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Piezoelectric line moment actuator for active radiation control from light-weight structures

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ABSTRACT

This article outlines the design of a piezoelectric line moment actuator used for active structural acoustic control. Actuators produce a dynamic bending moment that appears in the controlled structure resulting from the inertial forces when the attached piezoelectric stripe actuators start to oscillate. The article provides a detailed theoretical analysis necessary for the practical realization of these actuators, including considerations concerning their placement, a crucial factor in the overall system performance. Approximate formulas describing the dependency of the moment amplitude on the frequency and the required electric voltage are derived. Recommendations applicable for the system's design based on both theoretical and empirical results are provided.

1. Introduction

Active noise control techniques can provide a reasonable alternative to passive ones for attenuation of low-frequency noise. Besides other applications, they seem to be feasible for controlling sound radiated from a light-weight structure by application of vibrational forces or moments directly to the radiating structure. This technique is commonly called active structural acoustic control (ASAC) [8] and can also be used for improvement of transmission loss of such structure without significant increase of mass, with applications in aircraft or car industry. Recently, a number of studies have been carried out in order to find a suitable actuator for practical applications. Some of them are based on classical electrodynamic construction [5]. However, for theoretical studies as well as experimental verification of ASAC systems, various piezoelectric transdusers based on lead-zircanium-titanium (PZT) piezoceramics or polymer-polyvinylidene-fluoride (PVDF) foil are most commonly used [4,17,9,14]. Both types of piezoelectric actuators can act as sensors or actuators, however, PVDF transucers are usually used only for sensing. As this paper is focused on the construction and application of new actuator, the word transducer hereinafter means actuator.

Vibrating plate or shell structures are induced by actions of mechanical forces and moments, both of which can be distributed over certain area or concentrated into several points or along lines or curves (e.g. along the edges). Transducers configured to act as (point) force actuators can be represented by a small piezoelectric patch. This type of actuator can be suitable for ASAC using a decentralized control strategy e.g. [16,2,20]. The second possibility of excitation of a structure is

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by the moment of force, which can be advantageous in specific applications. This can be realized as pair of force actuators operating in opposite phases [11] or by another configuration using the bending moments of single-layer (unimorph) [12] or double-layer (bimorph) piezoelectric stripes [21].

This paper presents a new type of line moment actuator useful for excitation of thin plates and shells in ASAC experiments. The proposed actuator consists of piezoelectric bimorphs clamped on one side to a metallic handle. When external electric voltage is applied, the bimorphs start to oscillate and the bending moment arises along the handle as the result of inertial force. Using linearized piezoelectric state equations, simplified formulas are derived for amplitude spectrum of generated bending moment. It is shown that the moment is linearly dependent upon the applied voltage. The actuator uses the mechanical resonance of the stripes to maximize the generated moment.

For analysis and description, we will assume a thin rectangular plate with an attached actuator. For the reader's comfort, the thin plate theory will be briefly summarized and discussed.

2. Bending waves in thin plates

At low frequencies (when plate thickness is small compared to structural wavelength), the most important type of mechanical waves that couple with the surrounding fluid and radiate sound are bending waves. The longitudinal waves are hard to excite and the transverse deflection is caused only by the Poisson effect which is small compared with bending wave deflection, and shear waves become important only at high frequencies.

As the bending waves are described in detail by many authors (e.g. [7,19]) we will only briefly summarize the Kirchoff theory and show the corrections for rotary inertia and shear deformation which is assumed in the Midlin theory.

Let's assume a homogeneous and isotropic thin plate with negligible damping and thickness $2h$ induced mechanically so that the bending wave is travelling in it. Under the Kirchhoff assumption, the bending wave equation can be derived

$$D\Delta_2^2 u_3 + 2h\rho\ddot{u}_3 = f, \tag{1}$$

where D is bending stiffness u_3 is the normal component of plate displacement and f is the external forcing function, which will be discussed later in this article, and Δ_2 is the two-dimensional Laplace operator. Using the Midlin theory, one may easily obtain equations of motion of a thin plate for bending (flexural) waves

$$M_{\alpha\beta,\beta} - Q_\alpha = -\rho\frac{2h^3}{3}\ddot{\varphi}_\alpha, \tag{2}$$

$$Q_{\alpha,\alpha} = 2h\rho\ddot{u}_3 \tag{3}$$

where the internal moments and shear forces are given by equations

$$M_{\alpha\beta} = \int_{-h}^{h} x_3\tau_{\alpha\beta}\,\mathrm{d}x_3, \tag{4}$$

$$Q_\alpha = \int_{-h}^{h} \tau_{\alpha 3}\,\mathrm{d}x_3. \tag{5}$$

The transverse forces do not take into account the parabolic distribution of shear stress along the thickness of the plate, which leads to warping of the plate's cross-section. The discrepancy in total energy forces us to introduce a correction factor κ [3]

$$Q_\alpha = \kappa^2\int_{-h}^{h} \tau_{\alpha 3}\,\mathrm{d}x_3 = -\kappa^2\mu 2h(\varphi_\alpha - x_{3,\alpha}) \tag{6}$$

For the case presented above the factor κ is (see e.g. [10, pp. 68])

$$\kappa^2 \approx 0.76 + 0.3\nu. \tag{7}$$

It is useful to recall that the factor κ is related to Rayleigh's surface waves and also describes the ratio of Rayleigh's waves phase speed (c_R) to the speed of shear waves (c_s). The approximate equation above is the estimation of a real root of equation

$$\left(\frac{c_R^2}{c_s^2}\right)^3 - 8\left(\frac{c_R^2}{c_s^2}\right)^2 + \frac{8(2-\nu)}{1-\nu}\left(\frac{c_R^2}{c_s^2}\right) - \left(\frac{8}{1-\nu}\right) = 0.$$

From the physical standpoint, only the root smaller than one will be of our interest.

2.1. Forcing functions

The bending waves are excited in the thin plate by actions of external forces, point forces acting perpendicularly on the surface or moments within the surface. Assuming only the forces acting normally to the surface and in-plane oriented moments, the virtual work of these external sources is