A tuned vibration absorber constituted of shape memory alloy wires for vibration reduction of platform structures: design and implementation

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Abstract. Machinery can suffer from mechanical vibrations since resonance may be generated from time-varying external excitations under different operation conditions. These detrimental vibrations may significantly influence the device's performance, effectiveness and reliability in operation. In this paper, an innovative, simple and high-efficiency tuned vibration absorber (TVA) consisting of shape memory alloy (SMA) wires, which is referred to a wire-type tuned vibration absorber (WTVA), is proposed to reduce the induced vibration. Experiments are carried out using a six-degree-of-freedom platform which is designed to simulate the frame of precision machinery in practical applications. With the equivalent stiffness of SMA wires adjusted by the controlled electric current, the frequency tunability of WTVA can be achieved. When the natural frequency of WTVA tuned in with the disturbance frequency, the experimental results demonstrate that the efficiency in vibration reduction of the platform is drastically increased even with considerable weight difference between WTVA and the platform. Moreover, the tunable frequency span also increases greatly due to the new design of WTVA and the material characteristics of SMA wires.

1 Introduction

Due to advances in industry, the demands for product precision and reliability have become more stringent. Most of the machinery is operated under the influence of rotating drivers, such as motors and fans, which will incite the oscillations from their rotational imbalances. In some cases, the excitation frequency from devices during operation matches its natural frequency and induces the so-called resonant vibration. The resonance will usually cause excess noise, and influence not only the accuracy but also the service life of machinery. In more severe cases, it may lead to rapid catastrophic failure. Hence, many experts and scholars focus much of their efforts in how to effectively avoid and reduce vibration, especially under resonance. Basically, every physical system has more than one

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resonant frequency. While the machinery is operated under varied rotating speeds, resonance at the different frequencies may be generated due to varied excitation frequencies. Therefore, the requirements of robust vibration reduction for machinery must be adaptive and tunable.

Traditional solutions to vibration reduction that involve structural modifications are often time consuming and expensive. Blocking the problematic frequencies in variable nature limits the operation of the system by the user. One possible solution is an installation of a dynamic vibration absorber (DVA). The DVA was first invented by Frahm [1] in 1909. Basic operation principle of DVA is to vibrate out of phase with target structure, thereby applying a counteracting force. Furthermore, there are numerous ways of reducing and preventing vibration, for example, by changing the stiffness of a structure, by increasing damping using viscoelastic materials, or by using control technology. Three types of control methods can be categorized: passive [2], active [3] [4] and semi-active. The passive vibration absorber is designed beforehand by choosing adequate stiffness and/or damping, and the vibration caused by specific natural frequency of primary structure can be reduced by attaching the DVA. Usually, the passive DVA which aims at a specific and single resonant frequency is used on the well-defined system. For instance, Heo et al. [2] developed a passive DVA with fixed parameter to reduce the vibration and noise of disk drives at a certain rotating speed. However, vibration was only suppressed at a specific disk speed. Therefore, the passive DVA cannot cope with variable systems. In order to overcome this difficulty, Chang et al. [3] proposed the active DVA to suppress and reduce the vibration by voice coil motor as the actuator. To achieve active control, the actuator plays the key role in the active DVA. The active DVA always uses an actuator (usually pneumatic or hydraulic) to generate the actually equal and opposite external force. Chang et al. [4] further designed a controller to achieve a better performance of the active DVA with tunable frequency. Although the active DVA can effectively reduce the vibration with multiple speeds, the components and actuator of the active DVA are complex and expensive.

In this paper, a semi-active DVA is considered and designed. Since the parameter of semi-active DVA can be adjusted, it is the so-called adaptively tuned vibration absorber (TVA). TVA is more efficient than passive DVA and almost as effective as active DVA [5]. Most of all, it is more stable and energy conserving. The concept of semi-active configuration is to replace the active force generators with continually adjustable elements which can vary and/or shift the rate of energy dissipation in response to instantaneous condition of motion. The most important requirement of TVA is its adjustable parameter can directly correspond to the extent of required frequency. The adjustable characteristic can be realized by altering the equivalent stiffness which directly influences the natural frequency. Since conventional materials such as steel, copper and aluminium with fixed physical properties cannot meet the requirement of adjustable nature, intelligent materials with different kinds of adjustable material properties were introduced to design or applied to the TVA in previous literatures, such as viscoelastic solids [6, 7], shape memory alloys (SMAs) [8-11], ferromagnetic shape memory materials [12], piezoelectric materials [13, 14], electro-rheological fluid[15, 16], magnetorheological fluid [17-19] and shape memory polymer [20] etc. However, most designs only employ single tuned frequency in vibration reduction. The tunable frequency span is still quite limited.

The major purpose of this paper is to design an innovative, simple and high-efficiency TVA. A TVA constituted of the SMA wires, which is referred to a wire-type TVA (WTVA), is designed to reduce the vibration of the primary structure. The extremely large and recoverable strain characteristics of the SMA imply that it can satisfy the requirement of tunable frequency via the external straining of the WTVA. The primary structure is presented as a platform with six degrees of freedom in loading deformation and employed

to mimic the practical frame of machinery. Since the practical devices are mostly operated with multiple and variable speeds, more than one resonant frequency therefore is liable to be excited and further generate considerable vibration. To naturalize the vibration energy of the platform under resonance, the natural frequency of the WTVA must be tuned, by adjusting its axial force, as close as possible to the resonant frequency of platform. Moreover, the design of WTVA has to provide multiple tunable natural frequencies in order to extend its operational frequency span.

2 Tuned vibration absorber & shape memory alloy

2.1 Tuned vibration absorber

The simplest form of a TVA is an auxiliary mass that is attached to the vibrating system by a spring only. TVA is very robust in reducing vibration if a system is excited by a periodically varying force of constant frequency, especially when this frequency is very close to the resonant frequency. Theoretical formulation on the TVA can be found in many vibration textbooks [21]. Thus, derivation of its dynamic equations was not presented herein for brevity.

In this paper, the purpose is to design a WTVA with high efficiency for vibration reduction, extensively tunable frequency span with simple and compact configuration. Figure 1 illustrates the schematic diagram of the proposed WTVA. This WTVA consists of a spring element made of two Ni-Ti SMA wires and an auxiliary mass placed at the mid-span. When the auxiliary mass moves in lateral direction, the equivalent stiffness can be varied by adjusting the axial force of the wires. The adjustment screw, which moves the slider platform and the movable end of the SMA wire, provides the first static pretension setting. Moreover, the power supply provides the control electric current to the SMA wires and generates an additional tension by heating. Heating SMA wires controls the dynamically tunable tension and subsequently the stiffness of TVA.
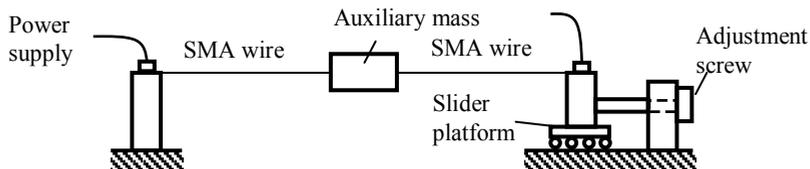

Fig. 1. Schematic diagram of the proposed WTVA.

2.2 Mathematical modelling of the WTVA

To derive the natural frequency which can be tuned by controlling axial force, a mathematical formulation is built to facilitate design procedure. Since their weights are considerably negligible comparing with auxiliary mass, the SMA wires are assumed to be weightless. Moreover, deformation of the auxiliary mass is much smaller than that of wires under loading. Only the wire's stiffness is considered in the overall stiffness of WTVA. WTVA can therefore be assumed to be a single degree of freedom system on a plane. Figure 2 shows the free-body diagram (FBD) of wire under oscillation. The SMA wires are assumed to be uniform and the tension P in the wires is constant. $w(x, t)$ represents the transverse displacement of the wire. ρ and θ, respectively, represent the mass per unit length and the slope of the deflected wire. Taking the equation of motion in lateral axis, the dynamic differential equation is derived as

$$\frac{\partial}{\partial x}\left(P\frac{\partial w(x,t)}{\partial x}\right)+f(x,t)=\rho\frac{\partial^2 w(x,t)}{\partial t^2}$$

(1)

If the external force $f(x, t) = 0$, then the free vibration equation could be obtained as

$$c^2\frac{\partial^2 w}{\partial x^2}-\frac{\partial^2 w}{\partial t^2}=0 \text{ , where } c=\sqrt{\frac{P}{\rho}}$$

(2)

The free vibration equation, Eq. (2), can be solved by method of separation of variable. The solution is written as the product of functions $W(x)$ and $T(t)$, which depend on coordinate x and time t, respectively:

$$w(x,t)=W(x)T(t)$$

(3)

By solving the separated second-order ordinary differential equations, these functions are given by

$$W(x)=A\cos\left(\frac{\omega x}{c}\right)+B\sin\left(\frac{\omega x}{c}\right)$$

(4)

$$T(t)=C\cos(\omega t)+D\sin(\omega t)$$

(5)

For the proposed WTVA, the wires are fixed at both ends, so one of the boundary conditions is $W(0) = 0$. The general solution of Eq. (3) can be written as

$$w(x,t)=B\sin\frac{\omega x}{c}(C\cos\omega t+D\sin\omega t)$$

(6)

Corresponding to the position of auxiliary mass, which is at $x = L/2$ (L represents the total length of wires) with the mass m, the boundary condition should be satisfied as

$$m\frac{\partial^2 w}{\partial t^2}\bigg|_{x=\frac{L}{2}}=2P\frac{\partial w}{\partial x}\bigg|_{x=\frac{L}{2}}$$

(7)

Substituting Eq. (6) into Eq. (7), we can find

$$\omega\tan\frac{\omega L}{2c}=-\frac{2P}{mc}$$

(8)

Thus, the relationship between axial force P and natural frequency ω of WTVA is obtained. The related parameters in Eq. (8) are the mass of auxiliary mass m, the total length L and mass per unit length ρ of the SMA wires, which will be first defined when designing the WTVA. Hence, Eq. (8) provides the design formulation that the tunable frequency can be realized by adjusting the axial force P.
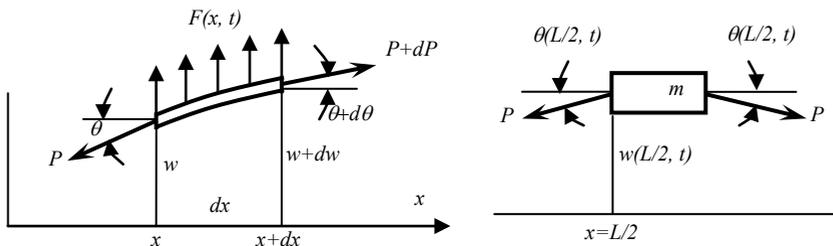

Fig. 2. Free body diagrams of the SMA wire and the auxillary mass in the WTVA under external loading.

2.2 Shape memory alloy

SMA is a type of intelligent material which has been shown to exhibit extremely large, recoverable strains (around 10%) and it is these temperature- and/or stress-controlled

properties which allow SMA to be utilized in many exciting and innovative engineering applications. In addition, SMA actuators also have attractive features such as high power to weight ratio, silence operation, no electromagnetic interference, and compact in size [22]. Two main types of SMAs are copper-aluminium-nickel and nickel-titanium (NiTi) alloys. NiTi-based SMAs are much more preferable for most applications because of their better mechanical properties compared with other existing SMAs [23]. Rustighi et al. [8] tuned the natural frequency by employing the tunable elastic modulus (stiffness) of Ni-Ti SMA with temperature. A change in the tunable frequency of 21.4% with 120 seconds of response time was obtained. However, 120 seconds of response time is only suitable for applications where the forcing frequency changes slowly with time, i.e. its practical application is limited. In spite of the attractive material property of SMA, several types of TVA consisting of other shape memory materials are proposed. For example, Lee et al. [20] studied the TVA which employs the hybrid shape memory materials in cantilevered configuration. By tuning the stiffness of the proposed TVA, more than 45% of tunable frequency span is obtained, and approximately 50% of vibration reduction is achieved with 70 seconds of response time. As shown in previous researches [8, 9, 20], the characteristics such as efficiency of vibration reduction, tunable frequency span and response time are still inferior for certain applications. Even in the active DVA which is proposed by Chang et al. [4], the vibration reduction is only improved by approximately 50% with tunable frequency. Thus, using different configuration design to improve the TVA performance is attempted in this study.

3 System descriptions

3.1 The dynamic characteristics of platform

The platform which is designed to simulate the practical frame for machinery is shown in Fig. 3. Under operation of the machinery, vibration will be generated due to slight imbalance in the rotor of the motor. An AC servo motor is used on the platform to excite the platform by adjusting the speed of motor. For example, the motor can drive a spindle in various speeds to satisfy the different machining needs. A pedestal is designed to place the WTVA. One side of the WTVA is fixed on a movable holder in order to adjust the initial pretension of the WTVA by screw. The other side of the WTVA is fixed on the fixed holder.
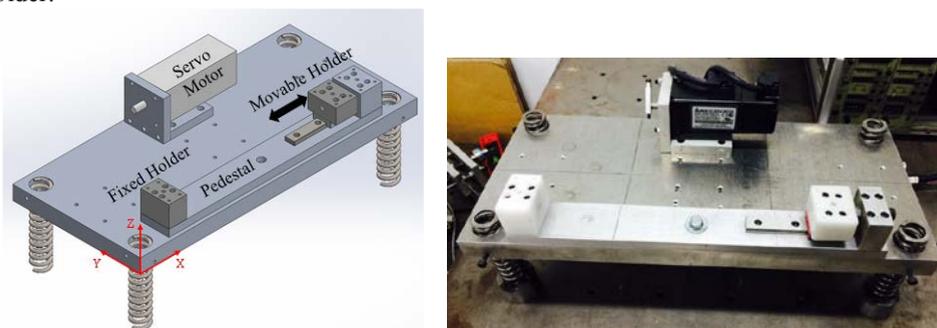

Fig. 3. Schematic diagram and picture of the platform structure.

Before designing the parameters of the WTVA, the dynamic properties of the target platform must be confirmed by simulation and experimental verification. The simulation model is established and simulated by SolidWorks Simulation® in advanced. Moreover, the simulation results are verified by experiment. The experimental confirmation utilizes an

impact hammer to perform the impulse modal testing. The comparison between simulation and experimental results is shown in Table 1. The modal shapes and corresponding natural frequencies of the first six modes of the platform are presented. Considering there are still a lot of details simplified in simulation model, the simulation error is reasonable and acceptable. In this paper, the speed of motor is deliberately regulated to stimulate the resonant frequency and imitate the practical device which suffers the resonance.

Table 1. Natural frequencies and corresponding modal shapes of the platform.

Mode	Natural Frequency (Hz)		Error(%)	Modal Shape
	SolidWorks Simulation®	Experimental Result		
1st	18.16	17.25	+5.28	*y*-axis translation
2nd	18.44	18.25	+1.04	*x*-axis translation
3rd	29.76	30.25	-1.62	*z*-axis rotation
4th	29.91	31.50	-5.05	*z*-axis translation
5th	36.71	42.25	-13.1	*x*-axis rotation
6th	50.52	51.50	-1.90	*y*-axis rotation

According to the configuration of the pedestal chosen for placing the WTVA, the controllable modes of the platform are 1st, 4th and 5th modes. The other modes are not included for vibration reduction demonstration in this paper. However, they are easy to implement. For instance, the WTVA just needs to be replaced along the Y-axis for controlling other modes.

3.2 Design of the WTVA

For the design of the proposed WTVA, its specific parameters, described in Eq. (8), should be determined according to the natural frequencies of the target platform. The diameter (d), total length (L) and density per unit length (ρ) of Ni-Ti SMA wire are 0.6 mm, 90 mm and 1.84E-6 kg/mm, respectively. The mass of rectangular-shaped auxiliary mass (m) is 0.054 kg, which is in the order of hundredth of the platform. In order to measure the magnitude of axial force which is generated from SMA wires, two strain gages are attached on opposite sides of the rectangular auxiliary mass block. By measuring the strain of the mass block under loading, the corresponding axial force generated from the SMA wires can be directly obtained.

To control the tunable frequency of WTVA, the operating procedures are explained in the following. At the first step, a pretension is exerted on the movable holder to deform the SMA wires by tightening the adjustment screw, as shown in Fig. 1. After exerting the initial pretension, the movable holder is fixed. The deformed WTVA is then heated by applying electric current, so that the SMA wires are prone to return to their original length because of shape memory effect. Since both ends are fixed, the SMA wires are restrained to return to their original lengths. Therefore, a further internal axial force is generated, attaining a large controllable and tunable frequency capability.

Before being installed on the platform, the WTVA must be first characterized to determine the relationship among pretension, control electric current and corresponding natural frequency. Figure 4 presents the natural frequency of the WTVA under applied electric current and various pretensions. By adjusting the pretension, the working frequency span of WTVA can be roughly adjusted to cover the target frequency. It is seen in Fig. 4(a) that the formulation predicts the natural frequency of the WTVA with good accuracy. With the control of electric current, the tunable frequency span of WTVA is found to be approximately from 15 Hz to 45 Hz, as presented in Fig. 4(b), which represents a change of

about 200% from the lowest frequency. Moreover, the little difference between the heating and cooling control demonstrates insignificant nonlinear effect and makes the control simpler. Compared with previous researches [8, 19, 20], the tunable frequency span is drastically improved due to the design of this WTVA.
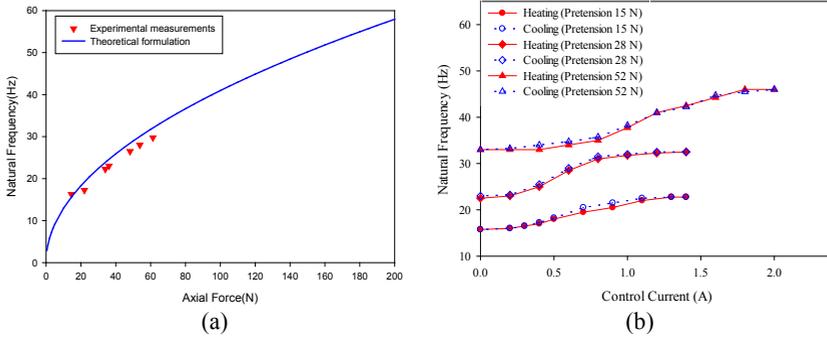

(a)   (b)

Fig. 4. The natural frequency of the WTVA under different applied pretensions: (a) natural frequency controlled by applied axial force, (b) natural frequency further controlled by applied electric current.

4 Experimental results and discussion

4.1 Experimental setup

WTVA is installed onto the platform as shown in Fig. 5. The DC power supply provides the control electric current to SMA wires in order to precisely adjust the natural frequency of the WTVA. The AC servo motor can excite the platform in different vibration frequencies by controlling its speed. A tri-axial accelerometer is utilized to measure the vibration and the effectiveness of vibration reduction can be evaluated. Both signals from tri-axial accelerometer and DC power supply are recorded and further processed by the dynamic signal analyser. According to its installed location, the WTVA can be employed to control the 1st mode (17.25 Hz), the 4th mode (31.5 Hz) and 5th mode (42.25 Hz) of the platform.
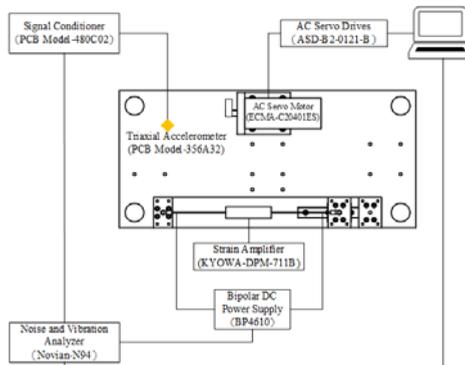

Fig. 5. Experimental setup for using WTVA in vibration control of a platform structure.

4.2 Performance of vibration reduction

For vibration reduction of the platform's 1st mode, the speed of the motor is first adjusted to reach the resonant frequency of 17.25 Hz (1035 rpm). A 0.4-A electric current with 15 N of

pretension is the closest to the driving frequency of the platform, as shown in Fig. 4. The measured vibration result is shown in Fig. 6. The power supply is adjusted from 0 A to 0.4 A at 3 s after the beginning of data recording for the heating situation shown in Fig. 6(a). It is seen that the amplitude of the platform reaches the steady state after 30 s. As the results before and after control show, the vibration reduction rate reaches approximately 84%. Apart from the heating procedure, the response time of cooling procedure is also considered since the rotating speed of the devices could alter in the practical application. To demonstrate the control effectiveness during cooling process, the current of the WTVA is initially adjusted to 1.3 A to offset from its resonant frequency. Afterwards, the control current on the WTVA is adjusted from 1.3 A to 0.4 A at same instant as heating example. The result presented in Fig. 6(b) shows the effect of vibration reduction can achieve around 77.6%.
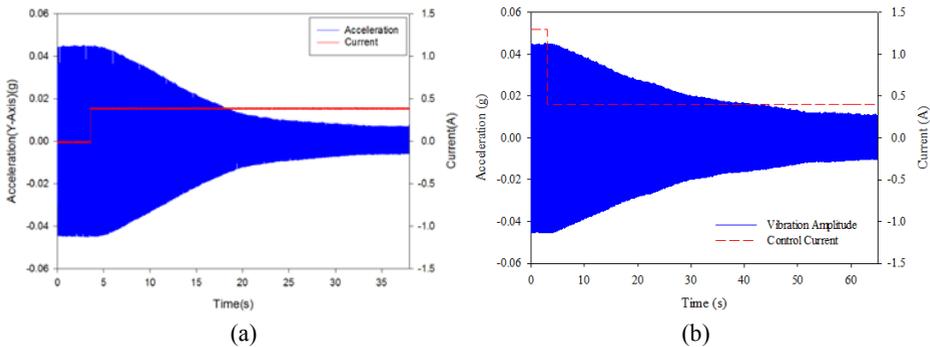

(a)   (b)

Fig. 6. Experimental results of 1st mode vibration reduction at 1035-rpm speed: (a) heating, (b) cooling.
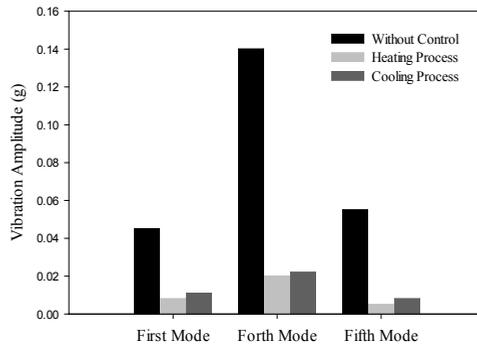

Fig. 7. Experimental results for vibration reduction of the platform.

The vibration control for the 4th and 5th modes of the platform with WTVA is also investigated. It should be noted that different modes have different natural frequencies and modal shapes. Nevertheless, the steps are same as those in the experiment for the first mode. Only the motor speed, pretension and electric current of the WTVA are different. The pretensions for controlling the 4th and 5th modes are respectively adjusted to 28N and 52N at the beginning. The electric currents for precisely tuning the natural frequency of WTVA are 0.8 A and 1.3 A, respectively. The speeds of AC servo motor are separately tuned to1890 rpm (31.5 Hz) and 2535 rpm (42.25 Hz) to excite the resonance of platform. Fig. 7 summarizes the measured results to compare the performance of vibration reduction. The vibration amplitude of the platform can greatly reduce up to 90% even with this WTVA having considerably small weight fraction comparing with platform. The results

demonstrate that the proposed WTVA not only can considerably increase the capability of vibration reduction compared with previous research, but also extend the controllable frequency span for practical application.

4.3 Improvement for steady-state time response

A long response time of the WTVA can influence its practical applications. Generally, vibration control requires timely response. It is evident that the response time of steady-state during cooling process is usually longer than heating, since the cooling speed of the SMA wires depends on the relative temperature between SMA wires and surrounding under natural convection. For time-varying systems, the control robustness is improved by decreasing the response time of the systems.

The 1st mode of the platform is chosen to demonstrate the efficiency of proposed speed-up approaches in this paper. In Fig. 8(a), the response time takes 27 s for achieving the steady-state which is slow response in practical application. As the concept for heating, the higher control current can accelerate the heating procedure. Therefore, the control current for heating process is doubled from 0.4 Ampere to 0.8A, and kept constant for 3 seconds. The result is showed in Fig. 10. The response time is reduced to 5 seconds, which is around 1/6th of the response time compared with Fig. 8(a). The result also reveals that the larger current can be first used to accelerate the heating response, then adjust to and keep the corresponding control current of natural frequency of the WTVA.

The approach which is employed to accelerate response time in the cooling procedure is to apply a fan to forcibly cool down the SMA wires. In a similar fashion to the experimental processes, the result obviously shows that the response time can be greatly reduced by force-cooling device, as shown in Fig. 8 Compared with the response time without forced cooling, and the response time is shortened by 50%.

In this paper, the natural frequency of the WTVA is tuned by manually controlling the electrical current. In order to increase the efficiency of the vibration reduction, an adaptive control system must be employed since the natural frequency of the WTVA must be as close as possible to the target's. Adaptive control system could not only increase the efficiency, but also appropriately adjust the heating current to improve the time response. Moreover, the vibration energy of the platform is absorbed to the WTVA. Meanwhile, the vibration amplitude of WTVA becomes extremely huge. Therefore, the vibration energy of the WTVA can be harvested and reused by design of an energy harvesting device.
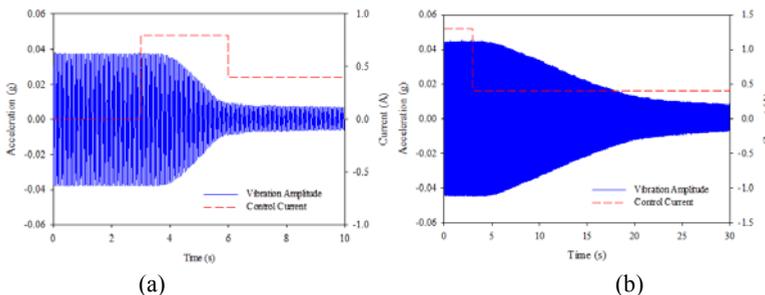

| (a) | (b) |

Fig. 8. The results of improved steady-state time response for 1st mode of platform: (a) with the regulation of electric current in heating procedure, (b) with forced cooling device in cooling procedure.

5 Conclusions

This paper proposes the feasibility of the wire-type vibration absorber (WTVA) with simple and tiny architecture, which consists of the shape memory alloy (SMA) wires and the auxiliary mass with strain gages. The tunable span of the WTVA is found to be approximately from 15 to 45 Hz, which represents a change from the lowest frequency of about 200%. The frequency variation is greatly increased with considerable weight difference compared with previous research. In addition, the experimental results confirm that the vibration amplitude of platform is effectively reduced, while natural frequency of the WTVA is adjusted to track the specific frequency of the platform. The maximum efficiency of vibration reduction achieves around 90%.

In this paper, the approaches for shortening response time are also proposed for practical application. In the heating procedure, the response time is greatly reduced by increasing the heating control current at beginning, since more power input can accelerate the thermal heating to achieve quickly the target temperature of the WTVA. As the result, the response time in heating procedure is improved. In the cooling procedure, the force-cooling device is utilized to accelerate the cooling speed of the WTVA. The results prove that the proposed approaches can reduce response time of the WTVA effectively.

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