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Synchronized Charge Extraction for Aeroelastic Energy Harvesting

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ABSTRACT

Aeroelastic instabilities have been frequently exploited for energy harvesting purpose to power standalone electronic systems, such as wireless sensors. Meanwhile, various energy harvesting interface circuits, such as synchronized charge extraction (SCE) and synchronized switching harvesting on inductor (SSHI), have been widely pursued in the literature for efficiency enhancement of energy harvesting from existing base vibrations. These interfaces, however, have not been applied for aeroelastic energy harvesting. This paper investigates the feasibility of the SCE interface in galloping-based piezoelectric energy harvesting, with a focus on its benefit for performance improvement and influence on the galloping dynamics in different electromechanical coupling regimes. A galloping-based piezoelectric energy harvester (GPEH) is prototyped with an aluminum cantilever bonded with a piezoelectric sheet. Wind tunnel test is conducted with a simple electrical interface composed of a resistive load. Circuit simulation is performed with equivalent circuit representation of the GPEH system and confirmed by experimental results. Consequently, a self-powered SCE interface is implemented with the capability of self peak-detecting and switching. Circuit simulation for various electromechanical coupling cases shows that the harvested power with SCE interface for GPEH is independent of the electrical load, similar to that for a vibration-based piezoelectric energy harvester (VPEH). The SCE interface outperforms the standard interface if the electromechanical coupling is weak, and requires much less piezoelectric material to achieve the maximum power output. Moreover, influence of electromechanical coupling on the dynamics of GPEH with SCE is found sensitive to the wind speed.

Keyword: aeroelastic energy harvesting, galloping, synchronized charge extraction, piezoelectric elements, wind energy

1. INTRODUCTION

Due to the continuously reduced power requirement of wireless sensing nodes in civil and environmental monitoring systems, the idea of converting ambient energy sources into electricity to implement self-powered wireless sensors has attracted numerous research interests. Most previous energy harvesting studies have been focused on the transformation of preexisting structural vibrations into electricity.¹⁻⁴ Another possible energy source is the wind flow around the monitoring applications, such as the airflow from heating, ventilation or air conditioning systems (HVAC)⁵ and the wind gusts around unmanned aerial vehicles (UAV).⁶ By exploiting aerodynamic instabilities, the structural vibrations induced by wind flow can be harnessed using piezoelectric energy generators. The early wind energy harvester was designed in the form of miniaturized windmill.⁷ Some recent researches have been focused on piezoelectric energy harvesting from vortex-induced vibrations.^{8,9} Vortex shedding from the bluff body, which is often a cylinder, induces periodic oscillations of the harvester when the structure's natural frequency is close to the vortex shedding frequency. Energy harvesters exploring aeroelastic flutter phenomenon have also been proposed with airfoil or other cross-sectioned wing configurations.¹⁰⁻¹³ Some researchers have studied harvesting wind energy through wake galloping.^{14,15} Galloping is another prospective aeroelastic instability source for piezoelectric wind energy harvesting with the merits of large-

amplitude of oscillations and capability of working in the infinite wind speed range.^{16,17} Considerable studies have been devoted to developing galloping-based wind energy harvesters (GPEH).¹⁸⁻²³ When wind speed exceeds a critical value, which is usually called the cut-in wind speed, limit cycle oscillations of certain cross-sectioned bluff body will occur, inducing alternating strain energy in the cantilever connected with the bluff body. With the electromechanical coupling characteristic of the piezoelectric materials, this strain energy can be transformed into electricity. However, from the perspective of the interface circuit, the aforementioned researches only considered a pure resistor. For practical uses of piezoelectric energy harvesters, either in wireless sensing nodes or other electronic devices, and for electrical energy storage, DC power signal is required.²⁴ An interface circuit for AC-DC rectification and regulation needs to be implemented for GPEH before they can be employed in real application.

On the other hand, various energy harvesting interface circuits have been investigated for maximizing the power output from vibration-based piezoelectric energy harvesters (VPEH). These interface circuits include standard interface,^{25,26} synchronized switching harvesting on inductor (SSHI),^{24,27-31} and synchronized charge extraction (SCE).^{30,32,33} Interface circuits for energy storage have also been analyzed in the literature.^{34,35} Liang and Liao²⁴ demonstrated with both analyses and experiments that their proposed self-powered SSHI interface can harvest up to 200% more power than the standard interface circuit. Lefevre et al.³² showed that the SCE interface increases the harvested power by 400% as compared with a standard interface circuit with a matched resistive load, and this performance is beneficially independent of load resistance. Due to these advantages, SCE technique has attracted great research interests. However, this technique has not been applied for aeroelastic energy harvesting.

In this paper, we seek to investigate the feasibility of implementing the SCE interface in GPEH. The performance improvement with SEC interface and its influence on the galloping dynamics in different electromechanical coupling regimes are considered. Section 2 introduces the basic working principle of a typical GPEH with the electroaeromechanical model, and gives the common utilized interface circuits for piezoelectric energy harvesting. Section 3 illustrates an equivalent circuit representation for GPEH to make possible the system level circuit simulation of the GPEH system. Section 4 presents the experimental results and verifies the equivalent circuit model. Section 5 investigates the performance of GPEH with a self-powered SCE interface via circuit simulation. Section 6 concludes the article.

2. GPEH SYSTEM

2.1 Configuration of a typical GPEH

Figure 1. A typical galloping-based piezoelectric energy harvester

Figure 1 shows the configuration of a typical GPEH. A bluff body with a specific cross section is connected to the free end of a cantilever. When subjected to an incoming flow, the bluff body undergoes oscillations in the direction normal to the flow due to the galloping phenomenon. The oscillatory bending of the cantilever results in alternating strain at the root area. A piece of piezoelectric sheet is attached to the root of the substrate beam, converting the strain energy into electricity. The example shown in the figure only includes a resistive load R_L in the interface circuit. In the following sections, a square-sectioned bluff body is utilized due to its better performance over the other shapes.¹⁶

2.2 Electro-aero-mechanical model:

Two parts of coupling models compose the whole electro-aero-mechanical model of the GPEH: the electromechanical model, or structural model, and the aerodynamic model. Available electromechanical models in the literature generally fall into two categories: lumped parameter model^{16,19} and distributed parameter model.²⁰⁻²² The aerodynamic models are all established based on quasi-steady hypothesis. Zhao et al.²³ presented a comparison of these analytical models and discussed their merits and disadvantages. Basically, both lumped parameter model and distributed parameter model can successfully predict the electroaeroelastic behavior of the GPEH. The main advantage of the lumped model lies in its simplicity and the ease of obtaining the coupling coefficient via test, while the benefit of the distributed model is its better representation of the aerodynamic force and ease of parametric study. Here we directly present the final governing equation of the GPEH system using a single-mode distributed parameter model.²³ Detailed derivation process is available in the aforementioned literature.

$$\begin{cases} \ddot{\eta}(t) + 2\zeta\omega\dot{\eta}(t) + \omega^2\eta(t) + \chi V(t) = \phi(L) \times \frac{1}{2} \rho_a h l_{ip} U^2 \sum_{i=1,2,\dots} A_i \left[\frac{\phi(L)\dot{\eta}(t)}{U} + \phi'(L)\eta(t) \right]^i \\ \frac{V(t)}{R_L} + C_p \dot{V}(t) - \chi \dot{\eta}(t) = 0 \end{cases} \quad (1)$$

Equation (1) is the governing electro-aero-mechanical equation of the GPEH system, where $\phi(x)$ is the mass normalized mode shape for the first vibration mode; $\eta(t)$ is the modal coordinate; ζ is the mechanical damping of the first vibration mode; ω is the undamped fundamental frequency; A_i are empirical coefficients for the aerodynamic force calculation; ρ_a , h and l_{ip} are air density, the frontal dimension and length of the bluff body, respectively; C_p is the total capacitance of the piezoelectric sheet; R_L is the resistive load; $V(t)$ is the generated voltage across the piezoelectric sheet; and χ is the modal electromechanical coupling term written as $\chi = \theta[\phi'(x_2) - \phi'(x_1)]$ with x_1 and x_2 being respectively the starting and ending positions of the piezoelectric sheets along the beam and θ the piezoelectric coupling term determined by the geometric and material parameters of composite beam.

2.3 Interface circuits

In this part we give the commonly used interface circuits for VPEH in the literature, and simply introduce their characteristics.

(1) Standard DC interface

The standard DC interface includes a full-wave rectifier, a filtering capacitor C_R and a resistor R_L ,³² as shown in Figure 2(a). The DC voltage V_{DC} is assumed to be constant if $C_R R_L$ is much larger than the oscillating period. If V is less than V_{DC} , the rectifier is blocked and outgoing current I is null. Once V reaches V_{DC} , the rectifier conducts and transfers the electrostatic energy from the piezoelectric transducer to C_R and R_L . The waveform is shown in Figure 2(b).

Figure 2. (a) Standard interface circuit and (b) corresponding waveforms of voltage V and tip displacement u (adapted from Lefeuvre et al.³², copyright: SAGE Publications)

(2) SCE interface

The SCE interface includes a full-wave rectifier, an inductor L_{SCE} , a diode D_{SCE} , a switch S , a storage capacitor C_R and a resistor R_L (Figure 3(a)). The switch is usually controlled by an external control circuit, and it is always open except the instants t_1 and t_2 (Figure 3(b) when structural displacement reaches maximum and minimum). With the switch being open the piezoelectric transducer experiences open-circuit condition and energy accumulates on its own piezoelectric capacitor. Once the structural displacement reaches peak amplitude, the switch is closed for a short time interval and the energy is transferred from the piezoelectric transducer to the inductor L_{SCE} , which will be further transferred to the capacitor C_R and R_L . The corresponding waveform is shown in Figure 3(b).

Figure 3. (a) SCE interface circuit and (b) corresponding waveforms of voltage V and tip displacement u (adapted from Lefevre et al.³², copyright: SAGE Publications)

(3) Self-powered SCE interface

In order to avoid the additional electronic units for displacement peak detection and switch control, self-powered nonlinear interfaces are enthusiastically pursued, such as self-powered SSHI interface²⁴ and self-powered SCE interface.³⁶ The key part in self-powered interfaces is the electronic breaker, which can automatically switch when structural displacement reaches peak amplitude. The electronic breaker comprises three parts: envelope detector, comparator and electrical switch.^{24,36} The schematic of the self-powered SCE interface will be detailed in Section 5.

3. EQUIVALENT CIRCUIT MODEL OF GPEH

With the practical interface circuits in the GPEH system which has much more complex behaviors than a pure resister, analytical formulations are quite cumbersome due to the multi-way coupling effect. An available solution is to exploit the equivalent circuit representation of the GPEH system, incorporating all the mechanical components, aerodynamic components and the interface components. Therefore, the performance of the whole system can be evaluated via system level circuit simulation.

The equivalent circuit model is established based on the analogy between mechanical and electrical domain parameters,^{37,38} as shown in Table 1. Before conducting the parameter transformation, we first relate the single-mode distributed parameter model in Equation (1) to an equal but simpler lumped parameter model, shown in Equation (2), with $M_{eff} = 1/\phi^2(L)$, $C_{eff} = 2\zeta\omega/\phi^2(L)$, $K_{eff} = \omega^2/\phi^2(L)$, $\Theta = \chi/\phi(L)$.

$$\begin{cases} M_{eff} \ddot{w}(L, t) + C_{eff} \dot{w}(L, t) + K_{eff} w(L, t) + \Theta V(t) = F_z(t) = \frac{1}{2} \rho_a h l_{tip} U^2 \sum_{i=1,2,\dots} A_i \left[\frac{\dot{w}(L, t)}{U} + w'(L, t) \right]^i \\ \frac{V(t)}{R_L} + C_p \dot{V}(t) - \Theta \dot{w}(L, t) = 0 \end{cases} \quad (2)$$

Table 1. Analogy between mechanical and electrical domain parameters

Electrical parameters	Mechanical parameters
Charge $q(t)$	Tip Displacement $w(L, t) = \phi(L)\eta(t)$
Current $I(t) = \dot{q}(t)$	Tip Velocity: $\dot{w}(L, t) = \phi(L)\dot{\eta}(t)$
Inductance L	Effective mass $M_{eff} = 1/\phi^2(L)$,
Resistance R	Effective damping $C_{eff} = 2\zeta\omega/\phi^2(L)$
Capacitance C	Reciprocal of effective stiffness $1/K_{eff} = \phi^2(L)/\omega^2$
Ideal transformer turn ratio N	Electromechanical coupling $\Theta = \chi/\phi(L)$

Another key factor in the equivalent circuit model is the representation of the aerodynamic force, which is implemented in the circuit model with an arbitrary source, shown as the box the top left corner of Figure 4. This arbitrary source is formulated as $\frac{1}{2} \rho_a h l_{ip} U^2 \sum_{i=1,2,\dots} A_i \left[\frac{q(t)}{U} + \beta C V_c(t) \right]^i$, where $\beta = \phi'(L)/\phi(L)$, and $V_c(t)$ is the voltage across the capacitor C . The equivalent circuit model for the GPEH with a simple resistor is presented in Figure 4. Other interface circuits can be implemented by replacing R_L with the corresponding interface components.

Figure 4. The equivalent circuit model for the GPEH with a simple

4. EXPERIMENTAL VERIFICATION OF EQUIVALENT CIRCUIT MODEL

4.1 Experimental setup

In order to verify the equivalent circuit model in Section 3, a prototype device of GPEH is fabricated and tested in the wind tunnel. The cantilever beam comprises an aluminum substrate and a piece of piezoelectric sheet (MFC M2814-P2, Smart Materials Corp.), which is attached at the root area. A bluff body with a square section is connected at the tip, made with polystyrene foam. The mass of the bluff body is 1.8g, and the dimension is 20×20×100mm. The installation of the prototype in the wind tunnel is shown in Figure 5(a). A metal support is used to fix the root of the cantilever. The damping ratio ζ is measured using logarithmic decrement technique. Properties of the GPEH prototype are listed in Table 2 and the corresponding equivalent circuit model parameters are shown in Table 3. During the wind tunnel test, the voltage signal is measured by the NI 9229 DAQ module (National Instruments), and the wind speed is measured with a hotwire anemometer. A resistive load R_L is applied as a simple interface circuit, and the average power is calculated by $P=(V_{RMS})^2/R_L$, where V_{RMS} is the root-mean-square voltage across R_L . The overall experimental setup is given in Figure 5(b).

Table 2. Properties of the GPEH prototype

Properties	Beam	Piezoelectric sheet
Length (mm)	130	28
Width (mm)	20	14
Thickness (mm)	0.6	0.3
Material	Aluminum	MFC M2814-P2
Mass Density (kg m ⁻³)	2700	5440
Capacitance (nF)	---	25.7
Young's Modulus (GPa)	69	30.336

Table 3. Equivalent circuit model parameters

Electrical parameters	Values
Inductance L	0.0027830
Resistance R	0.0065204
Capacitance C	0.0316819
Ideal transformer turn ratio N	0.0000960

Figure 5. (a) The installation of the prototype in the wind tunnel (b) overall experimental setup

4.2 Verification of the equivalent circuit model

Figure 6. Measured and predicted responses of average power versus (a) load resistance R_L with $U=4$ m/s and (b) wind speed U with $R_L=333$ kΩ.

With a constant wind speed of 4 m/s, the variations of average output power as a function of load resistance R_L measured by wind tunnel experiment and predicted by the equivalent circuit model are compared in Figure 6(a). The measured average power first increases with R_L until reaching the maximum, then decreases. Optimal R_L falls in the range of 320~340 kΩ, within which the output power barely changes. The equivalent circuit model successfully predicts the trend of power responses versus R_L , with an optimal R_L of 333 kΩ observed. With this optimal value of R_L , the measured and

predicted responses of average power versus wind speed U are further compared in Figure 6(b). It can be observed that the predicted results from the equivalent circuit model agree well with the experiments. The output power monotonically increases with the wind speed. The cut-in wind speed is measured to be 2.7m/s, while a value of 3m/s is predicted. This is attributed to the inevitable small turbulence in the wind tunnel that disturbs the prototype. In general, the equivalent circuit model predicts well agreed results with experiments, thus is verified. The performance of GPEH with SCE interface is further analyzed via system level circuit simulation with this verified model and compared to that with a standard interface in Section 5.

5. SELF-POWERED SCE INTERFACE

5.1 System schematic

Figure 7. Schematic of the GPEH system with the standard interface.

Figure 8. Schematic of GPEH system with the self-powered SCE interface.

The schematic of the standard interface circuit incorporating the equivalent circuit representation of the electro-aero-mechanical GPEH is shown in Figure 7. An ideal full-wave rectifier and a 100µF filtering capacitor (shown as C2 in Figure 7) are employed. For the GPEH with self-powered SCE interface, the overall schematic is given in Figure 8. The interface includes a full-wave rectifier, an electronic breaker and a flyback converter. The key electronic breaker works as an displacement peak detector as well as a digital switch controller, which can automatically switch on to transfer the energy accumulated in the piezoelectric sheet to the inductor in the flyback converter when structural displacement reaches peak amplitude.

5.2 Case studies with various coupling

Here we define an alternative electromechanical coupling coefficient as $k_e^2 = \chi^2 / \omega^2 C_p$, which makes convenient the study of the influence of the varying coupling on the performance of GPEH with SCE. Dividing k_e^2 by the damping ζ , the term k_e^2 / ζ is frequently employed to indicate the strength of coupling.^{26,28,29} With the corresponding parameters for the prototype, k_e^2 / ζ is obtained as 1.0326. The larger the value of k_e^2 / ζ , the stronger the electromechanical coupling is. By varying k_e^2 / ζ , we compare the performances of GPEH with the SCE and the standard interfaces in different coupling ranges.

(1) Case 1: Weak coupling

Figure 9. Weak coupling: responses of average power versus (a) load resistance R_L at 5m/s and (b) wind speed U at optimal R_L for GPEH with self-powered SCE interface and standard interface.

With $k_e^2 / \zeta = 1.0326$, circuit simulation is performed for both the self-powered SCE interface and the standard interface. The responses of average output power versus load resistance R_L at 5m/s are compared in Figure 9(a). Two important aspects are observed. Firstly, there exists an obvious optimal R_L for the GPEH with a standard interface, at which the output power achieves maximum, while the output power with the self-powered SCE interface is almost independent of R_L . This will be great advantageous since there is no requirement of searching for the matched impedance. Secondly, the maximum power obtained with self-powered SCE interface is 1.43mW, more than twice of that with standard interface, which is only 0.80mW. With R_L being fixed at the optimal value in the standard interface, circuit simulation is conducted for both interface techniques, and the responses of output power versus wind speed is given in Figure 9(b). It is observed that the cut-in wind speed with the self-powered SCE is a bit higher than that with the standard interface. However, the increasing rate of power versus wind speed (the slope of the plotted line) with the self-powered SCE is larger than that with the standard interface. Beyond an intersection wind speed (around 4.2m/s), the self-powered SCE interface generates more power than the standard interface. In addition, the higher is the wind speed, the greater the advantage of self-powered SCE is. Figure 10 shows the wave profile of the two techniques, which gives the same pattern with that in Figures 2 and 3. In conclusion, the self-powered SCE outperforms the standard interface for weak coupling.

Figure 10. Voltage profile for GPEH with (a) self-powered SCE interface and (b) standard interface.

(2) Case 2: Medium coupling

Figure 11. Medium coupling: responses of average power versus (a) load resistance R_L at 5m/s and (b) wind speed U at optimal R_L for GPEH with self-powered SCE interface and standard interface.

In this case we increase k_e^2/ζ to 1.4456, and conduct circuit simulation for the two interface techniques with the results shown in Figure 11. From Figure 11(a), the output power with self-powered SCE interface is still independent of R_L , but is only slightly larger than the maximum power obtained with the standard circuit. From Figure 11(b), the cut-in wind speed with self-powered SCE is obviously higher than that with the standard interface. Thus, for this medium coupling case, the performance of self-powered SCE is comparable to that of standard interface.

(3) Case 3: Strong coupling

Figure 12. Strong coupling: responses of average power versus (a) load resistance R_L at 5m/s and (b) wind speed U at optimal R_L for GPEH with self-powered SCE interface and standard interface.

We further increase k_e^2/ζ to 2.5815, and perform circuit simulation for the two interface techniques. From Figure 12(a), the output power with self-powered SCE interface is almost null as the harvester is excited around its cut-in wind speed (5m/s), which is much higher than that with the standard interface (Figure 11(b)). In general, no benefit will be achieved with SCE interface for low wind speed range (<6m/s).

5.3 Harvester behavior with SCE

Figure 13. (a) Average output power versus coupling k_e^2/ζ at 5m/s (b) peak tip displacement versus coupling k_e^2/ζ at 5m/s (c) cut-in wind speed versus coupling k_e^2/ζ .

The behaviors of GPEH with self-powered SCE are further studied and compared to those with standard interface, as presented in Figure 13. Figure 13(a) shows the variations of the average power as a function of k_e^2/ζ for the two interfaces. It should be noted that for the standard interface, the plotted power corresponds to the maximum power with the optimal R_L at each coupling value along the horizontal axis of the figure. For weak coupling with $k_e^2/\zeta < 1.5$, the self-powered SCE interface extracts more power than the standard interface. For medium coupling where k_e^2/ζ is around 1.5, the self-powered SCE interface does not ensure superior performance to the standard interface. For strong coupling with $k_e^2/\zeta > 1.5$, the self-powered SCE interface generates smaller power than the standard interface. The maximum output power values achieved by the two interface techniques are almost equal, but the self-powered SCE reaches this maximum power with much smaller electromechanical coupling. This is an important advantage because the smaller electromechanical coupling corresponds to less piezoelectric material required for the same prototype. The curves are obtained at a constant wind speed of 5m/s. However, the criteria for weak and strong coupling will be changed at another wind speed. This phenomenon is being further studied by the authors. Figure 13(b) shows the peak tip displacement (displacement of the bluff body) of GPEH with the two interfaces. The self-powered SCE owns smaller displacement amplitudes than the standard circuit for the whole considered coupling range, indicating that the interface-induced damping is always larger for the self-powered SCE. The cut-in wind speeds versus coupling with the two interfaces are plotted in Figure 13(c). With the increase of coupling, the cut-in wind speeds for both interfaces increase. Moreover, for all different coupling values, the self-powered SCE has a higher cut-in wind speed than the standard interface.

6. CONCLUSION

In this paper, we investigate the feasibility of the SCE interface in galloping-based piezoelectric energy harvesting. The basic working principles of different interfaces are presented. The equivalent circuit model is given based on the analogy between the mechanical domain and electrical domain parameters. A GPEH prototype is fabricated and tested in the wind tunnel, validating the equivalent circuit model. Consequently, a self-powered SCE interface is implemented with the capability of self peak-detecting and switching. Its performance for various electromechanical coupling cases is studied via circuit simulation, and compared to that of the standard interface. The present work shows that for GPEH with weak coupling, the self-powered SCE outperforms the standard interface; for GPEH with medium coupling, the self-powered SCE interface does not ensure superior performance to the standard interface; for GPEH with strong coupling, no benefit is achieved with the self-powered SCE interface for low wind speed range ($< 6\text{m/s}$). The harvested power with SCE interface for GPEH is independent of the electrical load, and the maximum power is achieved with a smaller coupling than that required by the standard interface. The influence of electromechanical coupling on the dynamics of GPEH with SCE is found sensitive to the wind speed, which will be further investigated in greater detail. In conclusion, the SCE interface is a prospective and beneficial technique for galloping energy harvesters, and deserves further investigations.

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