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On the electrode segmentation for piezoelectric energy harvesting from nonlinear limit cycle oscillations in axial flow

Carlos De Marqui Jr. [a,*], David Tan [b], Alper Erturk [b]

[a] *Department of Aeronautical Engineering, Sao Carlos School of Engineering, University of Sao Paulo, Sao Carlos, SP, Brazil*
[b] *G.W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA*

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ABSTRACT

Aeroelastic energy harvesters can be used for low-power electricity generation in various applications ranging from aircraft and rotorcraft to civil structures in high wind areas. Among the various alternative transduction mechanisms for airflow energy harvesting, piezoelectric energy harvesting from limit cycle oscillations of cantilever beams in axial flow has been pointed out as a geometrically scalable and simple option. The dynamic deformed shape of flexible beams during limit cycle oscillations involves more complex motions than simple standing waves and mode shapes. Such deformations yield moving strain nodes (inflection points), where the dynamic bending strain changes sign. As a result, the use of segmented piezoelectric layers to avoid charge cancellation is more involved as compared to modal vibration problems that have fixed strain nodes. To alleviate this issue without implementing complex optimization schemes, this work presents a criterion for segmentation of the piezoelectric layers to enhance the power extraction from aeroelastic limit cycle oscillations of a flexible cantilever in axial flow, based on a cyclic average of the strain node motion. A fluid–structure interaction model that couples the nonlinear governing equations of an electromechanically coupled beam with an unsteady aerodynamic model is implemented, and wind tunnel experiments are performed for validation. Theoretical predictions of the electromechanical response for a piezoelectric bimorph cantilever in axial flow are experimentally validated for both continuous and segmented configurations of the piezoelectric layers. More than 30% enhancement in the electrical power output is observed when piezoelectric layers are segmented based on the criterion given here.

1. Introduction

The literature of energy harvesting exhibits a growing volume of papers toward enabling geometrically scalable and simple flow energy harvesters. The goal is to convert flow energy into usable electrical energy to power small electronic components in applications ranging from health monitoring for aircraft components to wireless sensors located in high wind areas. The conversion of persistent aeroelastic and hydroelastic oscillations of airfoils and hydrofoils (Erturk et al., 2010; Sousa et al., 2011; De Marqui and Erturk, 2013; Dias et al., 2013; Bae and Inman, 2014; Abdelkefi et al., 2012), elastic wings (De Marqui et al., 2010, 2011; Bruni et al., 2017; Xiang et al., 2015) or beams in axial flow (Tang et al., 2009a; Dunnmon et al., 2011; Singh et al., 2012) combined with different transduction mechanisms are among the concepts and configurations investigated in the literature.

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[*] Corresponding author.
E-mail address: demarqui@sc.usp.br (C. De Marqui).

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The typical linear flutter behavior is well known from the classical literature of aeroelasticity (Theodorsen, 1935; Bisplinghoff et al., 1996). In that scenario, persistent oscillations occurring at the flutter boundary restrict the operation envelope of a linear flow energy harvester to a single airflow speed. However, real world applications often involve nonlinearities. Nonlinear aeroelastic systems offer persistent oscillations over a range of airflow speeds due to structural nonlinearities (concentrated or distributed) or aerodynamic nonlinearities (Dowell and Tang, 2002). Since the nonlinear aeroelastic behavior is more realistic and also useful for airflow energy harvesting, there has been growing research interest in nonlinear aeroelastic energy harvesters over the past few years (Abdelkefi et al., 2012a; Dunnmon et al., 2011; Sousa et al., 2011; Abdelkefi et al., 2012c; Abdelkefi and Hajj, 2013; Bae and Inman, 2014; Javed et al., 2015; Sousa and De Marqui, 2015).

Early papers discussing the aeroelastic behavior of cantilevers in axial flow assumed linear aeroelastic models and the goal was to investigate the stability of such systems (Kornecki et al., 1976; Shayo, 1980; Huang, 1995; Guo and Paidoussis, 2000). It appears from the literature that Kornecki et al. (1976) presented the first numerical investigation of the axial flutter problem considering a linear beam model combined with Theodorsen's theory for the two-dimensional unsteady aerodynamics. Their work was later extended to a plate formulation combined with Theodorsen's theory to provide a linear aeroelastic model (Shayo, 1980). Huang (1995) presented an experimentally validated linear beam model in axial flow to investigate human snoring that is related to flutter of soft tissue. Guo and Paidoussis (2000) investigated the axial flutter problem considering different structural boundary conditions of a linear beam model and the aerodynamic loads obtained from the direct solution of the potential flow.

Nonlinear aeroelastic behavior of beams in axial flow was first numerically investigated by Tang and Dowell (2002). A nonlinear structural model, which included nonlinearities in stiffness and inertia terms and also the inextensibility condition (Semler et al., 1994), was combined with the three-dimensional unsteady vortex lattice method to provide the nonlinear aeroelastic solution. Tang et al. (2003) presented experimental validations of the nonlinear aeroelastic model of Tang and Dowell (2002). In a series of papers (Tang and Paidoussis, 2007, 2008a, b, 2009; Tang et al., 2009b), the nonlinear aeroelastic behavior of flexible cantilevers in axial flow as well as the effects of different configurations (i.e. external springs, additional concentrated mass, interaction between two cantilevers) are discussed. Tang et al. (2009a) presented a rigorous analysis of the energy transfer from fluid to structure for self-excited vibrations of a cantilever under axial flow when a nonlinear structural model of a cantilever beam was combined with the unsteady lumped vortex method (ULVM). The numerical predictions were experimentally validated via wind tunnel tests of an electromagnetic flow energy harvester (the flutter mill). The authors concluded that arrays of large-scale harvesters could have similar performance of horizontal axis wind turbines. The nonlinear aeroelastic model used in Tang et al. (2009a) for flow energy harvesting purposes was previously presented in Tang and Paidoussis (2007), which was based on the work of Tang and Dowell (2002), showing that similar modeling assumptions have been employed by different authors.

Piezoelectric energy harvesting from nonlinear limit cycle oscillations (LCO) of a cantilever beam in axial flow was first discussed in Dunnmon et al. (2011). The equations of motion from Tang and Dowell (2002) were combined with linear piezoelectricity (Erturk and Inman, 2008), resulting in an electromechanically coupled nonlinear structural model (Dunnmon et al., 2011). The unsteady aerodynamic loads were obtained from the unsteady vortex lattice method. Experimental validations and also efficiency measures were reported in order to characterize the flow energy harvesting system. Pineirua et al. (2015) presented the optimization problem of electrodes configuration (position and dimensions along the length) of a nonlinear beam in axial flow for piezoelectric energy harvesting. Considering numerical results from a weakly nonlinear model and experimental data, they (Pineirua et al., 2015) discussed the numerical optimization of the energy flow among the fluid, structure, and electrical domains of the problem in three different configurations. For each case, the optimum electrode configuration was determined from the analysis of numerical results considering the effects of different parameters on the electroaeroelastic behavior the system. In a recent paper, Tang and Dowell (2018) presented a new inextensible nonlinear plate structural model that was combined with an electromechanical model and a rotated unsteady vortex lattice method to investigate the behavior of a piezoelectric laminated plate as the yaw angle between the clamped end and airflow direction changed.

In the current work, we present an experimentally validated simple criterion for electrode segmentation in order to reduce cancelation of electrical output from LCOs of flexible beams in axial flow. First, nonlinear aeroelastic model predictions for a plain flexible steel beam in axial flow are validated against wind tunnel results. The analysis of the aeroelastic response, particularly the dynamic strain distribution during LCOs within a cycle at different post-critical airflow speeds (i.e. at speeds above the critical speed), yields a criterion for segmentation of the electrodes (or of the piezoelectric material). Theoretical predictions of the electrical power output of a piezoelectric bimorph cantilever (PVDF - polyvinylidene fluoride- bimorph with steel substrate) in axial flow are experimentally validated for both continuous and segmented configurations of the piezoelectric layers, and performance enhancement via electrode segmentation is quantified.

2. Nonlinear aeroelastic model with piezoelectric coupling

From the aeroelastic side, the modeling approach employed in this work is similar to the ones presented by Tang and Dowell (2002), Tang and Paidoussis (2007), Tang et al. (2009a), and Dunnmon et al. (2011). As reviewed in the previous section, similar modeling assumptions have been employed in investigating the aeroelastic behavior of nonlinear flexible cantilevers in axial flow. Fig. 1(a) displays a cantilevered flexible piezoelectric beam of length L and width b in uniform