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Diagonal piezoelectric sensors on cylindrical shells

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ABSTRACT

Piezoelectric sensors are effective for distributed health monitoring and sensing of structures. The signals of piezoelectric sensors are related to the orientation of the sensors. In this study, a diagonal piezoelectric sensor is proposed for cylindrical shells. The sensor is made of a rectangular piezoelectric patch and diagonally attached on the shell surface; and piezoelectric actuators are used for excitation. An analytical model of the sensor is derived based on thin shell assumption with simply-supported boundary conditions. The orientation angle of the piezoelectric sensor is introduced as an independent variable. The proposed model consists of an integral term over the electrode area, which is divided into three regions for calculation. The sensing signal is decomposed into six components to evaluate the contributions of the strain components. Case studies on signals with respect to the orientation and aspect ratios are accomplished. The cylindrical shell with piezoelectric actuators and diagonal sensors is fabricated and tested under laboratory condition. Comparison of theoretical results with experimental data is conducted, and the model of the diagonal sensors is validated. The errors between the predictions and experimental results are less than 10% for all evaluated modes.

1. Introduction

Cylindrical shells are widely used in engineering applications, for example, pressure vessels, pipes, rocket body tube, and fairings. For dynamic control and health monitoring purposes, various methods of measurement have been proposed [1–3]. Smart structures with integrated sensors show advantages in measurement and health monitoring of distributed structures. In smart structures, piezoelectric materials are important smart materials used as actuators and sensors for their unique electro-mechanical characteristics [4–8].

Although most research focused on smart structures with plane configurations [7,9,10], a few research efforts have been put into the sensing of curved structures. For curved structures, the induced signals depend on the locations and geometry of the sensors, modes of the structures, and material properties [11,12]. In order to find the optimal location of piezoelectric sensors, a distributed neural sensing theory was proposed [13], which is a linear sensing theory for small deformation of shells. Based on von Karman geometric non-linearity assumptions, neural signal of distributed sensing element on conical shell was analyzed, the modal voltage and sensitivity were evaluated [14]. The distribution of sensing signals on shell surface can clearly illustrate the vibration of cylindrical shell panel. Signal components were evaluated to reveal the effect induced by each strain component, which can be utilized in design of piezoelectric actuators.

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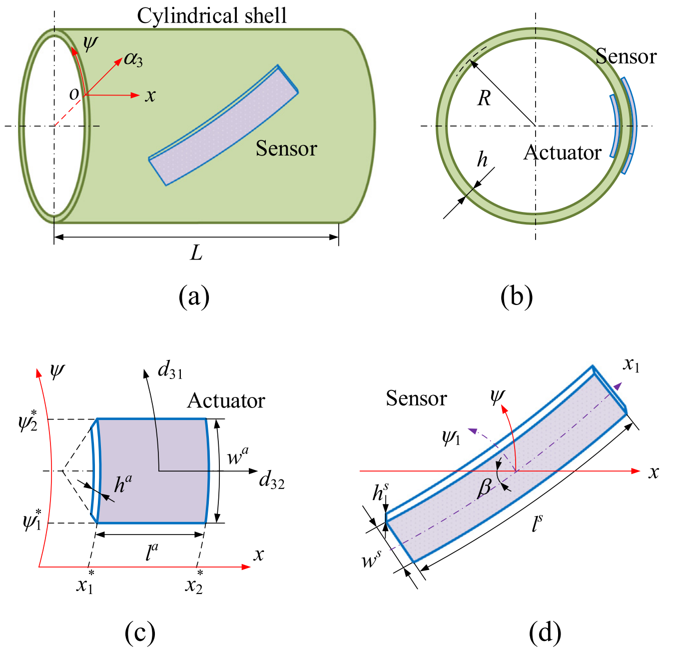

Fig. 1. Model of diagonal piezoelectric sensor on cylindrical shell with piezoelectric actuator, (a) 3D view of model; (b) lateral view of model; (c) actuator patch; (d) sensor patch.

Since the piezoelectric d_{31} and d_{32} are not the same for most piezoelectric materials, the orientation affects the dynamic characters of piezoelectric sensors and actuators [11,15]. In this study, the analytical model of diagonal piezoelectric sensors is derived, in which the orientation angle of the sensor is introduced as an independent variable. The model is then experimentally validated. The results show that the signal of a diagonal piezoelectric sensor changes with respect to orientation angle. Maximal signal amplitude at lowest modes are achieved when the orientation angle equals to π/4.

2. Model of diagonal sensors

To evaluate the signal characteristics of diagonal piezoelectric sensors, a mathematical model is needed. In this model, the orientation angles should be considered. It's assumed that the thin piezoelectric sensors are perfectly attached on shell surface; and the sensors are much thinner than the host structures, therefore, the effects of inertia and stiffness can be neglected. Piezoelectric actuators are used for excitation of the shell.

2.1. Strains of piezoelectric sensors

The boundary conditions of the host cylindrical shell are simply-supported. The piezoelectric sensors are diagonally attached on the outer surface of the cylindrical shell with the piezoelectric actuator on the inner surface, as shown in Fig. 1. L, R and h are the length, radius and thickness of cylindrical shell, respectively; l^a, w^a and h^a are the length, width and thickness of the actuator; x_1^* and x_2^* denote the actuator location in longitudinal direction; ψ_1^* and ψ_2^* denote the actuator location in circumferential direction. l^s, w^s and h^s are the length, width and thickness of the sensor, respectively; β is the orientation angle of the sensor; (x,ψ) is the global coordinate system and (x_1,ψ_1) the local coordinate system.

According to Kirchhoff-Love thin shell assumptions, only the in-plane strains S_{xx}, $S_{\psi\psi}$ and $S_{x\psi}$ are considered. The strain of the sensor is given as

$$S_{xx} = S_{xx}^o + r_x^s k_{xx} = \frac{\partial u_x}{\partial x} - r_x^s \frac{\partial^2 u_3}{\partial x^2} \tag{1a}$$

$$S_{\psi\psi} = S_{\psi\psi}^o + r_\psi^s k_{\psi\psi} = \frac{1}{R}\frac{\partial u_\psi}{\partial \psi} + \frac{u_3}{R} + \frac{r_\psi^s}{R^2}\left(\frac{\partial u_\psi}{\partial \psi} - \frac{\partial^2 u_3}{\partial \psi^2}\right) \tag{1b}$$

$$S_{x\psi} = S_{x\psi}^o + r_{x\psi}^s k_{x\psi} = \frac{\partial u_\psi}{\partial x} + \frac{1}{R}\frac{\partial u_x}{\partial \psi} + \frac{r_{x\psi}^s}{R}\left(\frac{\partial u_\psi}{\partial x} - 2\frac{\partial^2 u_3}{\partial x \partial \psi}\right) \tag{1c}$$