DISTRIBUTED SENSING AND CONTROLS OF FLEXIBLE PLATES AND SHELLS USING DISTRIBUTED PIEZOELECTRIC ELEMENTS

HORN-SEN TZOU
Department of Mechanical Engineering and Center for Robotics and Manufacturing Systems University of Kentucky Lexington, KY 40506-0046

ABSTRACT

Distributed sensing and control of high-performance flexible structures become of importance in recent years. This paper presents an integrated distributed piezoelectric sensor and distributed actuator design for flexible structures - shells and plates. The integrated piezoelectric sensor/actuator can monitor the oscillation as well as actively and directly control the oscillation of the flexible structures by the direct/converse piezoelectric effects, respectively. Theories on the distributed sensing and active vibration control using the piezoelectric elements are first proposed. A piezoelectric finite element formulation is also developed. The distributed sensing and control of a zero-curvature shell - a plate - are studied.

1. INTRODUCTION

Increasingly, dynamics and control of large flexible structures are becoming of importance in recent years due to the rapid development of light-weight high-performance large flexible structural and mechanical systems. The inherent natural damping of such structures is usually not sufficient enough to effectively and quickly suppress the system oscillation. Thus, effective vibration control techniques are usually used to control the structural oscillation. Vibration control techniques are generally classified into two major categories: 1) the "passive" method and 2) the "active" method. Usually, the passive control device is an energy absorption or dissipation device, e.g., viscoelastic damper, dynamic absorber, shock absorber, etc [1]. The active device - actuator/controller is a countering mechanism which generates an "opposing" force or moment to actively counteract the undesirable oscillation. One of the major advantages of active devices over passive devices is a "self-adaptivity" which offers variable control efforts for variety operational environments. However, because of this adaptivity, external power supplies (e.g., electrical, hydraulic, pneumatic, etc.) and a decision-making "brain" (such as a computer) are usually required [2,3]. In addition, in order to monitor the present dynamic state, sensors or transducers are also required to provide feedback signal. In this paper, distributed sensing and control of flexible structures using distributed piezoelectric elements are presented. Theories on active distributed vibration sensing and controls are proposed to monitor and control the flexible shell and plate structures. The proposed distributed sensing and control theories are for a generic shell structure. With appropriate simplification and substitution, this general shell theory can be simplified to account for many other geometries, such as plates, spheres, cylinders, beams, etc.

There are many synthetic and natural piezoelectric materials available today. In general, most of them are crystalline solids which are dense, brittle and relatively difficult to fabricate into complex shapes. In the sensing and control of "flexible" shells and plates, a "flexible" piezoelectric material is desirable for two reasons. First, the piezoelectric material needs to be closely coupled with the flexible structures, but not change the dynamic characteristics, e.g., natural frequencies and modes. Second, the material persists certain flexibility, not brittle, so that it will not break during structural vibration. Thus, a tough and pliant polyvinylidene fluoride (PVDF) is used in this study [4]. (However, it should be noted that the developed theories and finite element formulation are general. They are not limited to a specific piezoelectric material.)

Vibration control of beam structures using piezoelectrics were evaluated [5-8]. A distributed shell sensing/control theory was also proposed [9,10]. Tzou and Gadre developed a theory for a multi-layered shell with internal distributed piezoelectric shell actuators [11]. Tzou and Tseng derived a hexahedron piezoelectric solid element with internal degrees of freedom [12]. Distributed piezoelectric sensing theory [13] and its
finite element simulation [14] were also studied. Generic theories on distributed sensing and control of shells and plates still need to be further developed. In this paper, distributed sensing and active vibration control theories for flexible shell structures with integrated distributed piezoelectric sensor/actuator are derived. A piezoelectric hexahedron finite element is also formulated for modeling and analysis of composite piezoelectric structures. Simplification of the general theories to a simple beam/plate structure is demonstrated. Distributed sensing (modal voltage distribution) and vibration controls of a zero - curvature shell - a plate are studied using the developed piezoelectric finite element technique.

2. SYSTEM DEFINITION

In this study, an elastic shell model is sandwiched between two flexible piezoelectric shell layers. One of the piezoelectric layer serves as a distributed sensor and the other a distributed actuator. Figure 1 illustrates the three-layered generic shell model.

In the theoretical derivation, it is assumed that the piezoelectric sensor and actuator fully cover the shell model. Localization and discretization of the sensor/actuator can be achieved by step-functions and/or Dirac delta functions. Note that multi-layer of piezoelectric sheets could also be coupled with the flexible shell. One group can serve as a distributed sensor and the other serves as a distributed actuator for active vibration suppression and control.

The infinitesimal distance ds (Fig. 1) of a shell element in a curvilinear coordinate system, \((\alpha_1, \alpha_2, \alpha_3)\) is defined by a fundamental form: \([11, 15]\)

\[ds^2 = A_1^2 d\alpha_1^2 + A_2^2 d\alpha_2^2 + A_3^2 d\alpha_3^2,\]

where \(A_1\) and \(A_2\) are Lamé's parameters.

![Diagram](image)

Figure 1 A flexible shell with distributed piezoelectric/actuator.

The equations of motion of the flexible shell can be derived by using Hamilton's principle,

\[-\frac{\partial (N_{11} A_2)}{\partial \alpha_1} - \frac{\partial (N_{21} A_2)}{\partial \alpha_2} - N_{12} \frac{\partial A_1}{\partial \alpha_2} + N_{22} \frac{\partial A_2}{\partial \alpha_2} - A_1 A_2 \frac{Q_{13}}{R_1} + A_1 A_2 \rho h \ddot{u}_i = A_1 A_2 F_i,\]

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sensor/actuator of the advanced structure has "breakdown" voltage around 2000 volts. When the feedback voltage exceeds this breakdown voltage, the dipolar molecular structure of the PVDF will be destroyed. Besides, the temperature variation in the piezoelectric crystal could also affect the overall performance, which is not considered in this study.

ACKNOWLEDGEMENT

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REFERENCES


**APPENDIX**

**Table 1 Material Properties of the Piezoelectric PVDF**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>Mass Density</td>
<td>$0.1800 \times 10^4$ (Kg/m$^3$)</td>
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<tr>
<td>Modulus</td>
<td>$0.2000 \times 10^{10}$ (N/m$^2$)</td>
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<thead>
<tr>
<th>Piezoelectric Coefficients</th>
<th>Value</th>
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<tbody>
<tr>
<td>$\varepsilon_{31}$</td>
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</tr>
<tr>
<td>$\varepsilon_{32}$</td>
<td>0.0460 (C/m$^2$)</td>
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<tr>
<td>$\varepsilon_{33}$</td>
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<td>$1.062 \times 10^{-9}$ (F/m)</td>
</tr>
<tr>
<td>$\varepsilon_{22}$</td>
<td>$1.062 \times 10^{-9}$ (F/m)</td>
</tr>
<tr>
<td>$\varepsilon_{33}$</td>
<td>$1.062 \times 10^{-9}$ (F/m)</td>
</tr>
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(ShiPltCnl-Penn.Shell4)