Active Vibration Control Using Embedded Piezoceramics as both Actuators and Sensors

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Piezoceramics can be used as both actuators and sensors, named piezo-actuators and piezo-sensors, due to its respective attributes of inverse piezoelectric effect and direct piezoelectric effect. One of the application fields of the piezoceramics is active vibration and noise control. The early studies are mostly focused on surface glued piezoceramics but have problems with the protection of the ceramics and the connection wires, bad coupling with the base materials etc. With embedded piezoceramics, the patches can be placed to the optimal positions, especially the optimal deepness for the piezo-actuators, according to an optimization procedure before they are embedded, and the actuator effects and sensor signals are thereby enhanced. This paper deals with the active vibration control using embedded piezoceramics as both actuators and sensors. With several ceramics embedded into the composite material structures during the production process without knowing the structure behavior in advance, the actuator and sensor configuration can be selected during the self identification procedure at each time when needed. Then, the controller was designed based on the optimal control theory for the actuator and sensor pairs. The experimental results show that the vibration of the structure can be successfully suppressed.

1. INTRODUCTION

Active vibration control is widely used because of its broad frequency response range, low additional mass, high adaptability and good efficiency. Comparing to the passive vibration control, closed loop active vibration control needs sensors to sense the vibration of the structure and actuators to suppress the vibration. Piezoelectric materials such as sintered lead-zirconate-titanate (PZT) ceramics and polyvinylidene fluoride (PVDF) films can be produced to work as both actuators and sensors due to their characters of inverse piezoelectric effect and piezoelectric effect [1]. Piezoceramics have been used successfully for many years in the field of vibration control, owning to its high forces into the range of kilonewtons and short reaction times in the order of a few microseconds. The early studies [2,3] are mostly focused on surface glued piezoceramics which has some disadvantages such as difficulties to protect the ceramics and the connection wires, bad coupling with only one surface glued on the base materials, low signal-to-noise ratio etc. These problems can be solved with the embedded piezoceramics, and furthermore, the piezoceramics can be placed to the optimal positions, especially the optimal deepness for the piezo-actuators, according to an optimization procedure before they are embedded, and the actuator effects and sensor signals are thereby enhanced. This paper deals with the active vibration control using the embedded piezoceramics as both actuators and sensors. With several ceramics embedded into the composite material structures during the production process without knowing the structural behavior in advance, this paper makes use of a self identification procedure to get the models of the system. Apparently, the self identification method makes it possible to update the system models, at each time the models can not describe the dynamic behavior of the system correctly. After the dynamic model of the system is established, the controller is designed based on the optimal control theory for the selected actuator and sensor pairs with a full state observer and pole placement techniques. The online experiments are carried out for the carbon fiber-reinforced composite material beam with piezoceramics embedded, and the experimental results show that the vibration of the structure can be successfully suppressed with the power spectrum of the sensor signals reduced up to 15 dB. Due to the hardware limitations, only one of the piezoceramics works as the actuator and another one works as the sensor at the same time.

2. OPTIMAL DEEPNESS OF EMBEDDED PIEZOCERAMICS

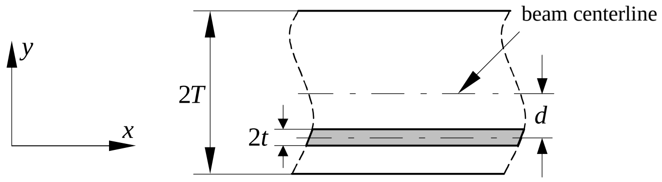

Figure 1. *Beam with Piezoceramics embedded*

The beam with piezoceramics embedded is show in Figure 1. Where, T and t are the half thicknesses of the beam and of the piezoceramics, respectively. d is the distance from the beam centerline to the centerline of the piezoceramics. The polarization direction of the piezoceramics is y direction. According to the optimization procedure, which will be presented in other papers, the piezoceramics can generate maximum moment when

$$d = \sqrt{\frac{E_s BT^3 + E_p bt^3}{3E_p bt}} \;. \tag{1}$$

E_s is the elastic modulus of the basis materials and E_p is the elastic modulus of the piezoceramics, while B is the width of the beam and b is the width of the piezoceramics. The relationship between the moment M, generated by the piezoceramics, and the distance d is described by equation (2).

$$M = \frac{-E_p E_s BT^3 Ubd_{31}d}{E_s BT^3 + 3E_p btd^2 + E_p bt^3} \tag{2}$$

Where, d_{31} is the charge constant of the piezoceramics with the driving voltage at the polarization direction and the deformation at the direction vertical to the polarization direction and U is the driving voltage. The equation (2) shows that the moment M is increased when E_s or E_p increases, but the distance d has a different influence to the moment as the Figure 2 shows the relationship between M and d. It can see from Figure 2 that the moment increases at first when the distance increases from 0, and the moment reaches the maximum value when d gets the value from equation (1), and after that the moment decreases with the distance still increases. Figure 2 also implies the influence of the elastic modulus of the basis materials and of the piezoceramics.

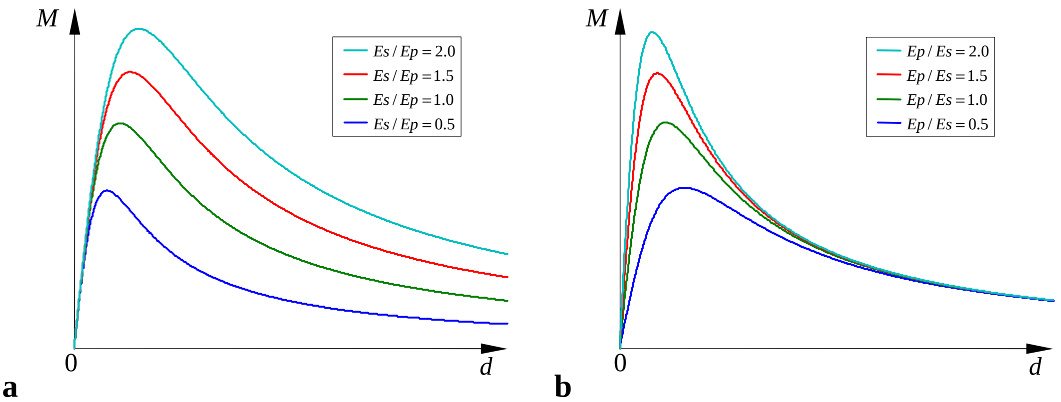

Figure 2. *Relationship between M and d*

a E_p *keeps as a constant and* E_s *increases,* **b** E_s *keeps as a constant and* E_p *increases*

The distance should satisfy $d \le T - t$, because the piezoceramics is embedded inside the beam. And thinking about equation (1), only when the ratio of the elastic modulus of the basis materials and of the piezoceramics should satisfy inequality (3), the optimal position of the piezoceramics will be inside the beam. Otherwise, the optimal position of the piezoceramics will be outside the beam.

$$r_E \le \frac{3r_T^2 - 6r_T + 2}{r_B r_T^3} \tag{3}$$

Where $r_E = E_s / E_p$, $r_T = T/t$, and $r_B = B/b$.

3. EXPERIMENT SETUP

In order to verify the above active vibration control method with embedded piezo-actuators and piezo-sensors, a carbon fiber-reinforced composite material beam with 5 PIC151 piezoceramics embedded is built. The 5 piezoceramics have the same size and have dimensions of length 50 mm, width 25 mm and thickness 1 mm. The distance between the beam centerline and the piezoceramics centerline is 0.75 mm, which is still not the optimal value in this configuration. The piezoceramics can serve as either actuators or sensors during the identification procedure described below. The beam itself has dimensions of length 500 mm, width 50 mm, and thickness 3 mm, and is clamped at both ends as shown in Figure 3. The experiment setup shown in Figure 4 consists of anti-aliasing and reconstruction filters, A/D-D/A converters, a personal computer to do data acquisition and signal processing, a power amplifier to drive the actuators, and two switches to select different actuator and sensor configurations.

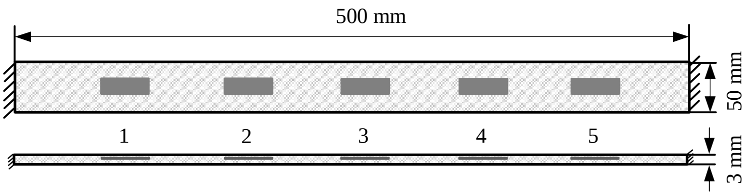

Figure 3. *Carbon fiber-reinforced composite material beam with piezoceramics embedded*

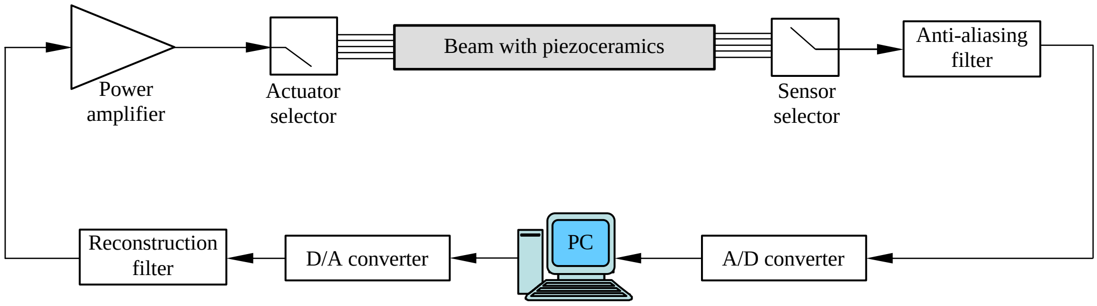

Figure 4. *Experiment setup*

4. IDENTIFICATION AND CONTROLLER DESIGN

For the identification process, one of the 5 piezoceramics was used as actuator and applied with a band limited white noise less than 3000 Hz in order to excite the beam and the responses are measured using one of the other piezoceramics. The excitation signal is generated by the computer and converted to continuous signal with the D/A converter, and on the other hand, the response signal is obtained after A/D conversion. Then, the actuator and sensor signals can be transformed to frequency domain using Fast Fourier Transform algorithm (FFT), and the frequency response of the actuator and sensor pairs are derived accordingly. Based on the frequency response, using mode analysis and frequency domain modal parameter identification technique [4], a state space model of the system can be identified as

$$\begin{aligned}\begin{Bmatrix}\dot{q}(t)\\ \ddot{q}(t)\end{Bmatrix} &= \begin{bmatrix}\mathbf{0} & \mathbf{I}\\ -\Omega^2 & -\Gamma\end{bmatrix}\begin{Bmatrix}q(t)\\ \dot{q}(t)\end{Bmatrix} + \begin{bmatrix}\mathbf{0}\\ \Phi_{\mathbf{b}}^T\end{bmatrix}u(t)\\ y(t) &= \begin{bmatrix}\Phi_{\mathbf{c}} & \mathbf{0}\end{bmatrix}\begin{Bmatrix}q(t)\\ \dot{q}(t)\end{Bmatrix}\end{aligned} \qquad (4)$$

$q(t)$ is the vector of modal displacement and $\mathbf{I}$ is identity matrix. $u(t)$ is the actuator input and $y(t)$ is the sensor output signal. Modal stiffness matrix Ω^2 is formed by the square of the modal frequencies at the diagonal entry. Modal damping matrix Γ is also a diagonal matrix and formed by $2z_i w_i$ at the diagonal entry, z_i is the damping ratio and w_i is the modal frequency. $\Phi_{\mathbf{b}}^T$ is the modal input matrix formed by modal input form vectors and $\Phi_{\mathbf{c}}$ is the modal output matrix formed by modal output form vectors. The equation (4) can be written into the standard form:

$$\begin{aligned} \dot{x}(t) &= \mathbf{A}x(t)+\mathbf{B}u(t) \\ y(t) &= \mathbf{C}x(t)+\mathbf{D}u(t) \end{aligned} \tag{5}$$

with $\mathbf{D} = \mathbf{0}$ and $x = \left[\dot{q}(t) \quad \ddot{q}(t)\right]^T$. There is only one sensor in the experiment setup at one time and it is not possible to get the information for all of the states to feed back. Thus, the full state observer technique is employed and the feedback gain matrix **K** is firstly obtained assuming that the full states are known, and then the state observer matrix **H** is designed using pole placement method.

5. EXPERIMENT RESULT

The above described identification method and the optimal controller design technique for carbon fiber-reinforced composite material beam with embedded piezoceramics are verified with an online experiment. Figure 5 shows the example of the calculated model and the identified pole/residue model. The model is very good identified for both amplitude and phase as the Figure 5 a shows. Not all of these modes can be included to design the controller due to the limitations of the hardware capabilities in this experiment setup, and only 9 modes, which have the high frequency response shown in the Figure 5 b, are included. Figure 6 shows a control result with ceramic 1 as actuator and ceramic 4 as sensor, and the vibration of the beam was generated by the ceramic 5 with a band limited white noise less than 3000 Hz.

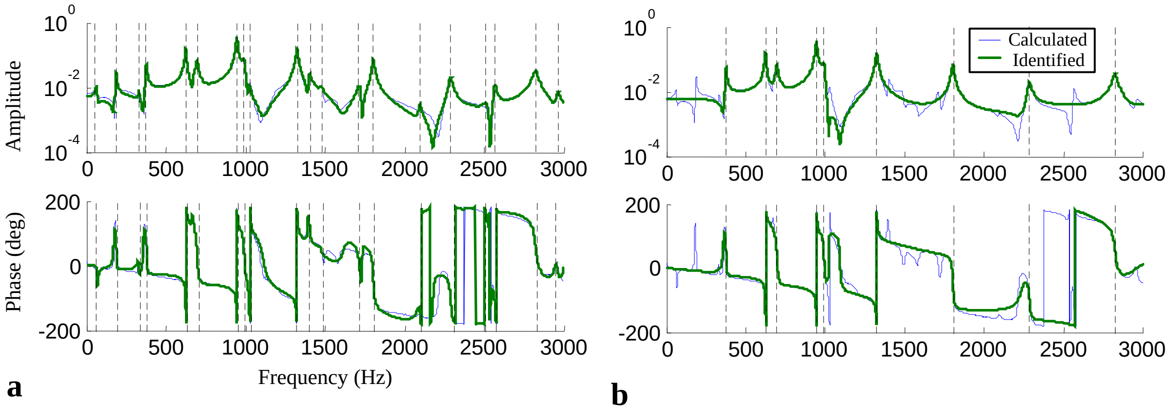

Figure 5. *Example of frequency response*
a *All modes in the identification band,* **b** *Modes used to design controller*

6. CONCLUSIONS

Composite material structures with piezoceramics embedded have several advantages compared to structures with surface glued piezoceramics. This paper describes a method to control the vibrations of the composite material structures with the embedded piezoceramics used as both actuators and sensors due to the advantages of the embedded piezoceramics. The optimal deepness and the relationship between the moment, which can be generated by the piezo-actuators, and the distance from the beam centerline to the centerline of the piezoceramics are given as equations and curves. The condition, by which the optimal position for piezoceramics is inside the beam, is also given. The online experiments with a carbon fiber-reinforced material beam with PIC151 type piezoceramics embedded show that the vibrations of the beam can be effectively suppressed by the embedded piezoceramics. The optimal controller is used in this paper, and the robust controller can be used to get more effective control result.

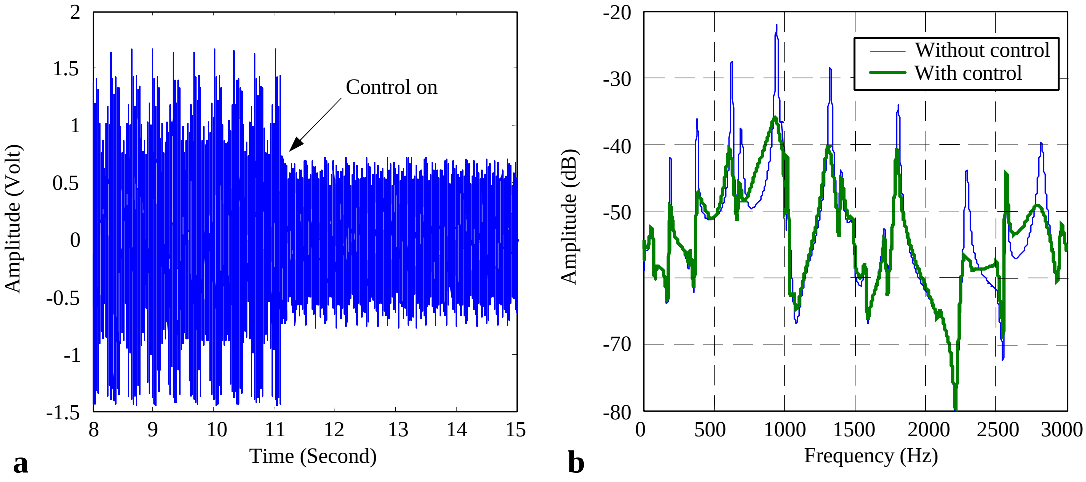

Figure 6. *Control result use ceramic 1 as actuator and ceramic 4 as sensor*
a *Sensor signal,* **b** *Power spectrum of the sensor signal*

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