CHAPTER 2

LITERATURE SURVEY

Many research investigations have been reported on the application of shape memory alloy in various fields. A summary of earlier investigations related to this topic of research are reviewed in this chapter. This chapter is divided into four sections, namely, (i) studies on shape memory effect of SMAs, (ii) studies on mechanical properties of SMA, (iii) study on application of SMA and (iv) problem identification.

2.1 STUDIES ON SHAPE MEMORY EFFECT OF SMA

(Wei et al. 1997) designed and fabricated an intelligent composite with shape memory alloys. It is an alloy that possesses shape memory effect, actuating functions, high damping capability, sensing environmental changes, pseudo-elasticity, etc. He fabricated SMA composites, in multilayer hetero structure with SMA thin films technology. From the experiment, he suggested that many research and development of the smart composites were still in its initial stage. Hence, many problems in conducting the experiments remain still unresolved. One of the key problems is to develop novel technology to bind shape memory materials with dissimilar components.
2.2 STUDY ON MATHEMATICAL PROPERTIES OF SMA

(Alberto Paiva et al. 2005), developed a constitutive model for shape memory alloy by considering its thermo-mechanical behaviour. It included study of both the plastic strains and tensile–compressive asymmetry that occur in the thermo-mechanical properties of SMAs. They made comparisons between numerical and experimental results and found that they were in close agreement with each other. In numerical simulations, his model has the capability to capture the behaviour of SMAs, along with important characteristics such as one-way and two-way shape memory effect, pseudo-elasticity, phase transformation, and tensile–compressive asymmetry.

(José R. Santiago Anadón 2002) introduced a linear actuator integrated with shape memory alloy and experimentally studied its performance. For implementation of shape memory alloys in large scale applications, they found three major complications. They are limited cycles, strain constraints and the actual usable force. He concentrated to study the amount of force from SMA and actuation cycles. Shape memory alloy wires in parallel array fashion was implemented in his prototype. In the experiment, he found that SMA was capable to lift more than 100 lbs with a stroke 0.80 inches. A controller with PID configuration was designed and implemented for testing the actuator for different loading conditions.

2.3 STUDY ON APPLICATION OF SMA

(Machado and Savi 2003) studied the medical applications of shape memory alloys and their properties. SMA posses two unique properties, one, shape memory effects and the other, pseudo-elastic properties. These unique properties created more interest for many investigators to utilise them for their applications. In their work, a brief discussion of the
thermomechanical behaviour of SMA and their applications in the medical field are reported. The biocompatibility nature of these alloys, makes them well suited for many medical applications, such as cardiovascular and orthopedic uses, and surgical instruments.

(Elwalee Awad Khidir et al. 2008) developed a new method for actuating a parallel manipulator using SMA. The SMA wire incorporated in the beam provides an actuating force that produces large bending with displacement. They developed a 3-UPU (universal–prismatic–universal) parallel manipulator using linear SMA actuators. The manipulator consisted of a fixed platform, a moving platform and three SMA actuators. An ON/OFF control configuration was designed for actuating the SMA wire by heating and cooling. They successfully implemented SMA for linear displacement applications and showed, the closeness with the experimental value with the simulation results.

(Hugo Rodrigueet al. 2017) manufactured shape memory alloy based curved actuators to achieve maximum bending angles with the same cross-section configuration as a straight actuator. They studied effects of multiple curved actuators with various initial bending angle and non-uniform initial curvatures on the maximum bending angle. Finally, they implemented multiple curved actuators in a simple gripper and compared the lifting force with straight actuators. From the results they found that the curved gripper has a lifting force nearly three times larger than the straight gripper.

(Reza Razavilar et al. 2017) studied the free vibration of a shape memory alloy beam with pseudoelastic behaviour. They have derived the equations of motion using the Hamilton principle and the Euler–Bernoulli theory. Also they derived partial differential equations using the Galerkin method and obtained a three-dimensional phenomenological model for shape
memory alloy. By simulating the model, they showed the property of shape memory alloy beam had great potential for using in damping applications.

2.3.1 **Study On Application of SMA in Vibration Control**

(V. Torra et al. 2007) investigated the damping ability for family homes with SMA reinforced cable in concrete structures. Large recoverable strain properties of shape memory alloys were used to develop solid state dampers in a family house. They modeled the thermo-mechanical behaviour and performed an experimental analysis for SMAs. The SMA models were simulated in ANSYS software and a complete damping solution was determined. Their simulation results showed that the SMA dampers had an ability to reduce the maximum amplitude of vibration.

(Dhanalakshmi et al. 2010) did experiment on vibration control of shape memory alloy actuators in a flexible cantilever beam with piezo sensor. They studied the performance of SMA actuator in vibration control by implementing it in parallel to the beam axis, both up and down. They developed and compared ON-OFF controller, PI and PID controller for controlling the actuation of SMA actuators. In their experiment they found that ON-OFF controller is the simplest one to control the first mode of vibration of the flexible beam. Also, LabVIEW software provided a very good and efficient platform to develop and to implement the controllers in real time. In experimentation, the closed loop responses obtained through simulation were found to match closely to the experimental results. SMA actuator exhibited substantial reduction in the amplitude of flexural vibration at its first mode resonance.

(Saadat et al. 2002) studied the behaviour of NiTi, and implemented it for structural vibration control. Though their experiment they
concluded that the feasibility of NiTi-based energy absorption in vibration isolation devices could not be used as primary components of a seismic mitigation system. NiTi-based seismic isolation can be focused on the future studies in innovative hybrid designs.

(Alaa et al. 2009) investigated the implementation of shape memory alloy damper in the application of cable-stayed bridges. They found that SMA dampers were able to reduce 70% of maximum towers base shear, bridge displacement, and towers base moment. It was also found that the overall bridge performance would be increased with the number of SMA dampers and distribution of the dampers between pier and tower connections. They conducted a sensitivity study on investigating the effect of SMAs hysteretic properties on the seismic behaviour of the bridge. Their study showed that the variation in strain hardening affected the maximum displacement response by 13% to 23%.

(S. Jose et al. 2017) conducted a coupled thermo-mechanical analysis on vibration isolator made of shape memory alloy. From the studies, they found that controlling the SMA under non-isothermal conditions are quite complicated. From simulation results, they suggested that the performance of the SMA bar as vibration isolator, undergoing uniaxial deformation, is seriously affected unless proper cooling is done.

(Filipe Amarante dos Santos and JoãoNunes 2017) used shape memory alloy as an adaptive vibration absorber in civil engineering structures. They control the elastic modulus of the structure through the Joule effect. By inducing thermal martensitic transformations, they control the stiffness of the absorber and thereby continuously tuning it to wide frequency range. By adaptive control approach, they effectively control the vibration of a lively footbridge.
(SoheilSaedi et al. 2017) designed structures to withstand dynamic environmental hazards such as earthquakes, strong winds, and hurricanes is of primary concern for civil engineers. In addition, they incorporate recent advances materials in architectural forms, structural systems, to enable the design of very slender and lightweight structures. These flexible structures are designed to be exposed in high levels of vibrations under strong winds and earthquakes, which may lead to structural damage and potential failure. They used shape memory alloys (SMAs) as a smart material that can be a passive vibration control devices for energy dissipating and re-centering purposes. From their studies, they explored the performance of recently developed NiTiHfPd alloys that have very high strength, high dissipation/damping capacity, good cyclic stability and large operating temperature for vibration control applications. The design of a novel passive vibration control device by utilising the superelastic effect of NiTiHfPd SMAs under compression shows a good performance in vibration control for civil structure.

(M Bodaghi et al. 2017) developed a model for vibration control of rectangular plates under dynamic loads with integrated polycrystalline NiTi shape memory alloy (SMA) ribbons. They simulate the thermo-mechanical behaviour of SMA ribbons under dominant axial and transverse shear stresses, by introducing a robust macroscopic constitutive model. Their model has the ability to accurately predict the martensite transformation, shape memory effect, pseudo-elasticity and in particular reorientation of martensite variants and ferro-elasticity features. They implemented Finite element and Newmark methods along with an iterative incremental process based on the elastic-predictor inelastic-corrector return mapping algorithm to solve the non-linear governing equations in spatial and time domains. From their work they concluded that the modeling of ferro-elasticity in the dynamic analysis of
SMA composite structures could lead to the passive vibration control capability in low-temperature SMA ribbons.

### 2.3.2 Application of SMA In Fire Sprinkler

(Xiangyang Zhou et al. 2012) studied the spray characterisation measurements of a pendent fire sprinkler. They used a laser – based shadow-imaging system to measure spray parameters such as velocity, droplet size and density of the spray. From his experiment it was found that changes in pressure influence the distribution of the water flux to varying degrees.

(Xiangyang Zhou and Hong-Zeng Yu 2011) carried out an experimental investigation on spray formation based on sprinkler geometry. A sprinkler typically consists of a deflector, a boss and sprinkler frame arms. They developed a prototype to study parameters such as water sheet thickness, sheet breakup distance, spray discharge angle, water flux and drop size distributions. From the experiment it was found that boss structure and deflector diameter had little impact on sheet breakup distance and drop size. They developed an integral model to determine the speed on the deflector and development of water sheet thickness for different degrees of viscous effect. Experiment conducted by them was very much useful for the development of a spray formation model for fire sprinklers.

(Jinsong Hua et al. 2002) carried out a numerical study on the interaction of water spray with a fire plume. They conducted a quantitative approach method to find the performance and effectiveness of water spray to optimise the design for different operating environments and types of fire. By introducing a numerical simulation approach, the quantitative analysis for the interactions occurring between water spray and fire plume were determined. Several fire suspension parameters, water spray pattern, water droplet size and
water spray flow rate were investigated. It was found that the water spray with solid cone pattern and finer water droplet size is more effective in extinguishing fire than the one with hollow cone pattern with coarse water droplet size. Also it was found that to suppress a fire, the minimum water spray flow rate had to be more than a certain critical value. However, even using high water spray flow rate did not increase fire suppression efficiency but it led to increased operational cost.

Some researchers used shape memory alloy to sense the temperature and actuate the fire sprinkler automatically. (Heinz S. Wolff 1990) designed a disc made of a shape memory alloy to break the shutter glass at a high temperature and to actuate the fire sprinkler automatically as shown in figure 2.1. At temperature-rise conditions shattering mechanism made up of a SMA, actuates the shutters and passes the fluid to impinge on a distributor (as in conventional sprinklers).

![Figure 2.1 Heinz S. Wolff’s fire sprinkler (US Patent 1990; 4896728)](image)
(George S. Polan 1996) introduced a C shape band made of a shape memory alloy, to actuate the control lever of a sprinkler and to discharge it at high temperatures. At an occurrence of a high-temperature condition, C shape control band spreads apart and releases all control levers and the valve plug from sealing engagement to discharge fluid, as shown in figure 2.2.

Figure 2.2 George S. Polan's Fire sprinkler (US Patent 1996; 5494113)

(Marthinus Cornelius 2009) used a shape memory effect to break the frangible bulb in fire sprinkler at high temperatures to discharge water automatically. A frangible bulb extends between the cage member and the seal is replaced by a shape memory alloy element associated with the frangible
bulb as shown in figure 2.3. As temperature rises, SMA in frangible bulb expands and breaks it to releasing the fluid through the passage.

![Diagram of fire sprinkler](image)

**Figure 2.3 Marthinus Cornelius’s Fire Sprinkler (US Patent 2009; 0242218A1)**

In the above literature survey, fire sprinklers can actuate to discharge water automatically at a high temperature, but discharging of water is not able to stopped once it opens, even when the temperature decreases (fire put off).

To stop the discharge of water, (Tom Goss 2012) designed a removable casing for fire sprinklers and it was fixed to the fire sprinkler manually. Casing has hinged shells that latch closed to form a watertight interior space as shown in figure 2.4.
(Hochiki Kabushiki 2012) introduced a fusible alloy along with shape memory alloy. The fusible alloy was only for actuation of the sprinkle and the shape memory alloy was for deactivating the sprinkle automatically.

(Lucian Burlacuet al. 2017) replace the ‘wet alloy’, used for sprinkler-triggering within automatic protection systems, made of shape memory alloy type. They used commercial NiTi rod, which was martensitic phase at room temperature, and thermoelastic reversible martensitic transformation as a governing function for actuator, which has completely reversible character, and enables the occurrence of two-way shape memory effect after the application of a thermomechanical treatment called ‘training’. Thus they stabilised a fully reversible NiTi rods as executive elements in resettable sprinkler for reparation.
2.4 PROBLEM IDENTIFICATION

From the literature review, it is found that mechanical properties of shape memory alloy will be varied based on manufacturing process. Hence the properties of NiTinol at different boundary conditions based on the applications have to be studied.

In vibration control system, the cantilever beam is mounted horizontally, where the SMA is used as a linear actuator on the top and at the bottom of it. Temperature and actuation force of SMA are to be measured periodically to control the martensite transformation. Mass of accelerometer also influences the vibration parameter of cantilever beam. Hence, miniature type piezo base accelerometer (20gm) is used to measure the vibration.

In electrical actuation, SMA wire was heated up uniformly to induce Martensitic transformation. Meanwhile, there will be thermal convection and radiation from the outer surface of SMA which is exposed to air. Hence, the entire setup is to be kept in an insulated chamber. In electrical actuation method, high voltage is passed through the SMA wire and hence, all sensors used in the system are to be properly insulated. In order to increase the actuation stroke, SMA wire can be shaped into a spring form. Based on the applications, required actuation force and stroke length of SMA springs are calculated and set to required shape by arresting the deformation during shape setting process.

From the literature review, it was found that fire sprinklers play a major role in fire extinguishing system. At present, commercially available sprinklers are able to sense the temperature and actuate automatically. But once it opens to discharge, it can not stop the water discharging automatically. Hence, it requires a high water storage, which leads to high initial cost.
## 2.5 SOURCES OF LITERATURE

<table>
<thead>
<tr>
<th>Author</th>
<th>Title of Journal</th>
<th>Survey Points</th>
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| Wei et al., 1997 | Design and fabrication of intelligent composites based on shape memory alloys | • Principles concepts of the basic design and the fabrication of SMA composites.  
• Novel technology to be developed for binding SMA with dissimilar components. |
| (Alberto Paiva et al. 2005), | A constitutive model for shape memory alloys considering tensile compressive asymmetry and plasticity | • Developed a constitutive model for shape memory alloy by considering its thermo-mechanical behaviour.  
• Model capture the important characteristics of SMAs such as one-way and two-way shape memory effect, pseudo-elasticity and phase transformation. |
| (José R. Santiago Anadón 2002) | Large Force Shape Memory Alloy Linear Actuator                                     | • Design of linear actuator integrated with shape memory alloy.  
• Studied the amount of force and actuation cycles from SMA.  
• Controlled by PID configuration controller. |
| (Machado and Savi 2003) | Medical applications of shape memory alloys                                        | • Studied the medical applications of shape memory alloys and their properties.  
• Applications of SMAs in medical devices such as cardiovascular, orthopedic and surgical instruments. |
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<tr>
<th>Reference</th>
<th>Method/Description</th>
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• Heating and cooling is controlled by ON/OFF controller.  
• SMA wire provides a large amount of actuating force with displacement. |
| Hugo Rodrigue et al. (2017) | Curved shape memory alloy-based soft actuators and application to soft gripper | • SMA introduce a curved actuator to achieve maximum bending angles.  
• Designed a simple gripper and compared the lifting force of curved with straight actuator.  
• Resulted three times larger than the straight gripper. |
| Reza Razavilar et al. (2017) | Free vibration analysis of a shape memory alloy beam with pseudoelastic behaviour | • Studied the free vibration of a shape memory alloy beam with pseudoelastic behaviour.  
• Derived partial differential equations using the Galerkin method and obtained three-dimensional model.  
• Property of SMA beam have great potential for using in damping applications. |
| V. Torra et al. (2007) | Built in dampers for family homes via SMA: An ANSYS computation scheme based on mesoscopic and microscopic experimental analyses | • Studied the damping characteristic of family homes with SMA reinforced cable in concrete structures.  
• Simulation results of SMA dampers reduces the maximum amplitude of vibration. |
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| Dhanakshmi et al. (2010) | Experimental Study on Vibration Control of Shape Memory Alloy Actuated Flexible Beam | • Experimentation vibration control of shape memory alloy actuators in a flexible cantilever simulation.  
• SMA actuator is mounted parallel to the cantilever beam axis, both up and down.  
• Experimental result shows SMA actuator reduces the amplitude of flexural vibration at its first mode effectively. |
| Saadat et al. (2002) | An overview of vibration and seismic applications of NiTi shape memory alloy | • Used SMA for structural vibration control.  
• They concluded that NiTi-based vibration isolator could not be used as primary components of a seismic mitigation system. |
| Alaa et al. (2009) | Application of shape memory alloy dampers in the seismic control of cable-stayed bridges | • Implemented shape memory alloy damper cable-stayed bridges.  
• SMA dampers were able to reduce 70% of towers base shear, bridge displacement, and towers base moment.  
• Overall bridge performance is increased with the number of SMA dampers. |
| S. Jose et al. (2017) | Coupled thermo-mechanical analysis of a vibration isolator made of shape memory alloy | • A coupled thermo-mechanical analysis on vibration isolator made of shape memory alloy.  
• Controlling the SMA under non-isothermal conditions are quite complicated.  
• Performance of the SMA bar as vibration isolator, fully dependence on proper cooling of it. |
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| Filipe Amarante dos Santos and João Nunes (2017) | Toward an adaptive vibration absorber using shape-memory alloys, for civil engineering applications | • Shape memory alloy is used as an adaptive vibration absorber in civil structure.  
• It was controlled by Joule effect.  
• Stiffness of the absorber is continuously turned it to wide frequency range by using martensitic transformations.  
• They implemented it on control the vibration of a lively footbridge. |
| Soheil Saedi et al. (2017) | Structural Vibration Control Using High Strength and Damping Capacity Shape Memory Alloys | • Designed civil structures to withstand dynamic environmental hazards such as earthquakes, strong winds, etc.  
• They used SMA as a passive vibration control devices for energy dissipating and re-centering purposes.  
• They design a passive vibration control device by utilising the super-elastic effect of NiTiHfPd SMAs.  
• It shows a good performance in vibration control for civil structure |
| M Bodaghi et al. (2017) | Passive vibration control of plate structures using shape memory alloy ribbons | • Developed a model for vibration control of rectangular plates integrated with polycrystalline NiTi shape memory alloy (SMA) ribbons.  
• Model accurately predict the martensite transformation and shape memory effect.  
• From SMA composite structure model, they concluded, that passive vibration control can be achieved at low-temperature. |
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<th>(Xiangyang Zhou and Stephen 2012)</th>
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<td>• Measure the spray parameter such as velocity, droplet size and density.</td>
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<td>• Experimentation shows that changes in pressure influence the distribution of the water flux.</td>
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<td>• Designed a disc made of a shape memory alloy to break the shutter glass at a high temperature.</td>
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<td>• Requires maintains to assemble it, once it opens.</td>
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<td>• Introduced a frangible bulb in fire sprinkler which actuates at high temperature to discharge water automatically.</td>
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<td>Tom Goss’s Fire Sprinkler (US Patent 2009; 0242218A1)</td>
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</table>
| (Lucian Burlacu et al. 2017) | NiTi Shape Memory Alloy Used for Multiple-Resetting Actuator for Fire Protection | • Used commercial NiTi rod to activate and deactivate fire sprinkler, by reversible martensitic transformation and Two-way shape memory effect.  
• Fully reversible NiTi rods reset the sprinkler for re-protection automatically. |

### 2.6 SUMMARY

In this chapter, a detailed literature survey was conducted in the application of shape memory effect in various fields. Investigations on mechanical properties of shape memory alloy and their results and findings are reviewed. Application of SMA in medical field, constructions, etc. are studied and respective findings, problem faced by researchers, and their results are discussed. Application of SMA in vibration control of family house, cantilever beam, seismic mitigation systems are discussed in detail. Various designs, actuation methods and registered patents on fire sprinklers are reviewed and their merits and demerits in the real time applications are discussed.