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Energy harvesting from coupled bending-twisting oscillations in carbon-fibre reinforced polymer laminates

Mengying Xie [a], Yan Zhang [a,*], Marcin J. Kraśny [a], Andrew Rhead [a], Chris Bowen [a], Mustafa Arafa [b]

[a] Mechanical Engineering Department, University of Bath, Bath A2 7AY, UK
[b] Mechanical Engineering Department, American University in Cairo, Egypt

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The energy harvesting capability of resonant harvesting structures, such as piezoelectric cantilever beams, can be improved by utilizing coupled oscillations that generate favourable strain mode distributions. In this work, we present the first demonstration of the use of a laminated carbon fibre reinforced polymer to create cantilever beams that undergo coupled bending-twisting oscillations for energy harvesting applications. Piezoelectric layers that operate in bending and shear mode are attached to the bend-twist coupled beam surface at locations of maximum bending and torsional strains in the first mode of vibration to fully exploit the strain distribution along the beam. Modelling of this new bend-twist harvesting system is presented, which compares favourably with experimental results. It is demonstrated that the variety of bend and torsional modes of the harvesters can be utilized to create a harvester that operates over a wider range of frequencies and such multi-modal device architectures provides a unique approach to tune the frequency response of resonant harvesting systems.

1. Introduction

The conversion of mechanical vibrations into useful electrical energy has been a subject of intensive research due to its application in self-powered sensors and wireless systems. A common architecture for vibration-based energy harvesting devices is a base-excited elastic structure, such as a mass-spring system or a cantilever beam, which is typically used in conjunction with electromagnetic and piezoelectric devices. One of the challenges in designing continuous systems, such as beams and plates, for piezoelectric energy harvesting applications lies in the placement of the energy generating materials, which are usually piezoelectric sheets or layers that are bonded or embedded within a host structure. These structures often have unique strain distributions in their vibration modes, and the highly strained parts of the structure that are most effective for energy harvesting occur only in localized regions. The placement of the energy generation materials at such discrete locations while leaving other parts of the structure uncovered causes the structure to be partially utilized for energy harvesting, which lowers the power density. This is the case, for example, for a cantilever beam undergoing flexural vibration at its first bending mode, where maximum strain occurs near the root. To overcome this difficulty, systems that operate across multiple vibration modes have been proposed [1,2] in order to utilize two or more vibration mode shapes for energy harvesting. The exploitation of more than one vibration mode also enables the device to harvest vibrations over a wider frequency range since in many cases the ambient vibrations to be harvested often span a range of frequencies and amplitudes.

* Corresponding author.
E-mail address: y.zhang2@bath.ac.uk (Y. Zhang).

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Nomenclature

C	damping matrix
F	force
I	effective mass moment of inertia
k	stiffness
k_T	torsional stiffness
$[K]$	stiffness matrix
l	arm length denoting bend-twist coupling
m	effective mass
$[M]$	mass matrix
t	time
T	kinetic energy
V	potential energy
x	transverse displacement of tip cross-section
y	base motion
Y	amplitude of base motion
α	damping coefficient for mass matrix
β	damping coefficient for stiffness matrix
δ	nodal degrees of freedom
ϕ	cross-section rotation due to torsional loads
θ	cross-section rotation under no torsional loads
ω	angular frequency

Vibration modes involving mixed deformations, in particular bending and twisting motions, are particularly appealing in this respect since these motions can be controlled by design of the harvesting structure. The study of coupled bend-twist oscillations has been of interest to the aeronautical engineering community for decades owing to its application in the vibration analysis of aircraft wings and rotating turbine blades. Recent interest in morphing structures has spurred research in the use of piezoelectric actuators to achieve a controlled bend-twist deformation [3–5]. The use of bend-twist oscillations in energy harvesting applications is relatively recent. In this context, reference is made to the work of Abdelkefi et al. [6] who designed a unimorph cantilever beam undergoing bending–torsion vibrations consisting of a single piezoelectric layer and two asymmetric tip masses, thereby generating a twisting moment from a base excitation. This structure was tuned to provide a broader band energy harvester by adjusting the first two global natural frequencies to be relatively close to each other. Reference is also made to the work of Gao et al. [7] in which torsional vibration at the second mode of a cantilever beam with an eccentric proof mass was employed for energy harvesting using a lead zirconate titanate (PZT) material. The main advantages of this design approach were the small displacement amplitudes and low natural frequency. Shan et al. [8] employed vortex-induced vibrations to design a piezoelectric energy harvester with bending-torsion vibration.

An effective way of designing structures with inherent bend-twist coupling behaviour is the use of composite laminates. By tailoring the laminate lay-up these anisotropic structures can be deliberately designed to exhibit interactions between extension, shear, bending and twisting [9], which are not present in conventional isotropic materials. In this work, we shall employ for the purpose of energy harvesting, a laminated carbon fibre reinforced polymer (CFRP) composite cantilever beam that has a laminate lay-up that is selected to achieve coupled bending and twisting deformations. Specifically, this includes the use of a laminate with an unbalanced stacking sequence in which not all plies with a positive rotation in the stacking sequence have a counterpart ply with an equal and negative rotation. Such an unbalanced structure introduces extension-shear coupling and when the laminate (or a single ply with fibres misaligned with the load direction) is subject to a unaxial tensile or compressive load it will attempt to shear. The sign of the shear is dependent on whether the load is tensile or compressive. Under a bending deformation, loading changes from being compressive on one side of the neutral axis to tensile on the other and this leads to plies on opposite surfaces attempting to shear in opposite directions, thereby resulting in twisting of the laminate. This approach is particularly attractive since it removes the need for more complex design configurations; such as the use of an eccentric proof mass or asymmetric tip masses. The ability to tailor the bend-twist coupled laminate architecture also provides scope for a wide design space to tailor the cantilever response to the vibration spectrum being harvested. To utilize larger portions of the beam for power generation, we employ two different types of PZT materials that are attached to the beam's surface. One PZT patch (MFC M8557-P1) responds to uniaxial straining (extension-mode) since the active piezoelectric material is aligned along its length and is placed close to the beam's root for effective harvesting of the bending mode. The other material (MFC M8557-F1) operates in the shear-mode, and in this case the piezoelectric is aligned at 45° to its length, and is placed along the beam's mid span where torsional shear strains are higher. This effort is expected to eventually yield energy harvesting devices with greater power densities, and greater bandwidths which are increasingly in high demand for small sensors and other applications where miniaturization is of the essence.