Study on the Application of Smart Materials in Vibration Control of Civil Engineering Structures

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Abstract. Challenges as severe as the depletion of natural resources, natural disasters, extreme weather conditions or overpopulation require smart resolutions, especially in construction. This paper reviews smart material-based technologies currently applied or developed in civil structures, with a focus on smart material applications for actuation or sensing. After giving a definition and classification of smart materials, the materials studied (i.e. piezoelectric materials, memory materials, magnetic fluids) are presented for applications in construction and civil engineering. While some materials are already very favorable in terms of applications, others still require further research for real-world construction applications. This review should be consolidated in the near future through systematic research work.

Keywords: Smart materials · engineering · vibration control

1 Introduction

The development of permanent structures has evolved as a protective mechanism against climate extremes, natural catastrophes, human and animal dangers, and other environmental consequences since people transitioned from nomadic to sedentary living [1]. As a result of changes in environmental and societal demands, dwellings have evolved into structures with a new emphasis on less vibration, or, in other words, more stability and durability. However, what material should be the best choice for controlling vibration in a civil engineering structure? The use of smart materials, which are those that can detect or respond to environmental changes, in constructing buildings could be a suitable key response approach for this goal. The maturity, the variety of potential uses, and the sustainable development and innovation of smart materials make them stand out from other materials. Although smart materials are relatively new, they have advanced rapidly in recent decades and are now well-known and widely used in building construction, such as piezoelectric sensors for structural safety control. Numerous smart materials are also well-known and in use in a variety of industries, for instance, aerospace, automotive, and healthcare.

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Smart materials offer a wide range of possible applications, including in the construction of civil engineering projects [2]. Concerning civil engineering structures, the emergence and advancement of smart material structural systems and their application technologies not only increase structural functionality but also, more importantly, renew many concepts of conventional civil engineering structural design, building, preservation, and use control. For example, the use of intelligent materials in structural systems can truly reflect the characteristics of structural control integration. Such vibration control systems not only simplify the structure but can also automatically make vibration control responses under the action of uncertain dynamic loads such as earthquakes, enhancing the seismic resistance of the structural system. In this paper, we focused on three smart materials: piezoelectric materials, shape memory alloys, and magnetorheological fluids. The principle of how each material is used in vibration control is shown in the first place. The applications and experiments of the materials in the past twelve years in different controlling scenarios are illustrated in the second part. Additionally, there are prospects and suggestions for the future of smart materials.

2 Piezoelectric Materials

2.1 Principles of Piezoelectric Materials

Piezoelectric materials (PEMs) are certain crystals or ceramics that produce a voltage when subjected to pressure, Jacques Curie and Pierre Curie pioneered research on piezoelectric crystals. Compressing or stretching this material produces an opposite electrical charge [3], proportional to the load applied to it. This is known as the piezoelectric effect (see Fig. 1).

Natural PEM includes minerals such as quartz, wood, and organic matter. When it is subjected to stress, the spacing of the atoms changes, leading to polarisation and the creation of an electric field. Only 20 of the 32 types of crystals have piezoelectric

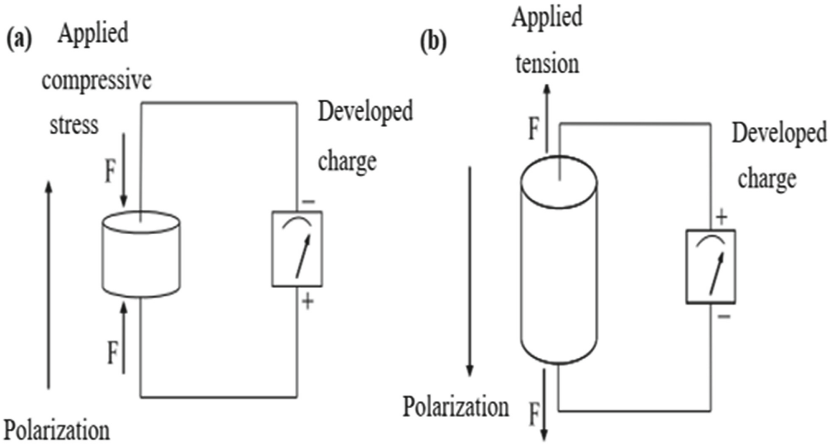

Fig. 1. The direct piezo effect at applied compressive stress (a) and tension (b) [4].

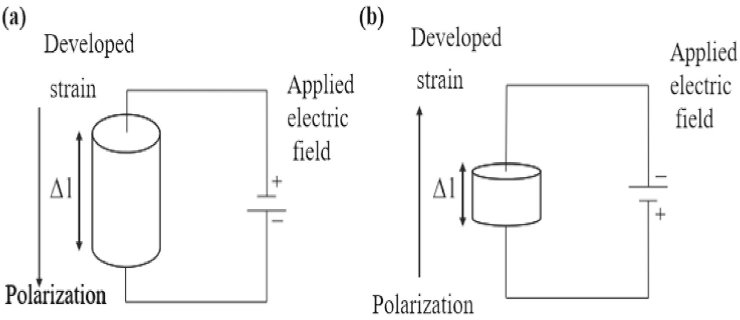

Fig. 2. Inverse piezo effect when an electric field is introduced [4].

properties [4]. By firing a mixture of some special powders and binders and applying an electric field at a certain temperature, the arrangement of the atoms in them can take on a polar character, at which point the application of pressure can change the degree of polarity and have piezoelectric properties. This is used to make piezoelectric ceramics (see Fig. 2).

Quartz (SiO2) is the most widely used piezoelectric material. In World War I, piezoelectric materials were widely used as materials for sonar to detect submarines. Piezoelectric fibres are also used in high-end sports equipment to reduce vibrations [5]. For vibration control, piezoelectric materials are usually attached to the surface of an object as sheets, which in addition to damping vibrations can also harvest energy.

2.2 Applications of Piezoelectric Materials

In 2011, Li, F.-M. et al. investigated the active vibration control of conical structures with piezoelectric inductor sheets as shown in Fig. 3 [6]. To derive the displacement equations

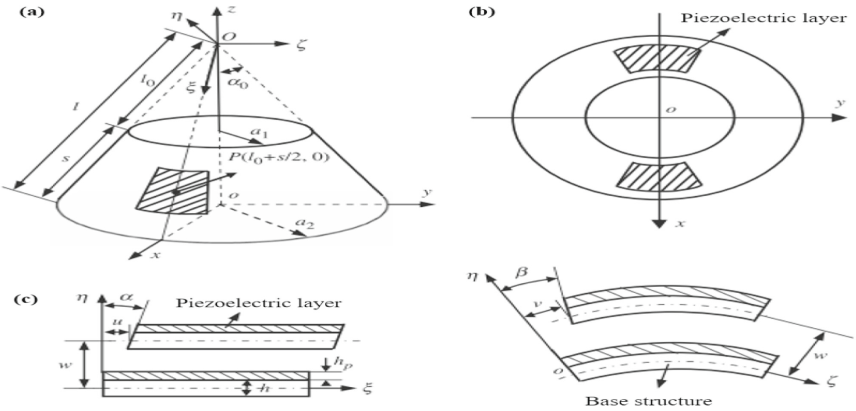

Fig. 3. The conical shell system with np piezoelectric patches is shown schematically. (a) Looking forward. (b) Aerial perspective. (c) The structural and kinematical characteristics of the piezoelectric patches and conical shell [6].

for the combination of cone and piezoelectric material, they used Hamilton's principle and the hypothetical modal method. The best position for the piezoelectric sheets was then determined through simulations using linear quadratic regulator algorithms and negative velocity feedback. The best location for two piezoelectric patches on a beam structure was investigated by Liao, Y. and H. A. Sodano in 2012 by calculating the loss factor based on wave propagation and determining the different intrinsic frequencies for different placements to analyze the impact of various factors on the ideal placement [7]. In 2018, research was conducted by Li, J. et al. on the features of functional gradient piezoelectric material plates (FGPM) in vibration reduction. The required voltage for various control effects, as well as the impact of the density of the FGPM material and the location of the applied voltage on the vibration control effect, were calculated using the equations of motion of FGPM plates under an electric field, Hamilton's principle, and the Rayleigh-Ritz method. In 2016, O. Abdeljaber, O. Avci, and D. J. Inman developed a flexible cantilever control plate that combines a neural network controller and a piezoelectric sensor using the finite difference approach to calculate the degradation model of a damping plate with the addition of a Kalman filter [8]. Nguyen et al. examined the effect of pore density on vibration through a geometric finite element method using Bézier for square, circular, and toroidal porous plates of functional gradient piezoelectric materials in 2019 [9].

3 Shape Memory Alloys

Materials with special characteristics like the shape memory effect (SME) and pseudo-elasticity are known as shape memory materials (SMMs) [10]. An attractive class of SMMs is shape memory alloys (SMAs), which are metallic alloys that recover their original shape after a large deformation by phase change. The shape memory polymer is yet another SMM that can be triggered by temperature stimuli, magnetic fields, and even light (SMP), a smart material with promising applications in the field of structural vibration control [11], using its shape memory effect, super elasticity, and high damping properties.

3.1 Principles of Shape Memory Alloys

SMA typically exists in two crystalline states: the stronger martensite state, which is heat stable and low stresses, and the weaker austenitic condition, which is stable at high temperatures and low stresses [12]. SMA is deformed when the martensitic phase is subjected to external stresses because of a de-entanglement procedure that converts numerous martensitic variations into a particular form with the greatest amount of elongation (see Fig. 4). The martensitic phase's parallelogram structure is fragile and sensitive to outside forces [13]. Contrarily, the austenitic phase is extremely ductile and has a single potential crystal shape.

The ability of a material to resume its former shape after heating in the temperature phase is known as SME, and pseudo-elasticity is one of the two distinguishing characteristics of SMA [14]. SMA experiences significant inelastic deformation known as pseudo-elasticity before resuming its original shape following unloading. In the absence

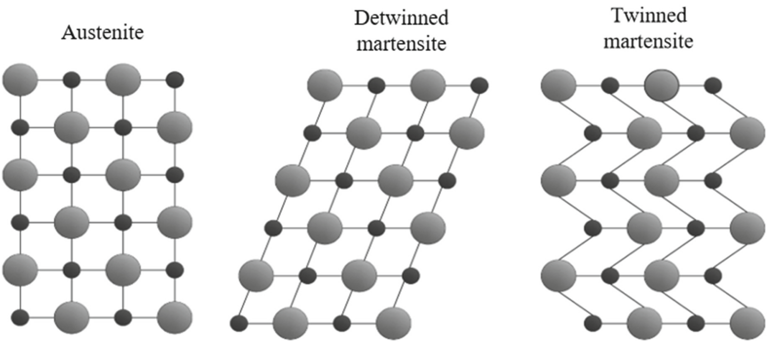

Fig. 4. Different crystal structures of SMAs [13].

of external stress, the SMA can be heated to cause the change from martensite to austenite. The austenite onset temperature is the point at which a material changes from twinned martensite to austenite. The temperature occurs when the material has entirely undergone austenite transformation and is at austenite completion temperature [15]. In other words, the original shape of SMA changes into a martensite structure if the temperature exceeds a particular threshold.

3.2 Applications of Shape Memory Alloys

Whether in the hyperelastic phase or under the shape memory effect, shape memory alloys are highly damped and can absorb a large amount of vibration energy under vibrating loads [16]. Dissipating dampers made from this material can be installed on machinery, buildings, and bridge structures to reduce the vibration response caused by various factors and to achieve passive or active vibration control of engineering structures.

Wang Sheliang et al. conducted an experimental study on the physical (MSMA has large deformation characteristics and therefore requires special equipment to measure

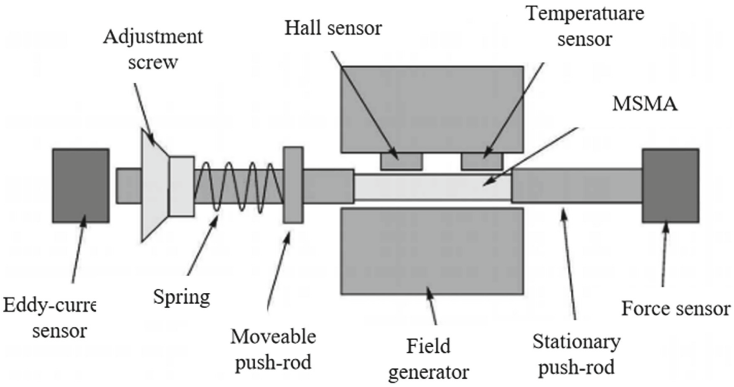

Fig. 5. Magnetism test diagram [17].

magnetic and mechanical properties, most importantly magnetic field strength, temperature, mechanical stress, and strain, the exact experimental principle of which can be found in Fig. 5 and mechanical properties of shape memory alloys [17], established a phase change pseudo-elastic restoring force model for shape memory alloys, and used the model to establish a mechanical analysis model for the seismic response of passively controlled building structures, and explored the mechanical properties of MSMA materials and their application in the seismic control of structures. By changing the temperature of shape memory alloy recovery elements, Filipe et al. investigated the frequency self-tuning potential of a new adaptive damper for structures in civil engineering [18], and performed a series of simulations using a numerical model of a busy footbridge to further comprehend the tremendous potential of this adaptive control strategy for vibration reduction in civil engineering structures. Zhenyu Liang et al. chose the martensite austenite ratio for the shape memory alloy. Based on the beam model, a mechanical model of the shape memory alloy was created [19]. The shape memory alloy has a specific impact on structural vibration control in the martensite-austenite coexistence condition, according to the numerical analysis findings of the computer simulation study of the structure conducted using Matlab software. Wang Wei et al. conducted an experimental study on the control of the dynamic response of a three-story steel frame structure with shape memory alloy cables under seismic action [20]. The steel frame structure's maximum acceleration and displacement for each floor were tested both with and without SMA cables, and it was finally explored that the dissipation efficiency of the SMA dampers greatly reduced the vibration response of the steel frame structure.

4 Magnetorheological Fluids

4.1 Principles of Magnetorheological Fluids

Magnetorheological fluids are smart materials that have been a novel and hot focus in the field of vibration control for scientists in recent years [21]. It is abbreviated to MRF, which has unique rheological properties that, by using a magnetic field, can change from its liquid state into its solid state in milliseconds [22]. By applying a magnetic field to MRF, it is believed that, to some extent, the creation of the particles within the fluid raises viscosity. In addition, the magnetic field and the chains of the particles held the particles together and the phenomenon shown in Fig. 6, which made MRF behave like a solid.

Magnetorheological fluids are often used as dampers in engineering. Making MRF dampers a good choice for vibration control is contributed by this controllable change of states with several desirable characteristics [23], such as good stability, low consumption, and a quick response time. A semi-active control mechanism that regenerates regulated damping force is known as an MRF damper [24]. MRF dampers are usually classified by different working modes into 4 categories: dampers that operate in the flow, flow and shear combination, squeeze, and shear modes.

4.2 Applications of Magnetorheological Fluids

In 2018, a study set two MRF dampers with a fuzzy logic-based controller (FLC) at the ends of the bridge to mitigate the vibration [25]. A railroad bridge under the influence

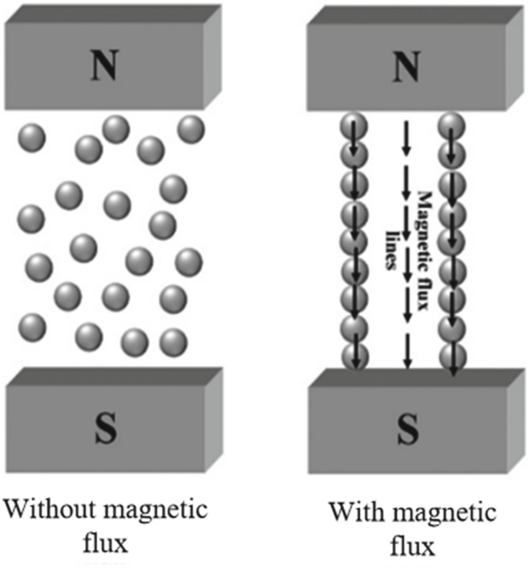

Fig. 6. Chain formation in a magnetorheological fluid under magnetic flux [22].

of a moving load is subjected to dynamic analysis. Moving loads are simulated using the six-axle train, and the Euler-Bernoulli beam theory is used to model the railroad bridge. After the results were examined, it was found that the MRF dampers mitigated the deflection and acceleration of the midpoint of the bridge, which showed good performance in safety and comfort. The dependability of MRF dampers in the rotational responses of irregular constructions was investigated in a research in 2020 [26]. The test structure for this project was a three-dimensional, two-story skyscraper. In the first story, an eccentric mass was inserted to assure plan irregularity. Two MRF dampers placed between the base and the first level were used to moderate the responses after unidirectional seismic stimulation was applied to the structure. Two controlled scenarios, passive control, semi-active control, and uncontrolled scenario were examined in this experiment. The results have demonstrated that MRF dampers work satisfactorily in managing torsional-lateral reactions, particularly in the semi-active control situation. To enhance the performance of the vehicle suspension, an MRF damper-equipped semi-active suspension system was planned in 2021 [27]. Based on a new neuro-inverse model of the MRF damper, an optimized fuzzy skyhook controller was created using the grey wolf optimizer (GWO) method. The findings demonstrated how the MRF damper's semi-active vibration management could effectively increase the suspension's ride comfort by concurrently reducing the magnitude of vertical displacement, cushion deflection, and tire load applied.

5 Conclusions

The key developments in the application of smart materials in civil engineering and construction are examined in this study [28]. Piezoelectric technology has been demonstrated to be the most well-established class of smart materials in this sector, particularly in sensor applications and where fast response times are required. Magnetorheological fluids have been employed in structural engineering, notably in the area of seismic and vibration management, and shape-memory materials have also made significant advancements over the past decade. Numerous successful implementations in the areas of engineering and construction are currently feasible as a result of considerable basic research into smart materials and technologies, natural disasters and environmental influences are placing increasing demands on the seismic resistance of buildings, and therefore on the vibration control systems of building structures. At present, intelligent materials are increasingly dominating vibration control in civil engineering structures, mainly because of their rich material sources, control forms and response characteristics [29]. In practice, if the best intelligent vibration control materials can be selected according to the characteristics of the project, the safety of the building can be ensured and a win-win situation in terms of cost and effect can be achieved.

In addition, the vibration damping drive made of intelligent materials is simple in construction, convenient in production, reliable and stable in performance, and has several applications in civil engineering constructions [30], such as the control of wind vibration and seismic response in high-rise buildings, seismic isolation control of seismic response in multi-story buildings, control of vertical seismic response in large-span trusses and grids, wind vibration control of suspension structures, vibration control of marine platforms under wave excitation, etc. To make intelligent materials more widely used, efforts should be made in the following two aspects: (1) The problem of improving the performance of smart materials, such as the settling of solid particles after long-term shelving of MR and its effect on fluid stability performance, the demagnetization effect of MR, etc. (2) To exploit the potential of smart materials and to broaden their existing applications to better meet the needs of civil engineering construction.

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