Effects of random orientation of bluff body on the onset speed of galloping-based piezoelectric energy harvester

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1. INTRODUCTION & OBJECTIVE

Vibration-based energy harvesters offer promising solutions to meet the growing power needs of small-scale devices. Considerable attention has been directed toward galloping-based piezoelectric energy harvesters (GPEH), particularly because wind energy represents a sustainable and renewable resource. The positioning of a vertical cylinder in the wind flow path is known to critically influence energy harvesting performance. Even slight forward or backward tilts of this cylinder can have a marked impact on the amount of power generated [3]. Since manual installation of the vertical cylinder on a cantilever beam can introduce small orientation errors, understanding these effects is crucial. The speed at which galloping begins, the onset speed (Ug), is key to harvesting efficiency, as oscillations and thus energy generation only occur beyond this threshold. This study explores how minor random misalignments of the vertical cylinder affect the onset speed of galloping. Monte Carlo simulations are employed to assess the influence of these variations, with conclusions drawn from the resulting probability distribution analysis.

2. METHODS OF ANALYSIS

In this study, Forward and backward tilts were defined as positive and negative, respectively Figure 1. Inclination angles within –10° to +10° were generated from a Gaussian distribution using Latin Hypercube Sampling (LHS). The governing equations of the piezoelectric harvester were expressed in state–space form [1], and the onset speed was determined from the linear coefficient of the aerodynamic galloping force [4]. This force was modeled using quasi-steady theory, where the lift coefficient was represented by a 7th-order polynomial fit for higher accuracy [2]. The linear coefficient was further curve-fitted with an Artificial Neural Network (ANN) to capture inclination effects. Finally, Monte Carlo simulations with 10,000 samples were carried out to estimate the probability distribution of onset speeds.

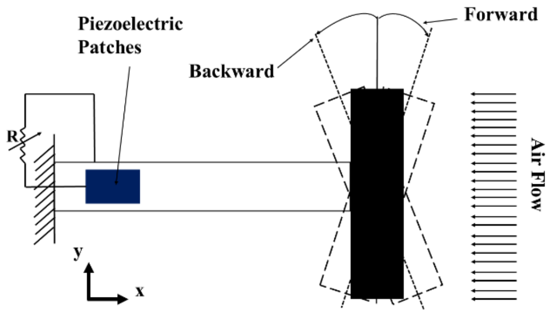

Figure 1: GPEH system with forward and backward inclination

3. RESULTS AND/OR HIGHLIGHTS OF IMPORTANT POINTS

Figure 2(b) presents the probability density function (PDF) of the onset speed of galloping, obtained from Monte Carlo simulations where inclination angles were sampled from a normal distribution centered at 0°. The results show that the onset speed is not fixed but exhibits statistical variability due to random orientation of the bluff body. The peak probability density occurs in the range of 1.75–1.8, representing the most probable onset speed. The distribution is skewed toward higher speeds, with values extending up to ~2.1, which correspond to backward inclinations delaying the initiation of galloping. This asymmetry highlights that forward inclinations facilitate galloping at lower speeds, enhancing energy harvesting initiation, while backward inclinations increase the onset threshold, thereby reducing efficiency.

To further illustrate this behavior, Figure 2 (a) shows the deterministic variation of onset speed with inclination angle. A clear trend emerges: onset speed decreases progressively from negative inclinations (backward tilt) toward a minimum near +5°, after which it increases again with larger forward inclinations. This U-shaped dependence explains the probabilistic spread observed in the Monte Carlo simulations. Specifically, the lower onset speeds associated with forward inclinations dominate the probability distribution, while the higher speeds from backward inclinations contribute to the tail.

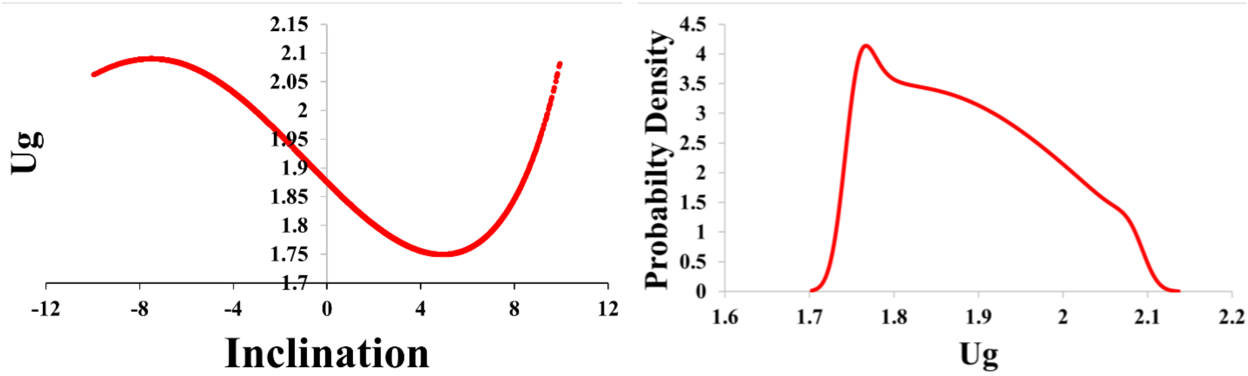

Figure 2 : (a) Onset speed of galloping vs. Inclination plot (b) PDF plot for onset speed of galloping

4. CONCLUSIONS

This study investigated the onset speed of galloping in a galloping-based piezoelectric energy harvester (GPEH) under varying bluff body inclinations. Using a quasi-steady aerodynamic model with a 7th-order polynomial fit, the linear stability parameter was identified and evaluated through Artificial Neural Network (ANN) curve-fitting across inclination angles generated via Latin Hypercube Sampling (LHS). Monte Carlo simulations with 10,000 samples revealed that forward inclinations consistently lower the onset speed, while backward inclinations delay galloping and contribute to a skewed probability distribution. These results demonstrate that even small orientation changes can significantly affect stability and harvesting performance. Hence, maintaining a slight forward inclination is recommended for experimental setups and practical deployments to ensure earlier and more consistent galloping initiation.

5. REFERENCES

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