

Energy Harvesting from Aerodynamic Instabilities: Current prospect and Future Trends

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Abstract. This paper evaluates the layout and advancement of energy harvesting based on aerodynamic instabilities of an aircraft. Vibration and thermoelectric energy harvesters are substantiated as most suitable alternative low-power sources for aerospace applications. Furthermore, the facility associated with the aircraft applications in harvesting the mechanical vibrations and converting it to electric energy has fascinated the researchers. These devices are designed as an alternative to a battery-based solution especially for small aircrafts, wireless structural health monitoring for aircraft systems, and harvester plates employed in UAVs to enhance the endurance and operational flight missions. We will emphasize on various sources of energy harvesting that are designed to come from aerodynamic flow-induced vibrations, specific attention is then given at those technologies that may offer, today or in the near future, a potential benefit to reduce both the cost and emissions of the aviation industry. The advancements achieved in the energy harvesting based on aerodynamic instabilities show very good scope for many piezoelectric harvesters in the field of aerospace, specifically green aviation technology in the future.

1. Introduction

Energy harvesting (EH) deals with the energy conversion from external driving sources (like solar power, thermal energy, vibrational energy, mechanical deformation, etc.) into electrical energy which can then be captured and stored for small autonomous devices like those used in wearable electronics and wireless sensor networks [1]. The basic concept of EH technology is to obtain the electrical energy by energy conversion from a wasted heat, vibration, mechanical deformation, potential energy, etc. The general mechanism of this EH is depicted in figure 1. The energy converted derived from these ambient sources is either directly consumed, or stored in a rechargeable battery for future use.





Figure 1. Schematic of general mechanism of energy harvesting principle.

One study has outlined three energy architecture networks as harvest-consume, harvest-store-consume, and harvest-store/consume to explain the final utilization of the harvested energy [2]. Each of the energy conversion methods used in EH has its own performance characteristics such as power density described by the power-to-weight, power-to-area or power-to-volume ratio. Therefore, due to its substantial applications, many investigators have been studying EH technology in various fields such as material science, electrical engineering, mechanical engineering, biomedical science, etc.

Moreover, in the past decade, many research investigations have been concerned with harvesting energy from base vibrations [3]. Hence, being such a fascination for research in EH from aeroelastic vibrations [3], the contemporary research focus of aeroelastic EH need to be reviewed. Recent developments in aeroelastic EH have been comprehensively penned by many authors, including the development and applications of piezoelectric (PZT) harvesters in aerospace applications. The significant progresses of EH capability of aeroelastic phenomena have been attracting engineers and researchers from different fields [3,4].

Aerospace EH application is one of these interested fields because billions of dollars are lost each year as maintenance cost, fuel consumption due to additional weight, and emissions from different systems. The high-efficient energy harvesters may convert vibrations, acoustic and dissipated heat into electrical energy. The potential for energy savings is enormous. The impact of energy efficiency improvement of aircraft systems on the environment has been highlighted by Lee [5].

As the conventional sources of energy need to be replaced by the renewable sources due to limited stock and high emission of pollutants, Boeing has started testing solar and thermal EH to power electronic windows, as a way to reduce wiring, weight, fuel use and carbon emissions. The research of EH has enhanced the possibility of green energy. One promising way for EH is vibrations, and hence our study will enumerate various EH techniques from different aerodynamic instabilities, that can employ different transduction methods to transfer these instability phenomena into electrical energy.

2. Aerodynamic instabilities and energy harvesting

Structures subjected to flow loads may exhibit different responses which include bifurcations, limit-cycle oscillations, internal resonances and chaotic motions [4,6]. Aerodynamic phenomena like

vortex-induced vibrations, flutter, buffeting, and galloping, may cause unwanted and excessive vibrations which are to be avoided in large scale applications such as bridges, aircrafts, pipelines, buildings etc. Huge emphasis laid on research to design structures which are capable of sustaining damages.

When aeroelastic instabilities occur, the phase difference between the motions of the structure and the aerodynamic forces becomes such that the structure absorbs energy from the air leading to structural vibrations with increasing amplitude for which failure is the catastrophe. The aeroelastic phenomena were classified according to their fundamental causes and major characteristics as shown in fig. 2, and such a classification is also proposed in the general book by Naudascher and Rockwell dealing with flow-induced vibrations [7].

The three types of excitations as defined in figure 2 are 1) extraneously induced excitation (EIE); independent of any fluid instability due to the structure or its motion, e.g. turbulence in the oncoming flow-field or influence of the wake of an obstacle located upstream, 2) instability induced excitation (IIE); flow instability due to the presence of the structure, e.g. alternate vortex shedding (in the sense of Von Karman), or buffeting loads, and 3) motion induced excitation (MIE); fluctuating forces due to the motion of the structure. It leads to self-excited phenomena where energy transfers from the flow-field to the structure, e.g. flutter.

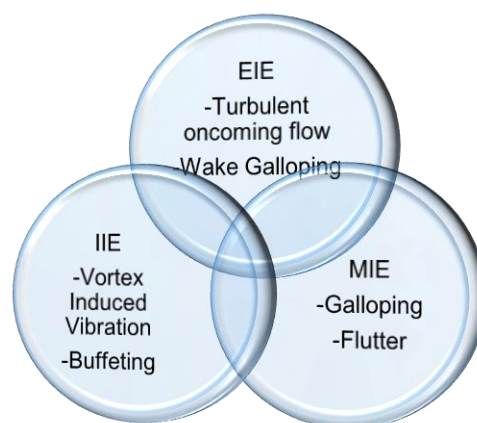


Figure 2. Classification of the aeroelastic instabilities of bluff-bodies.

In the literature of aero-elasticity, PZT materials (as actuators, converse effect) and other actuators have been used as active and semi-passive controllers to modify the aero-elastic behaviour of wings along with the effects of passive controllers have also been investigated by several researchers to increase the linear flutter speed. Researchers have also used PZT materials as actuators for morphing in aircrafts and macro-fibre-composite actuators have been used to suppress buffeting oscillations on the vertical fins of an F-18. On a flip side, these aerodynamic phenomena associated with structural nonlinearities have been proposed as a new source of power generation in small scale systems which are classified as distributed and concentrated based on the region of their existence.

Distributed nonlinearities arise generally from deformations of the entire structure whereas concentrated nonlinearities arise from loose or worn hinges of control surfaces. To harvest energy, the harvester is placed in a flow field and excited to undergo large limit-cycle oscillations that can be converted to electrical energy using PZT and/or electromagnetic transducers. Thus, findings of this research in chronological order; flutter in airfoil sections, vortex-induced vibrations in circular

cylinders, galloping in prismatic structures, and wake galloping in parallel cylinders. The following subsections will enlighten about the contemporary investigations in the field of EH from aerodynamic instabilities and discuss possible designs of galloping (also wake galloping), flutter and vortex induced vibrations (VIV).

2.1 Energy Harvesting by Galloping

Galloping is a typical phenomenon of aeroelastic instability involving lightweight and lightly damped slender structures, usually with non-circular, bluff cross sections. It can be characterized as a velocity-dependent, damping-controlled instability problem with low-frequency, large-amplitude oscillations, mainly in the crosswind direction. Isolated structural elements, mono-tubular towers and cables subjected to icing conditions, lighting poles with heavy equipment at the top, tall buildings and high-rise structures are typical examples of structures susceptible to galloping when the mean wind velocity exceeds certain critical values.

Xu et al [8] investigated the EH by the aeroelastic galloping of a cantilever with attached prism, and found that the electric power output depends primarily on the length of the cantilever. As shown in figure 3, a PZT wake-galloping FEH consists of a mechanical oscillator coupled to an EH circuit through a PZT element. The oscillator is placed in the downstream of a bluff body or an obstacle. Laminar fluid flows once past the obstacle, undergoes symmetry breaking in the form of a Von Karman vortex sheet with periodic shedding vortices from the trailing edge thereby inducing alternating pressure forces which, in turn, generate a periodic lift on the mechanical oscillator.

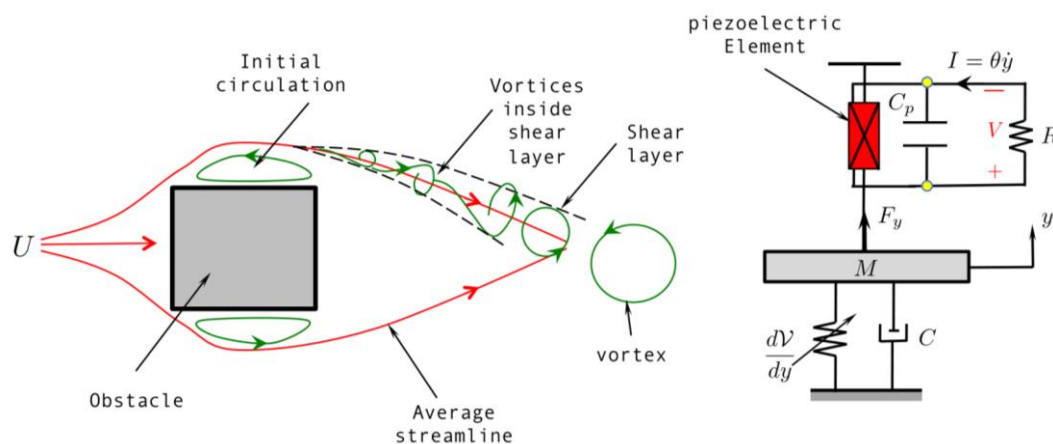


Figure 3. A schematic of a lumped parameters model of a nonlinear wake galloping energy harvester [9].

Alhadidi et al. [9] communicated that the lock-in region of a wake-galloping flow energy harvester can be improved by exploiting a bi-stable restoring force as shown in fig. 3. The results depicted the comparison with the linear design; bi-stability can be used to improve the steady-state bandwidth considerably. Raj et al [10] presented a vertical cantilever PZT energy harvester that exploits wind energy for vibration. It was concluded that the voltage, power output and onset of galloping wind force are significantly influenced by the attached load resistance.

Abdelmaula et al [11] investigated the potential of the electrical capacitance and inductance on the performance of galloping-based PZT systems for EH and control purposes. The results indicated that these experiments were not fruitful for energy harvesting. Javed et al [12] introduced an enhanced stability characterization for aero-elastic energy harvesters by using both the normal form of the Hopf

bifurcation and shooting method. It is shown that this tool is strong in terms of designing reliable aero-elastic energy harvesters. The results show that this technique can accurately predict the harvester's response only near bifurcation, however, cannot predict the stable solutions of the harvester when subcritical Hopf bifurcation takes place. Then shooting method is employed which in turn proved to be beneficial in determining the stable and un-stable solutions of the system and associated turning points by covering draw backs.

Dai et al [13] presented an investigation on the suppression of vibration amplitudes of an elastically-mounted square prism subjected to galloping oscillations by using a non-linear energy sink. The results shows that this approach can be efficiently implemented to significantly reduce the galloping amplitude of the square prism. Wang et al [14] investigated the EH from both vortex-induced vibration and galloping phenomenon from self-excited vibration of a square cylinder under different wind speeds. For VIV, the maximum harvested power reached 1.14×10^{-5} watt at 1×10^6 ohm resistance. For galloping, the harvested power is 1.4 watt at 2×10^5 ohm resistance. It can be concluded that synchronization phenomenon can be utilized to harvest power when the velocity of wind is low.

2.2 Energy harvesting by Flutter

Flutter is an aeroelastic instability involving 2 degrees of freedom, one flap wise and one torsional. It is a self-feeding and potentially destructive vibration where aerodynamic forces on an object couple with a structure's natural mode of vibration to produce rapid periodic motion. Flutter can occur in any object within a strong fluid flow, under the conditions that a positive feedback occurs between the structure's natural vibration and the aerodynamic forces. That implies the vibrational movement of the object increases an aerodynamic loads which in turn drives the object to move further. If the energy during the period of aerodynamic excitation is larger than the natural damping of the system, the level of vibration will increase. The vibration levels can thus build up and are only limited when the aerodynamic or mechanical damping of the object match the energy input; this often results in large amplitudes and can lead to rapid failure. Thus, structures exposed to aerodynamic forces including wings, aero-foils, but also chimneys and bridges are designed carefully within known parameters to avoid flutter.

Piñeirua et al [15] in particular investigated the energy transfer between a flow and a fluttering PZT plate as shown in figure 4, and benefits of the use of a synchronized switch harvesting on inductor (SSHI) circuit. The results presented show that a significant improvement of the harvested energy can be obtained using SSHI circuits compared to basic resistive circuits. Wang et al [16] proposed a novel structure for pre-rolled flexible PZT cantilevers that use wind energy to power a sub-munition electrical device. The PZT generator is composed of a PZT cantilever and a power management circuit with wind speed set to 40 m/s to ensure that the PZT cantilever would flutter at large amplitude, thereby ensuring that it could generate electrical energy.



Figure 4. Schematic of the multilayer composition of the piezoelectric flag [15].

Akbar et al [17] presented an investigation on the EH exerted by the dynamic bending responses of a PZT embedded wing-box. A simulation for civil jet aircraft wing-box with PZT skin layer has been presented. Flutter is unlikely to be encountered during normal flight of civil jet aircraft and the structure constructed from more complicated configuration, i.e. skins, ribs and spars. Based on simulation results, the voltage and power responses could attain a promising level, in the order of 101–102 volts and 102–104 watts.

Hobeck and Inman [18] presented an analytical and experimental investigation of a flow-induced vibration phenomenon referred to as dual cantilever flutter (DCF). DCF occurs when two similar adjacent beams are placed normal cross-flow at a particular velocity and separation distance. Experimental results show that during DCF both beams become phase-locked 180 degrees out-of-phase while they undergo persistent large-amplitude vibration at their first bending mode frequency.

Bruni et al [19] presented an investigation to identify the best configuration of PZT elements for a typical condition of wing aeroelastic instability with attention to flutter behaviour of the structure. Best results are achieved with optimisation of frequency ratio, stiffness ratio, and load resistance value for flutter postponement and energy harvesting.

McCarthy et al [20] investigated the response of a fluttering PZT energy harvester in smooth flow and in aspects of replicated atmospheric boundary layer turbulence (12.7% intensity, 310-mm longitudinal integral length scale). The harvester was yawed and pitched, and the effects on the power output were examined. Key findings were the following: (1) off-axis flow conditions rapidly degraded the mean output power of the harvester; (2) turbulence, for this specific harvester, acted similarly to a dynamic damping mechanism.

2.3 Energy Harvesting by Vortex Induced Vibrations

Vortex induced-vibration is probably the most classical type of wind flow-induced vibration that takes place in flow velocities specified by the Strouhal number. In this flow, vortices are created at the back of the body and detach periodically from either side. Vortex-induced vibration is unlikely to be a major vibration problem for cable-stayed bridges. By adding a small amount of damping, vortex excitation can be suppressed effectively. When an elastic bluff body encounters uniform fluid flow, for high enough Reynolds numbers (RN) ($RN > 100$), the flow separates from the body surface and generates an unsteady broad wake. This wake is recognized by two vortices in each side of the body which are shed into the current, periodically. This periodic vortex shedding generates asymmetric pressure distribution around the body that provides periodic forces which consequently lead to a limited amplitude vibration in the body.

Zhang and Wang [21] investigated a rigid circular cylinder with two PZT beams attached on through vortex-induced vibrations (VIV) and wake-induced vibrations (WIV) by installing a big cylinder fixed upstream as seen in fig. 5, in order to study the influence of the different flow induced vibrations types. The VIV test shows that the output voltage increases with the increases of load resistance; an optimal load resistance exists for the maximum output power. The WIV test shows that the vibration of the small cylinder is controlled by the vortex frequency of the large one.

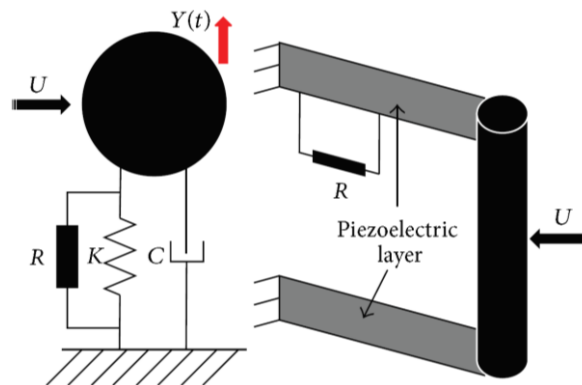


Figure 5. Schematic of a piezoelectric energy harvester [21].

Dai et al [22] investigated the characteristics and performances of four distinct VIVs PZT energy harvesters. Experiments show that the synchronization regions of the bottom, top, and horizontal configurations are almost the same at low wind speeds (around 1.5 m/s). The vertical configuration has the highest wind speed for synchronization (around 3.5 m/s) with the largest harvested power, which is explained by its highest natural frequency and the smallest coupled damping. Dai et al also [23] studied the mitigation of VIVs of a circular cylinder by utilizing a passive nonlinear targeted energy transfer. The chaotic vibrations of a VIV energy converter enhanced by a bistable stiffness element.

Wen et al [24] proposed a miniaturized VIV fluid energy harvester. A fluid-structure interaction simulation was carried out to optimize the structure of the energy harvester. As a result, the efficiency is greatly increased, which is experimentally proved. The demonstrations are working in the airflow velocity of 2 m/s, and reaches the maximum efficiency at 3.6 m/s. Jiang et al [25] investigated the VIV phenomena related to self-excited energy harvesters consisting of square cylinders by using the BGK incompressible lattice Boltzmann method. In this study, such a harvester is placed inside a channel flow and is allowed to oscillate without a structural restoring force in a direction normal to the flow. Arionfard and Nishi [26] investigated the VIV of a pivoted cylinder as a potential source of energy harvesting. The maximum efficiency of 31.4% has been observed for downstream placement of the pivot point by taking advantage of drag force and 2% for the upstream placement. Although the range of RN with high efficiency is wider when the pivot is located at the downstream, the performance of the system doesn't necessarily improve with increasing the RN in both cases.

Bhattacharya et al [27] investigated the angular oscillations of an elliptical cylinder attached to a torsional spring using computational methods, with axis placed perpendicular to a uniform flow, at RN of 100 and 200. The equilibrium angle and stiffness of the torsional spring is chosen such that the ellipse reaches stable equilibrium at an angle of roughly 45° with respect to the incoming flow. They found that the frequency spectra of fluid torque have only one peak up till density ratio of 3, and that a secondary peak emerges at higher density ratios. Power output is maximum when density ratios ranging from 3 and 10, and increases with RN. Peak efficiency of the generator is 1.7% at RN of 200. Xu et al [8] presented a theoretical study of the coupling between a VIV cylindrical resonator and its associated linear electromagnetic generator. It has been found that the proposed configuration has a maximum hydrodynamic to mechanical to electrical conversion efficiency (based on the VIV resonator oscillation amplitude) of 8%. For a cylindrical resonator of 10 cm long with a 2-cm

diameter, this translates into an output power of 20 to 160mW for water stream velocities in the range from 0.5 to 1 m s⁻¹.

3. Future challenges in the research

A retrospect based on several flow-induced vibration phenomena has been presented. Different EH techniques with a particular emphasis on EH from aerodynamic instabilities and the exploration of using the harvested energy to contribute to green aviation were discussed. Many researchers addressed EH from aerodynamic instabilities for aircraft or unmanned aircraft applications [3, 4]. In these references, concepts and experimental prototypes have been introduced to harvest energy from base excitation, gust and other sources of vibrational energy by equipping the wing with a number of transducers. Several challenges that hinder the future development and application of aerodynamic instabilities-based EH in the aerospace have also been enlighten [4].

Nevertheless, many promising results have been obtained from EH research studies, but it is noticed that this technology has not been achieved in real aerospace applications. One of the challenges is that the harvested vibrational energy is low compared to the energy needed to operate sensors and electronics installed on-board aerial platforms. Also, there are many performance parameters that should be given keen consideration, like operating environment, cut-in speed and operating bandwidth of transducers to enhance output density/conversion efficiency, improve robustness and increase the life time.

4. Conclusion

EH technologies based aerodynamic instabilities of an aircraft have been presented in this paper. The retrospect on the EH literature has depicted that these types of EH techniques have achieved significant improvements in a very small period of time. In our study, most of the critical milestones in EH research has been presented on the applications of aircraft systems and other aerospace vehicles. The applications of these aircraft systems have employed ambient vibration EH and other forms of energy to reduce the dependency on conventional sources of energy like chemical batteries etc. In addition, the feasibility of EH principle allows for a safer environment and reliable energy cost management for the aviation industry. We have concluded our study by stating the future trends in the research of flow-induced EH techniques. It is demonstrated that harvesting vibration energy from induced aerodynamic instability phenomena such as galloping, flutter, and vortex induced vibration is one of the trending research areas among the researchers of aerospace.

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