



A generic double-curvature piezoelectric shell energy harvester: Linear/nonlinear theory and applications



X.F. Zhang^a, S.D. Hu^a, H.S. Tzou^{a,b,*}

^a *StrucTronics and Control Lab, School of Aeronautics and Astronautics, Zhejiang University, Hangzhou, Zhejiang 310027, China*

^b *The State Key Lab of Fluid Power Transmission and Control, Department of Mechanical Engineering, Zhejiang University, Hangzhou, Zhejiang 310027, China*

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ABSTRACT

Converting vibration energy to useful electric energy has attracted much attention in recent years. Based on the electromechanical coupling of piezoelectricity, distributed piezoelectric zero-curvature type (e.g., beams and plates) energy harvesters have been proposed and evaluated. The objective of this study is to develop a generic linear and nonlinear piezoelectric shell energy harvesting theory based on a double-curvature shell. The generic piezoelectric shell energy harvester consists of an elastic double-curvature shell and piezoelectric patches laminated on its surface(s). With a current model in the closed-circuit condition, output voltages and energies across a resistive load are evaluated when the shell is subjected to harmonic excitations. Steady-state voltage and power outputs across the resistive load are calculated at resonance for each shell mode. The piezoelectric shell energy harvesting mechanism can be simplified to shell (e.g., cylindrical, conical, spherical, paraboloidal, etc.) and non-shell (beam, plate, ring, arch, etc.) distributed harvesters using two Lamé parameters and two curvature radii of the selected harvester geometry. To demonstrate the utility and simplification procedures, the generic linear/nonlinear shell energy harvester mechanism is simplified to three specific structures, i.e., a cantilever beam case, a circular ring case and a conical shell case. Results show the versatility of the generic linear/nonlinear shell energy harvesting mechanism and the validity of the simplification procedures.

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1. Introduction

Development of energy harvesting technologies, e.g., converting vibration energy to electric energy, has attracted much attention in recent years. Among the proposed technologies, piezoelectric energy harvesters can easily convert the vibration induced energy to useful electric energy with the electromechanical coupling of piezoelectricity [1–5]. Most piezoelectric energy harvesters have been designed based on various non-shell structures, such as cantilever beams and plates. Erturk and Inman studied the piezoelectric cantilever-beam energy harvester, derived voltage/power on the resistive load in the closed-circuit condition and also carried out laboratory experiments to validate the output powers [6,7]. Karami et al. presented a single-crystal energy harvesters based on a unimorph beam and compared the analytical results of the voltage

* Corresponding author at: StrucTronics and Control Lab, School of Aeronautics and Astronautics, Zhejiang University, Hangzhou, Zhejiang 310027, China.
E-mail address: hstzou@zju.edu.cn (H.S. Tzou).

on the resistive shunt with the experimental data [8]. Kim et al. [9] proposed an energy harvester based on a clamped unimorph piezoelectric plate structure and the results were validated in experiments [10].

Electromechanical coupling mechanism and distributed sensing of shell structures, which are commonly used in aerospace, civil and mechanical systems, also have captured researchers' attention for decades. Howard et al. studied the modal voltages in an open-circuit condition based on a generic double-curvature shell and applied the generic sensing theory to beams and conical shells [11]. Piezoelectric electromechanical coupling mechanisms based on other shells have also been studied, such as circular cylindrical panels, circular cylindrical shells, circular rings, conical shells and paraboloidal shells, etc. [12–17]. However, most of them only considered the signal generations in the open-circuit condition and the sensing theory becomes impractical when it is used to power electric devices whose impedance can no longer be ignored. Therefore, the output energy across a resistive load in a closed-circuit condition for the shell energy harvesters should be exploited. Axisymmetric cylindrical energy harvester in the closed-circuit condition was proposed and the voltage output across the resistive load was estimated [18]. And based on a circular ring-type energy harvester [19], voltage output and power across an external resistive load were also derived. However, these energy harvesting mechanisms of specific shell structures are limited in their applications. Accordingly, this study focuses on a development of a generic piezoelectric shell energy harvesting mechanism that can be simplified and applied to many linear/nonlinear shell and non-shell distributed energy harvesters.

In this study, the generic shell energy harvester is made of a double-curvature shell laminated with a piezoelectric patch defined by its corner coordinates. Based on the linear or nonlinear strains generated by the harmonic shell vibration and a closed-circuit current model, one can estimate the power generation of the shell energy harvester. Once the power generation and energy equations are established, with Lamé parameters and radii of curvature of a selected distributed harvester design, one can simplify the shell equations to account for many linear/nonlinear shell and non-shell-type energy harvesters in engineering applications. This procedure is demonstrated in a beam model, a circular ring harvester and a conical shell harvester in case studies.

2. Dynamic responses of a generic double-curvature shell

Power and energy generation is based on dynamic strains in the piezoelectric patch. This section focuses on dynamic strain generation of a generic double-curvature piezoelectric energy harvester. Since the harvester is mostly excited at resonance to maximize the energy output, a harmonic excitation is considered and its steady-state dynamic response is defined.

2.1. Dynamic strains of generic double-curvature shell

As shown in Fig. 1, a generic double-curvature shell is defined in a tri-orthogonal curvilinear coordinate system with α_1 and α_2 defining the shell neutral surface and α_3 the normal direction. R_1 and R_2 are the curvature radii of the α_1 and α_2 axes, respectively; $q_3(\alpha_1, \alpha_2)$ is a transverse excitation. The generic double-curvature shell, which has the uniform thickness h , is laminated with a piezoelectric patch (thickness is h^e). It is assumed the patch is perfectly laminated on the shell surface and its stiffness and mass effects are ignored since the patch thickness h^e is much thinner than the shell thickness h . The patch location and size is defined by its four-corner coordinates, Fig. 1. The energy harvester patch can be assumed to be an equivalent circuit where C_p is the equivalent capacitance of the piezoelectric patch. The energy harvester is used to power a resistive load R_L in the closed-circuit condition.

Since the piezoelectric patch is laminated perfectly on the surface of the double-curvature shell, the strain in the piezoelectric patch is assumed to be consistent with the local strain on the generic double-curvature shell. Based on the thin shell theory and Kirchhoff–Love assumptions, normal strain and shear strains in the transverse direction can be neglected, i.e., $S_{33} = S_{13} = S_{23} = 0$. Thus, the normal and shear strains in the piezoelectric patch in the α_1 and α_2 directions are defined as

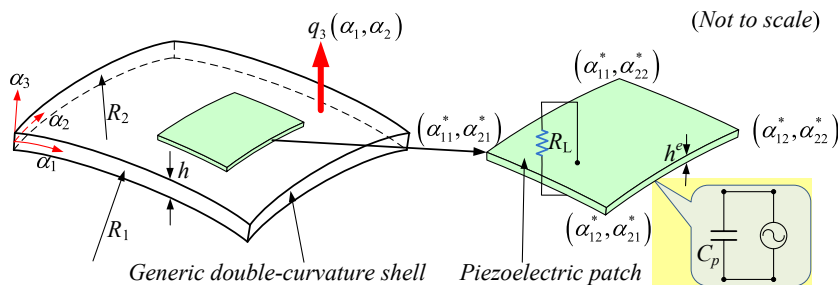


Fig. 1. Model of a generic piezoelectric shell energy harvester.

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