Vib.* **2018**, *434*, 192–212. [CrossRef]
115. Susheelkumar, G.N.; Murigendrappa, S.M.; Gangadharan, K.V. Theoretical and experimental investigation of model-free adaptive fuzzy sliding mode control for MRE based adaptive tuned vibration absorber. *Smart Mater. Struct.* **2019**, *28*, 45017. [CrossRef]
116. Zapateiro, M.; Luo, N.; Karimi, H.R.; Vehí, J. Vibration control of a class of semiactive suspension system using neural network and backstepping techniques. *Mech. Syst. Signal Process.* **2009**, *23*, 1946–1953. [CrossRef]
117. Zapateiro, M.; Luo, N.S.; Harimi, H.R. Neural Network—Backstepping Control for Vibration Reduction in a Magnetorheological Suspension System. *Solid State Phenom.* **2009**, *147–149*, 839–844. [CrossRef]
118. Metered, H.; Bonello, P.; Oyadiji, S.O. The experimental identification of magnetorheological dampers and evaluation of their controllers. *Mech. Syst. Signal Process.* **2010**, *24*, 976–994. [CrossRef]
119. Metered, H.; Bonello, P.; Oyadiji, S.O. An investigation into the use of neural networks for the semi-active control of a magnetorheologically damped vehicle suspension. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2010**, *224*, 829–848. [CrossRef]
120. Ubaidillah; Priyandoko, G.; Nizam, M.; Yahya, I. Modeling of Magnetorheological Damper Using Back Propagation Neural Network. *Adv. Mater. Res.* **2014**, *896*, 396–400. [CrossRef]
121. Guo, D.L.; Hu, H.Y.; Yi, J.Q. Neural Network Control for a Semi-Active Vehicle Suspension with a Magnetorheological Damper. *J. Vib. Control* **2004**, *10*, 461–471. [CrossRef]
122. Liu, C.; Hemmatian, M.; Sedaghati, R.; Wen, G. Development and Control of Magnetorheological Elastomer-Based Semi-active Seat Suspension Isolator Using Adaptive Neural Network. *Front. Mater.* **2020**, *7*, 171. [CrossRef]
123. Nguyen, X.B.; Komatsuzaki, T.; Truong, H.T. Novel semiactive suspension using a magnetorheological elastomer (MRE)-based absorber and adaptive neural network controller for systems with input constraints. *Mech. Sci.* **2020**, *11*, 465–479. [CrossRef]
124. Yu, Y.; Li, Y.; Li, J. Nonparametric modeling of magnetorheological elastomer base isolator based on artificial neural network optimized by ant colony algorithm. *J. Intell. Mater. Syst. Struct.* **2015**, *26*, 1789–1798. [CrossRef]
125. Fu, J.; Liao, G.; Yu, M.; Li, P.; Lai, J. NARX neural network modeling and robustness analysis of magnetorheological elastomer isolator. *Smart Mater. Struct.* **2016**, *25*, 125019. [CrossRef]
126. Gu, X.; Yu, Y.; Li, J.; Li, Y. Semi-active control of magnetorheological elastomer base isolation system utilising learning-based inverse model. *J. Sound Vib.* **2017**, *406*, 346–362. [CrossRef]
127. Yu, Y.; Wang, C.; Gu, X.; Li, J. A novel deep learning-based method for damage identification of smart building structures. *Struct. Health Monit.* **2019**, *18*, 143–163. [CrossRef]
128. Gu, X.; Yu, Y.; Li, Y.; Li, J.; Askari, M.; Samali, B. Experimental study of semi-active magnetorheological elastomer base isolation system using optimal neuro fuzzy logic control. *Mech. Syst. Signal Process.* **2019**, *119*, 380–398. [CrossRef]
129. Brancati, R.; Di Massa, G.; Pagano, S.; Petrillo, A.; Santini, S. A combined neural network and model predictive control approach for ball transfer unit–magnetorheological elastomer–based vibration isolation of lightweight structures. *JVC J. Vib. Control* **2020**, *26*, 1668–1682. [CrossRef]
130. Perez-Ramirez, C.A.; Dominguez-Gonzalez, A.; Toledano-Ayala, M.; Pablo Amezquita-Sanchez, J.; Valtierra-Rodriguez, M. Model reference Neural Network-based methodology for vibration control in a five-story steel structure. In Proceedings of the 2020 17th International Conference on Electrical Engineering, Computing Science and Automatic Control (CCE), Mexico City, Mexico, 11–13 November 2020; IEEE: Mexico City, Mexico, 2020; pp. 1–6.
131. Choi, S.B.; Sung, K.G. Vibration control of magnetorheological damper system subjected to parameter variations. *Int. J. Veh. Des.* **2008**, *46*, 94–110. [CrossRef]
132. Prabakar, R.S.; Sujatha, C.; Narayanan, S. Optimal semi-active preview control response of a half car vehicle model with magnetorheological damper. *J. Sound Vib.* **2009**, *326*, 400–420. [CrossRef]
133. Fallah, M.S.; Bhat, R.B.; Xie, W.F. Optimized control of semiactive suspension systems using H∞ robust control theory and current signal estimation. *IEEEASME Trans. Mechatron.* **2012**, *17*, 767–778. [CrossRef]

134. Félix-Herrán, L.C.; Mehdi, D.; Rodrguez-Ortiz, J.D.J.; Soto, R.; Ramrez-Mendoza, R. H∞ control of a suspension with a magnetorheological damper. *Int. J. Control* **2012**, *85*, 1026–1038. [CrossRef]
135. Wu, J.; Zhou, H.; Liu, Z.; Gu, M. A load-dependent PWA-H∞ controller for semi-active suspensions to exploit the performance of MR dampers. *Mech. Syst. Signal Process.* **2019**, *127*, 441–462. [CrossRef]
136. Félix-Herrán, L.C.; Mehdi, D.; de Jesús Rodríguez-Ortiz, J.; Benitez, V.H.; Ramirez-Mendoza, R.A.; Soto, R. Disturbance Rejection in a One-Half Semiactive Vehicle Suspension by means of a *Fuzzy-*$H_\infty$ Controller. *Shock. Vib.* **2019**, *2019*, 4532635. [CrossRef]
137. Hosseini, S.S.; Marzbanrad, J. Robust H∞ Controller in a MRF Engine Mount for Improving the Vehicle Ride Comfort. *Int. J. Acoust. Vib.* **2020**, *25*, 219–225. [CrossRef]
138. Bolat, F.; Sivrioglu, S. Active Control of a Small-Scale Wind Turbine Blade Containing Magnetorheological Fluid. *Micromachines* **2018**, *9*, 80. [CrossRef] [PubMed]
139. Bolat, F.C.; Sivrioglu, S. Active vibration suppression of elastic blade structure: Using a novel magnetorheological layer patch. *J. Intell. Mater. Syst. Struct.* **2018**, *29*, 3792–3803. [CrossRef]
140. Sivrioglu, S.; Bolat, F.C. Active Robust Control of Elastic Blade Element Containing Magnetorheological Fluid. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *326*, 012017. [CrossRef]
141. Zapateiro, M.; Karimi, H.R.; Luo, N.; Phillips, B.M.; Spencer, B.F. A mixed H2/H∞-based semiactive control for vibration mitigation in flexible structures. In Proceedings of the 48h IEEE Conference on Decision and Control (CDC) Held Jointly with 2009 28th Chinese Control Conference, Shanghai, China, 15 December 2009; IEEE: Shanghai, China, 2009; pp. 2186–2191.
142. Gao, X.; Castaneda, N.; Dyke, S.J. Experimental Validation of a Generalized Procedure for MDOF Real-Time Hybrid Simulation. *J. Eng. Mech.* **2014**, *140*, 04013006. [CrossRef]
143. Félix-Herrán, L.C.; de Jesús Rodríguez-Ortiz, J.; Soto, R.; Ramírez-Mendoza, R. Modeling and Control for a Semi-active Suspension with a Magnetorheological Damper Including the Actuator Dynamics. In Proceedings of the 2008 Electronics, Robotics and Automotive Mechanics Conference (CERMA '08), Cuernavaca, Mexico, 3 October 2008; Volume 2008, pp. 338–343. [CrossRef]
144. Ding, R.; Wang, R.; Meng, X.; Liu, W.; Chen, L. Intelligent switching control of hybrid electromagnetic active suspension based on road identification. *Mech. Syst. Signal Process.* **2021**, *152*, 107355. [CrossRef]
145. Luong, Q.V.; Jang, D.-S.; Hwang, J.-H. Robust adaptive control for an aircraft landing gear equipped with a magnetorheological damper. *Appl. Sci. Switz.* **2020**, *10*, 1459. [CrossRef]
146. Park, K.-S.; Jung, H.-J.; Spencer, B.F.; Lee, I.-W. Hybrid control systems for seismic protection of a phase II benchmark cable-stayed bridge. *J. Struct. Control* **2003**, *10*, 231–247. [CrossRef]
147. Fisco, N.R.; Adeli, H. Smart structures: Part I—Active and semi-active control. *Sci. Iran.* **2011**, *18*, 275–284. [CrossRef]
148. Chen, B.; Zheng, J. Intelligent hybrid control of smart-material structure system by using magnetorheological fluids and isolators. *Adv. Sci. Lett.* **2012**, *5*, 836–839. [CrossRef]
149. Kemerli, M.; Şahin, Ö.; Yazıcı, İ.; Çağlar, N.; Engin, T. Comparison of discrete-time sliding mode control algorithms for seismic control of buildings with magnetorheological fluid dampers. *JVC J. Vib. Control* **2022**. [CrossRef]
150. Wirawan, J.W.; Ubaidillah, U.; Lenggana, B.W.; Purnomo, E.D.; Widyarso, W.; Mazlan, S.A. Design and Performance Analysis of Magnetorheological Valve for Upside-Down Damper. *J. Adv. Res. Fluid Mech. Therm. Sci.* **2019**, *63*, 164–173.
151. Dutta, S.; Choi, S.-B. Control of a shimmy vibration in vehicle steering system using a magneto-rheological damper. *J. Vib. Control* **2018**, *24*, 797–807. [CrossRef]
152. Phu Do, X.; Hung Nguyen, Q.; Choi, S.-B. New hybrid optimal controller applied to a vibration control system subjected to severe disturbances. *Mech. Syst. Signal Process.* **2019**, *124*, 408–423. [CrossRef]
153. Phu, D.X.; Quoc Hung, N.; Choi, S.-B. A novel adaptive controller featuring inversely fuzzified values with application to vibration control of magneto-rheological seat suspension system. *J. Vib. Control* **2018**, *24*, 5000–5018. [CrossRef]
154. Oh, J.-S.; Lee, T.-H.; Choi, S.-B. Design and Analysis of a New Magnetorheological Damper for Generation of Tunable Shock-Wave Profiles. *Shock Vib.* **2018**, *2018*, e8963491. [CrossRef]
155. Kim, H.-C.; Oh, J.-S.; Choi, S.-B. The field-dependent shock profiles of a magnetorhelogical damper due to high impact: An experimental investigation. *Smart Mater. Struct.* **2014**, *24*, 025008. [CrossRef]
156. Zając, K.; Kowal, J.; Konieczny, J. Skyhook Control Law Extension for Suspension with Nonlinear Spring Characteristics. *Energies* **2022**, *15*, 754. [CrossRef]
157. Hiemenz, G.J.; Hu, W.; Wereley, N.M. Semi-Active Magnetorheological Helicopter Crew Seat Suspension for Vibration Isolation. *J. Aircr.* **2008**, *45*, 945–953. [CrossRef]
158. Wang, D.H.; Liao, W.H. Semi-active suspension systems for railway vehicles using magnetorheological dampers. Part I: System integration and modelling. *Veh. Syst. Dyn.* **2009**, *47*, 1305–1325. [CrossRef]
159. Sun, S.; Deng, H.; Li, W.; Du, H.; Ni, Y.Q.; Zhang, J.; Yang, J. Improving the critical speeds of high-speed trains using magnetorheological technology. *Smart Mater. Struct.* **2013**, *22*, 115012. [CrossRef]
160. Lau, Y.K.; Liao, W.H. Design and Analysis of Magnetorheological Dampers for Train Suspension. *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit* **2005**, *219*, 261–276. [CrossRef]
161. Ha, S.H.; Choi, S.-B.; Lee, K.-S.; Cho, M.-W. Ride Quality Evaluation of Railway Vehicle Suspension System Featured by Magnetorheological Fluid Damper. *Adv. Sci. Lett.* **2012**, *12*, 209–213. [CrossRef]
162. Wei, X.; Zhu, M.; Jia, L. A semi-active control suspension system for railway vehicles with magnetorheological fluid dampers. *Veh. Syst. Dyn.* **2016**, *54*, 982–1003. [CrossRef]

163. Milwitzky, B.; Cook, F.E. *Analysis of Landing-Gear Behavior*; World Scientific: Singapore, 2002.
164. Sadraey, M. Landing gear design. In *Aircraft Design: A System Engineering Approach*; Wiley: New York, NY, USA, 2012; pp. 479–544.
165. Skorupka, Z.; Harla, R. Investigations on Landing Gear Shock Absorber Active Force Control. In Proceedings of the 32nd Congress of the International Council of the Aeronautical Sciences, ICAS2020_0513, Shanghai, China, 6–10 September 2021.
166. Holnicki-Szulc, J.; Pawłowski, P.; Mikułowski, M.; Graczykowski, C. *Adaptive Impact Absorption and Applications to Landing Devices*; Springer: Berlin/Heidelberg, Germany, 2008; pp. 609–613.
167. Mikułowski, G.M.; Holnicki-Szulc, J. Adaptive landing gear concept—Feedback control validation. *Smart Mater. Struct.* **2007**, *16*, 2146. [CrossRef]
168. Han, C.; Kim, B.-G.; Choi, S.-B. Design of a New Magnetorheological Damper Based on Passive Oleo-Pneumatic Landing Gear. *J. Aircr.* **2018**, *55*, 2510–2520. [CrossRef]
169. Luong, Q.V.; Jang, D.-S.; Hwang, J.-H. Semi-Active Control for a Helicopter with Multiple Landing Gears Equipped with Magnetorheological Dampers. *Appl. Sci.* **2021**, *11*, 3667. [CrossRef]
170. Nguyen, Q.H.; Phu, D.X.; Park, J.H.; Choi, S.B.; Kang, O.H. Development of high damping magneto-rheological mount for ship engines. *Appl. Mech. Mater.* **2013**, *336–338*, 953–959. [CrossRef]
171. Phu, D.X.; Quoc, N.V.; Park, J.H.; Choi, S.B. Design of a novel adaptive fuzzy sliding mode controller and application for vibration control of magnetorheological mount. *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.* **2014**, *228*, 2285–2302. [CrossRef]
172. Lu, K.; Liu, L.; Yang, Z.; Gong, X.; Rao, Z.; Xie, Z. Semi-active dynamic absorber of a ship propulsion shafting based on MREs. *Zhendong Yu Chongji J. Vib. Shock* **2017**, *36*, 36–42. [CrossRef]
173. Yang, Z.; Qin, C.; Rao, Z.; Ta, N.; Gong, X. Design and analyses of axial semi-active dynamic vibration absorbers based on magnetorheological elastomers. *J. Intell. Mater. Syst. Struct.* **2014**, *25*, 2199–2207. [CrossRef]
174. Zhong, J.-P.; Cheng, Y.-S. MR damper based semi-active vibration fuzzy control on the mast of warships. *Chuan Bo Li Xue J. Ship Mech.* **2008**, *12*, 657–662.
175. Li, Y.; Li, J.; Tian, T.; Li, W. A highly adjustable magnetorheological elastomer base isolator for applications of real-time adaptive control. *Smart Mater. Struct.* **2013**, *22*, 095020. [CrossRef]
176. Sun, Y.; Ke, S.; Wang, G.; Liu, Z. Control Strategy Simulation Analysis of a New Micro-cultivator MR Elastomer Vibration Isolation System. *Gongcheng Kexue Yu Jishu Adv. Eng. Sci.* **2020**, *52*, 218–225. [CrossRef]
177. Masa'id, A.; Lenggana, B.W.; Ubaidillah; Imaduddin, F.; Muslih, Y.; Harjana; Priyandoko, G.; Ardion, F.S. Effect of Damping and Stiffness Constants on the Vibration Properties of Seismic Building: Simulation Approach. *Lect. Notes Mech. Eng.* **2022**, *1*, 327–331. [CrossRef]
178. Li, L.; Liang, H. Semiactive Control of Structural Nonlinear Vibration Considering the MR Damper Model. *J. Aerosp. Eng.* **2018**, *31*, 04018095. [CrossRef]
179. Ohtori, Y.; Christenson, R.E.; Spencer, B.F.; Dyke, S.J. Benchmark Control Problems for Seismically Excited Nonlinear Buildings. *J. Eng. Mech.* **2004**, *130*, 366–385. [CrossRef]
180. Abdeddaim, M.; Ounis, A.; Shrimali, M.K.; Datta, T.K. Retrofitting of a weaker building by coupling it to an adjacent stronger building using MR dampers. *Struct. Eng. Mech.* **2017**, *62*, 197–208. [CrossRef]
181. Al-Fahdawi, O.A.S.; Barroso, L.R.; Soares, R.W. Utilizing the Adaptive Control in Mitigating the Seismic Response of Adjacent Buildings Connected with MR Dampers. In Proceedings of the 2018 Annual American Control Conference (ACC), Milwaukee, WI, USA, 27–29 June 2018; pp. 912–917.
182. Fali, L.; Djermane, M.; Zizouni, K.; Sadek, Y. Adaptive sliding mode vibrations control for civil engineering earthquake excited structures. *Int. J. Dyn. Control* **2019**, *7*, 955–965. [CrossRef]
183. Weber, F.; Distl, H. Amplitude and frequency independent cable damping of Sutong Bridge and Russky Bridge by magnetorheological dampers: Amplitude and frequency independent cable damping. *Struct. Control Health Monit.* **2015**, *22*, 237–254. [CrossRef]
184. Heo, G.; Joonryong, J. Semi-active vibration control in cable-stayed bridges under the condition of random wind load. *Smart Mater. Struct.* **2014**, *23*, 075027. [CrossRef]
185. Duan, Y.F.; Ni, Y.Q.; Ko, J.M. State-Derivative Feedback Control of Cable Vibration Using Semiactive Magnetorheological Dampers. *Comput.-Aided Civ. Infrastruct. Eng.* **2005**, *20*, 431–449. [CrossRef]
186. Xu, Y.-W.; Xu, Z.-D.; Guo, Y.-Q.; Zhou, M.; Zhao, Y.-L.; Yang, Y.; Dai, J.; Zhang, J.; Zhu, C.; Ji, B.-H.; et al. A programmable pseudo negative stiffness control device and its role in stay cable vibration control. *Mech. Syst. Signal Process.* **2022**, *173*, 109054. [CrossRef]
187. Weber, F. Semi-active vibration absorber based on real-time controlled MR damper. *Mech. Syst. Signal Process.* **2014**, *46*, 272–288. [CrossRef]
188. Zhang, X.Z.; Li, W.H. Adaptive tuned dynamic vibration absorbers working with MR elastomers. *Smart Struct. Syst.* **2009**, *5*, 517–529. [CrossRef]
189. Choi, S.-B.; Hong, S.-R.; Sung, K.-G.; Sohn, J.-W. Optimal control of structural vibrations using a mixed-mode magnetorheological fluid mount. *Int. J. Mech. Sci.* **2008**, *50*, 559–568. [CrossRef]
190. Hong, S.-R.; Choi, S.-B. Vibration Control of a Structural System Using Magneto-Rheological Fluid Mount. *J. Intell. Mater. Syst. Struct.* **2005**, *16*, 931–936. [CrossRef]

191. Xu, Z.; Gong, X.; Liao, G.; Chen, X. An Active-damping-compensated Magnetorheological Elastomer Adaptive Tuned Vibration Absorber. *J. Intell. Mater. Syst. Struct.* **2010**, *21*, 1039–1047. [CrossRef]
192. McCulloch, W.S.; Pitts, W. A logical calculus of the ideas immanent in nervous activity. *Bull. Math. Biophys.* **1943**, *5*, 115–133. [CrossRef]