Active control of structures using macro-fiber composite (MFC)

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Abstract. This paper presents the use of macro-fiber composites (MFC) for vibration reduces of structures. The MFC consist of polimimid films with IDE-electrodes that are glued on the top and the bottom of rectangular piezoceramic fibers. The interdigitated electrodes deliver the electric field required to activate the piezoelectric effect in the fibers and allows to invoke the stronger longitudinal piezoelectric effect along the length of the fibers. When this actuator embedded in a surface or attached to flexible structures, the MFC actuator provides distributed solid-state deflection and vibration control. The major advantages of the piezoelectric fibre composite actuators are their high performance, flexibility, and durability when compared with the traditional piezoceramic (PZT) actuators. In addition, the ability of MFC devices to couple the electrical and mechanical fields is larger than in monolithic PZT. In this study, we showed the experimental results that an MFC could be used as actuator to find modal parameters and reduce vibration for structures such as an aluminium beam and metal music plate. Two MFC actuators were attached to the surfaces of test subjects. First MFC actuator used to supply a signal as exciter of vibration and second MFC show his application for reduction of vibration in the range of resonance frequencies. Experimental results of aluminium beam with MFC actuators compared with finite element model which modelled in ANSYS software. The applied voltage is modelled as a thermal load according to thermal analogy for MFC. The experimental and numerical results presented in this paper confirm the potential of MFC for use in the vibration control of structures.

1. Introduction

The development of smart structure technology offers great potential in the field of active vibration control and noise control of structures in different fields of application, such as aerospace, civil, and mechanical engineering.

During the past few years, piezoelectric materials have been extensively used as actuators and sensors for noise and vibration control. This new structural concept requires the use of sensors and actuators for controlling the mechanical behavior of structural systems when using the converse piezoelectric effect to induce control forces and moments.
Due to increasing interest in the design of complex smart structures with piezoelectric actuators and the need for fast and simple implementation of piezoelectric control systems, technology developers are beginning to provide more convenient tools to model smart structures.

The use of piezoceramic PZT materials for structural actuation and sensing is a fairly well-developed area. Monolithic PZT, however, imposes certain restrictions for its practical use in real-world applications. For instance, the extremely brittle nature of the PZT material requires extra attention during the handling and bonding procedures. In addition, the conformability to curved surfaces is extremely poor requiring extra treatment of the surfaces and additional manufacturing capabilities.

The idea of using active piezoceramic composite actuators to overcome these limitations has been explored, producing a number of solutions. This new piezoelectric actuators evolved as a viable alternative to using a monolithic piezoelectric material. There are several types of active composites available commercially or under development at research institutes, namely 1–3 composites by Smart Materials Corp. [1], Active Fiber Composite actuator developed by MIT [2], and Macro fiber composite (MFC) actuators constructed at NASA Langley Center [3].

The actuator consists of polyamide films with interdigitated electrodes that are glued on the top and bottom of piezoceramic fibers, this configuration is shown in figure 1. The interdigitated electrodes deliver the electric field required to activate the piezoelectric effect in the fibers and allows invoking the stronger longitudinal piezoelectric effect along the length of the fibers.

Due to the MFC’s construction using piezofibers, the overall strength of the material is greatly increased when compared to that of the base material, while affording the MFC greatly increased flexibility. Furthermore, the interdigitated electrodes allow the applied electric field to run axially allowing the higher $d_{33}$ coefficient to come into play, rather than the $d_{31}$ coefficient active in a monolithic PZT. The result is that the MFC has a substantially larger electromechanical coupling coefficient and produces larger force and free displacement.

In compare with MFC, the circular cross-section PZT fibers of the AFC had very little contact area between the interdigitated electrodes and the fibers, which resulted in the transfer of the electric field into the PZT fibers inefficiently. The rectangular PZT fibers of the MFC improved the maximum contact area between the PZT fibers and the interdigitated electrodes. An overview and comparison of these actuators can be found in the literature [4].

In this paper, a review is presented for vibration suppression of Experimental results of aluminium beam with MFC actuators compared with finite element model which modelled in ANSYS software. The applied voltage is modelled as a thermal load according to thermal analogy for MFC.
The thermal analogy basis on uses thermally induced strain to model straining of the actuator due to an applied voltage field based on the analogy between thermal strains and piezoelectric strains. An applied electric field is input as a thermal load and piezoelectric strain coefficient characterizing an actuator are modeled as thermal expansion coefficient determined by the following relationship:

\[ \alpha_i = \frac{d_{ij}}{\Delta_{ES}} \]  

where \( d_{ij} \) is the effective piezoelectric constant and \( \Delta_{ES} \) is the electrode spacing taken as \( \Delta_{ES} = 0.5 \text{ mm} \).

This approach is then used to find modal shape forms of a cantilever aluminium beam with surface bonded MFC actuators in finite element program ANSYS and for demonstration the reduction of vibration.

2. Experiment results

2.1. Aluminium beam

The control problem of cantilever flexible beam has been investigated by various researchers [5-8], where the piezoelectric actuators were used. Present time the MFC actuator is is an innovative actuator that offers high performance and flexibility in a cost-competitive device. The application of this actuator for vibration control was showed in the present work.

The application of MFC actuators for vibration control of beam was presented in this work in compare with experimental and finite element results of beam.

Our first experiment includes investigation the use of MFC to control and reduce the vibration of a rectangular aluminum beam.

The test were performed on an aluminum beam of dimensions 620x62x1.95 mm with MFC mounted on the top and bottom at the root of the beam, as shown in figure 2. The dimensions of the active part of MFC actuators were: 85x28x0.3 mm. The polyamide film outside the active region and the epoxy bond between the MFC actuator and aluminum beam were ignored.

The material properties of the components are as follows:

- **Aluminum:**
  
  \( E = 13.790 \text{ GPa}, \ G = 2.000 \text{ GPa}, \ \nu = 0.44, \ \rho = 11300 \text{ kg/m}^3 \)

- **MFC:**
  
  \( E_x = 30.0 \text{ GPa}, \ E_y = 15.5 \text{ GPa}, \ E_z = 15.5 \text{ GPa}, \ G_{xz} = 10.7 \text{ GPa}, \ G_{yz} = 10.7 \text{ GPa}, \ G_{xy} = 5.7 \text{ GPa}, \)

  \( \nu_{xy} = 0.4, \ \nu_{xz} = 0.4, \ \nu_{yz} = 0.35, \ d_{33} = 4.18 \times 10^{-10} \text{ m/V}, \ d_{32} = d_{31} = -1.98 \times 10^{-10} \text{ m/V}, \)

  \( \rho = 4700 \text{ kg/m}^3 \)

Here, \( E \) is Young’s modulus, \( G \) is the shear modulus, \( \nu \) is Poisson’s ratio, \( \rho \) is the density and \( d_{ij} \) is the effective piezoelectric constant.

Figure 2. Schematic of aluminium beam with MFC.
The modal analysis obtained with application Polytec laser scanning vibrometer systems, when one MFC is exciter and second as suppressor (figure 3).

A vibrometer system is comprised of controller electronics and a non-contact standard-optic or fiber-optic sensor head. The controller provides signals and power for the sensor head, and processes the vibration signals. These are electronically converted by specially developed decoders within the controller to obtain velocity and displacement information about the test structure. This information is provided by OFV-5000 in either analog or digital form, for further data evaluation.

The beam is excited using MFC attached to it. The MFC actuator is connected to an amplifier and the frequency is varied using frequency generator. Response of beam is measured by the scanning laser and stored on PC. To enable a better scanning the beam are painted in white. The beam is excited continuously and the laser measures its response. Then the experimental results are compared with the predicted frequencies, which are calculated by the finite element program ANSYS.

The testing results of using MFC as exciter are shown in figure 4. Parallel modal analysis have been done with using of finite element program ANSYS and with application of analytic result for first three frequencies (Table 1). Results from table show good coincidence between Polytec laser scanning vibrometer systems, ANSYS and analytic results.
Figure 4. Experimental frequency response of cantilever aluminium beam.

The same experiment was modeled in ANSYS, when the piezoelectric thermal analogy implemented in ANSYS, as described above. The results of experiment for second mode shape are shown in table 2. From this table may see that with increase of voltage the amplitude of displacement decrease and reduction of vibration increase. The function of reduction $R$ is given by formula

$$R = \left(1 - \frac{A}{A_0}\right) \cdot 100\%$$  \hspace{1cm} (2)

where $A$ is the amplitude of displacement with voltage $V \neq 0$, and $A_0$ is the amplitude of displacement with voltage $V = 0$.

| No of modes | Frequency, Hz |
|-------------|---------------|
| 1           | 4.25          |
| 2           | 25.75         |
| 3           | 71.50         |
| 4           | 77.50         |
| 5           | 134.00        |
| 6           | 139.75        |
| 7           | 231.25        |
| 8           | 233.50        |
| 9           | 346.50        |
| 10          | 392.75        |

Table 1. frequency response for 10 mode shapes.

When voltage achieves 5 Volt the reduction is maximal 100%. The numerical results from ANSYS confirm reduction of beam like in experiment.

| Voltage, V | Amplitude, $A$ (m) | Reduction, $R$ (%) |
|------------|--------------------|--------------------|
| 0          | 1.950E-04          | 0                  |
| 1          | 1.600E-04          | 17.95              |
| 2          | 1.200E-04          | 38.46              |
| 3          | 8.000E-05          | 58.97              |
| 4          | 4.000E-05          | 79.49              |
| 5          | 1.100E-13          | 100.00             |
| 6          | 3.90E-05           | 80.00              |
| 7          | 7.20E-05           | 63.07              |

Table 2. Optimal voltage, reduction, and amplitude for the second mode shape.

2.2. Test of Plate

The second experiment includes investigation the use of MFC to control and reduce the vibration of a musical plate.

The test were performed on a musical plate with 2 MFC mounted on the top of plate, as shown in figure 5. The dimensions of the active part of MFC actuators (the polyamide film outside the active
region and the epoxy bond between the MFC actuator and aluminum plate were ignored) were: 85x28x0.3 mm.

![Experimental equipment and test object.](image)

**Figure 5.** Experimental equipment and test object.

First all the modal analysis obtained with application of ISI-SYS equipment where Vibrograph is the main component of measure. Natural frequencies of the plate are measured using vibrograph employing shearography technique. The principle of operation to find of natural frequencies is the same like above for Polytec equipment. The MFC actuator is connected to an amplifier and the frequency is varied using frequency generator. Response of beam is measured by the scanning laser and stored on PC. The testing results of using one MFC actuator as exciter are shown in figure 6.

![Experimental frequency response of music plate.](image)

**Figure 6.** Experimental frequency response of music plate.

The visual test for reduction of vibration was modeled for all frequencies in the range from 0 until 1600 Hz. Example of reduction show in figure 7. The monitor show mode shape, when frequency is 1399.4 Hz. After application of second MFC actuator as suppression the mode shape evanesce and view of plate look as without application of exciter. This experiment visual demonstrate the application of MFC as suppression for reduction of vibration.
3. Conclusions
An overview was presented for vibration suppression of structures with special emphasis laid upon smart structures with piezoelectric control actuation.

The Macro Fiber Composite Actuator, recently developed by NASA Langley Research Center, has been investigated here as an actuator for control of vibrations. The unique design of MFC provides more desirable characteristics when compared with monolithic PZT-based. The results presented here have shown that an MFC actuator works exceptionally well as part of a modal-testing system and a control system.

The tests illustrate the effectiveness and usefulness of the MFC device as an exciter and suppression. The experiments include the modal testing show good results in compare with finite element models for aluminium beam. The experiments for aluminium beam with MFC actuator based on thermal analogy method for vibration of reduction are compared with ANSYS results and excellent agreement is observed.

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