Control of vibration by using dynamic vibration absorber

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Abstract: Vibration is one of the most important problems that engineering systems and suspension systems which negatively affected the performance of the system as it leads to energy loss, equipment damage, mechanical parts erosion, low product cost and quality. Therefore, many methods have been studied to reduce the vibrations, and the most important of these methods is the use of a vibration absorber. Several different technologies have been used to improve the performance of adaptation, and the important one from these technologies is the use of smart materials. The present invention relates to a vibration absorber which an absorber end mass is coupled to a primary mass from two degrees of freedom, with shape memory alloy (SMA) springs. Preferably, the end mass is coupled to the primary mass with several discrete SMA springs, which may be individually heated. When each of the SMA spring is heat above a predetermined temperature, the SMA material undergoes a phase change that results in a change in the stiffness of the SMA spring. Experimental and theoretical results have shown that the SMA-based dynamic vibration absorption is more effective in reducing the vibration amplitude for a wider frequency range. The range of error does not exceed 20% approximately. Therefore, good agreements between theoretical and experimental results in 2DOF system are obtained.

1. Introduction
Frahm first proposed the dynamic vibration absorber (DVA) around a century before. A standard tuned vibration absorber is one DOF regime that can be utilized for suppressing a bothersome resonance or for attenuating the structure’s vibration at a specific pressuring frequency. Presumed that the chief structure characterized via single degree of freedom regime, there are (3) variables that can be chosen via the designer of vibration absorber for tuning the absorber performance: the ratio of frequency, the damping ratio of vibration absorber, and the absorber mass. The ratio of mass between the principal mass of regime and the (DVA) mass is typically presumed as fixed parameter well-defined in the stage of pre-design and is limited owing to the practical features. Due to such cause, the majority of the printed investigations content themselves with double design parameters \cite{1}.

Sung et al. \cite{2} reviewed the shape memory alloy materials uses for the passive, active and semi active governors of the civil constructions. They provided the SMA characteristics overview, studied the (SME) effect as well as the false flexibility, the (2) main SMA features connected with thermal or reversible hysterical phase-induced conversion between the martensite and the austenite It was found that such only features assist the shape memory alloy use as triggers and passive energy dispersants as well as dampers to control the civil construction. Mani et al. \cite{3} used a dynamic vibration absorber (DVA) as an effective vibration control device. It is an accessory block that attached to the creative regime via the damper and spring. The (DVA) usual frequency was adjusted, so it matches with the undesirable vibration frequency in the creative regime. That leads to inertial energy absorption transfer from the basic structure. A dynamic vibratory absorber for adaptation was developed with shape memory alloy springs assistance for relieving the vibration for an excitation frequencies range. The only characteristic of Young's temperature-based standards vigorously varies the spring hardness was
used to control vibration. Experimental results showed that the dynamic vibration absorption based on SMA being higher influential to reduce the amplitude of vibration for a broader range of frequency.

Chavan [4] studied the dynamic trend of a composite beam that is embedded with the shape memory alloy wires, and via using an electrical current, the wires converted the thermal energy into mechanical. The result showed that the supply of current passing through the number of wires is directly proportional to temperature rise, so when the shape memory alloy wires are activated, the beam stiffness varies proportionally, and this causes a shift in the beam natural frequency. At the range of current 0 to 1.5 Amps, the beam natural frequency being a maximum, and after that, the natural frequency decreases due to increasing heat of the beam. The damping factor of the composite beam increased at 0 to 1.5 Amp current and then reduced because the stiffness of beam decreased. Elahinia et al. [5] used SMAs in the passive tuned vibration absorbers for improving the robustness of the tuned vibration absorbers that are subjected to the variation of mass in the initial regime. For the robustness analysis, the initial mass of regime is changed by \( \pm 30\% \) of its nominal mass. The results of simulation depicted that the shape memory alloys in tuned vibration absorbers is highly robust than the corresponding passive tuned vibration absorbers in decreasing the ultimate vibrations in the initial regime that is subjected to the variation of its mass.

Wagner et al. [7] focused on the deterministic harmonic loads and dealt with the new tuned mass dampers’ locations that are automatically till now. They used standard tuned vibration absorber as 1 DOF regime, for suppressing a bothersome resonance or attenuating the structure vibration at a specific pressuring frequency and using the finite element approach for discretizing the continuous construction. Santos et al. [8] explored the abilities of an original adaptive vibration absorber for the civil engineering constructions, depending upon the temperature modulation of SMA restitution elements. The SMAs real time temperature modulation, throughout the Joule influence, assisted to govern the modulus of elasticity of such elements, by making the thermal transformations of martensitic, and permitted for the absorber stiffness adaptation, so as to become uninterruptedly tunable for a broad range of frequency. The absorber included a suspended mass that is linked to the principal construction via a set of SMA cables, utilizing a multiple pulleys system for making the governing system highly compact.

The aim of this work, building a smart system using smart materials to control vibrations. Application of smart systems in practical applications, such as smart joints and suspension system in cars. Study the effect of many sites of spring types and finding the ideal sites that have the effect of resisting and damping vibrations.

2. The equations used in the present study

This section treats with the 2DOF systems that require (2) independent coordinates for describing their motion. The motion coupled equations of system are derived employing the Newton’s second law of motion. Through stating, such equations are recognized in a form of matrix, the system matrices of mass and stiffness.

Case one: two masses and three spring

\[
\begin{align*}
K_1 x_1 + K_2 (x_1 - x_2) &= F_1(t) + F_2(t) \\
K_3 x_2 &= F_2(t)
\end{align*}
\]
\begin{align*}
\omega_1^2 &= \left(\frac{k_1 + k_2}{m_1} \frac{k_2 + k_3}{m_2}\right) + \sqrt{\left(\frac{k_1 + k_2}{m_1}\right)^2 + \left(\frac{2k_2 + k_3}{m_2}\right)^2 - 4\left(\frac{k_1 k_2 + k_1 k_3 + k_2 k_3}{m_1 m_2}\right)} \\
\omega_2^2 &= \left(\frac{k_1 + k_2}{m_1} \frac{k_2 + k_3}{m_2}\right) - \sqrt{\left(\frac{k_1 + k_2}{m_1}\right)^2 + \left(\frac{2k_2 + k_3}{m_2}\right)^2 - 4\left(\frac{k_1 k_2 + k_1 k_3 + k_2 k_3}{m_1 m_2}\right)}
\end{align*}

**Case two: two masses and two springs**

3. **The experimental work**

The materials used in the preparation of the device consist of three cars made of acrylic material, and Table (1) lists the characteristics of acrylic material [9]. Four types of steel springs have different lengths and diameters; Table (2) shows the physical properties of steel springs. A shape memory alloy springs (nitinol), a perfect combination near 50/50 of nickel and titanium. The diameters of the nitinol spring wire are 0.5 mm.

Experimental test rig is constructed in this work in order to evaluate the effects of SMA springs on the vibrations of spring-mass system; and how that damped the vibrations. Aluminum rail with length 110 cm are used and three cars made from acrylic material fixed in the rail with allowable to remove one of those cars from the rail. One accelerometer is fixed in each car by silicon foam and many springs made from steel and SMA are connected between these cars, one thermo-cable is fixed on each SMA using silicon foam, both ends for each SMA springs are connected to electrical current in order to control in temperature of SMA spring. Volt-ampere reader reads the temperatures. Electrical current is controlled by Arduino cart, as shown in figure (1).
Figure 1. Photo of the experimental rig.

Table 1. The properties of acrylic material

| properties              | Value       |
|-------------------------|-------------|
| Tenacity                | 2-4.2 g/den |
| Density                 | 1.16 g/cm³  |
| Elongation at break     | 20-55 %     |
| Resiliency              | Good        |
| Melting point           | 230⁰ C      |
| Ability to protest friction | Good      |

Table 2. The properties of spring steel

| properties              | Value       |
|-------------------------|-------------|
| Tensile strength        | 685 MPa     |
| Yield strength          | 525 MPa     |
| Shear modulus           | 80.0 GPa    |
| Elastic modulus         | 190-210 GPa |
| Poisson’s ratio         | 0.27-0.30   |
| Density                 | 7.85 g/cm³  |
| Melting point           | 1515⁰ C     |

4. Test procedure
In experiments, different types of steel springs (lengths and diameters) were used with one type of shape memory alloy springs. Spring position has been changed to obtain the best position to control the system and thus control vibration. The process of changing the spring location was repeated in different cases of all the control systems (passive, semi active and active).
5. Results and Discussion

Table (3) shows the variation of the natural frequencies of four cases in 2DOF with the stiffness of first spring ($K_1$). In that table, it is observed that when the $K_1$ variation is from 12.0548 N/mm to 28.3682 N/mm. The frequencies increased about 37% and 23%, respectively. On the other hand, in same table the frequencies increased about 21% and 14%, respectively.

**Table 3.** The relation between the variations of natural frequencies with the stiffness of first steel spring ($K_1$) in different cases.

| cases | 2nd spring (N/mm) | 3rd spring (N/mm) | First natural frequency (Hz) | Second natural frequency (Hz) |
|-------|-------------------|-------------------|-------------------------------|-------------------------------|
|       |                   |                   | $K_1=12.05$ $K_2=19.7$ $K_3=28.3$ | $K_1=12.0$ $K_2=19.76$ $K_3=28.36$ |
| Case 1 | 19.7              | 19.7              | 6.6624                        | 13.0150                      |
| Case 2 | 19.7              | 19.7              | 3.8279                        | 12.1580                      |

Table (4) shows the variation of the natural frequencies of four cases in 2DOF with the stiffness of second spring ($K_2$). In that table, when the $K_2$ variation is from 12.0548 N/mm to 28.3682 N/mm. The frequencies increased about 13%. On the other hand, in same table, the second natural frequencies increased about 34%.

**Table 4.** The relation between the variations of natural frequencies with the stiffness of second steel spring ($K_2$) in different cases.

| No of cases | 2nd spring (N/mm) | 3rd spring (N/mm) | First natural frequency (Hz) | Second natural frequency (Hz) |
|-------------|-------------------|-------------------|-------------------------------|-------------------------------|
|             |                   |                   | $K_2=12.05$ $K_2=19.7$ $K_3=28.3$ | $K_2=12.0$ $K_2=19.76$ $K_3=28.36$ |
| Case 1      | 19.7609           | 0                 | 7.5140                        | 13.0150                      |
| Case 2      | 0                 | 0                 | 4.2590                        | 12.1580                      |

The variation of the natural frequencies of four cases in 2DOF with the stiffness of third spring ($K_3$) is shown in Table (5). In that table, it is noticed that when the $K_3$ variation is from 12.0548 N/mm to 28.3682 N/mm. The first and second natural frequency increased about 23% and 8%, respectively.

**Table 5.** The relation between the variations of natural frequencies with the stiffness of third steel spring ($K_3$) in different cases.

| No of cases | 2nd spring (N/mm) | 3rd spring (N/mm) | First natural frequency (Hz) | Second natural frequency (Hz) |
|-------------|-------------------|-------------------|-------------------------------|-------------------------------|
|             |                   |                   | $K_3=12.0$ $K_3=19.7$ $K_3=28.3$ | $K_3=12.0$ $K_3=19.7$ $K_3=28.36$ |
| Case 1      | 19.76             | 19.76             | 6.6624                        | 13.0150                      |
| Case 2      | 19.76             | 0                 | 4.6439                        | 12.1580                      |

Table (6) shows the variation between the natural frequencies and the increasing of masses. In this table, when the value of the first mass was increased from 0.30 kg to 0.50 kg, the natural frequencies decreased, and the first and second natural frequency from case one decreased 7%. In case two, the first and second natural frequency decreased 9%.

Table (6) shows the variation of the natural frequencies of four cases in 2DOF with the stiffness of third spring ($K_3$). In that table, it is observed that when the $K_3$ variation is from 12.0548 N/mm to 28.3682 N/mm. The frequencies increased about 37% and 23%, respectively. On the other hand, in same table the frequencies increased about 21% and 14%, respectively.

**Table 6.** The relation between the variations of natural frequencies with the stiffness of third steel spring ($K_3$) in different cases.

| No of cases | 2nd spring (N/mm) | 3rd spring (N/mm) | First natural frequency (Hz) | Second natural frequency (Hz) |
|-------------|-------------------|-------------------|-------------------------------|-------------------------------|
|             |                   |                   | $K_3=12.0$ $K_3=19.7$ $K_3=28.3$ | $K_3=12.0$ $K_3=19.7$ $K_3=28.36$ |
| Case 1      | 19.76             | 19.76             | 6.6624                        | 13.0150                      |
| Case 2      | 19.76             | 0                 | 4.6439                        | 12.1580                      |
Table 6. The variation between of natural frequencies with the increasing first masses from 0.30 kg to 0.50 kg in different cases.

| Value of first mass | Value of second mass | First natural frequency(Hz) | Second natural frequency(Hz) |
|---------------------|----------------------|-----------------------------|-----------------------------|
|                     |                      | First case                  | Second case                 |
| 0.30                | 0.35                 | 7.786                       | 4.736                       |
| 0.35                | 0.35                 | 7.514                       | 4.643                       |
| 0.40                | 0.35                 | 7.251                       | 4.553                       |
| 0.45                | 0.35                 | 7.001                       | 4.465                       |
| 0.50                | 0.35                 | 7.251                       | 4.379                       |

6. Conclusion

1. At room temperature (martensite stage), the use of shape memory alloys springs increases the natural frequencies.
2. When the temperature was increased to 40°C (the shape memory alloy springs switched to the austenite stage), the natural frequencies increased (higher than the martensite phase). This feature is useful for avoiding the resonance by controlling the natural frequency values for vibration patterns.
3. It was found in 2DOF system that the greatest effect of the spring site on the natural frequencies is in free systems from one end of it and the largest effect of the spring when the spring is connected between the fixing point and the first mass ($k_1$).
4. The hybrid systems (semi active) of 2DOF were found to have the greatest spring effect when the SMA spring was installed between the two masses ($k_2$).
5. It was obtained in the active systems of 2DOF when changing the temperature of the SMA springs from 37°C to 85°C, the first natural frequency increased about 33%, while the second natural frequency was about 15%.

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