Chapter 10
Vibration Energy Harvesting in Fluctuating Fluid Flows

S. Krishna Kumar, Sunetra Sarkar and Sayan Gupta

Abstract Ambient energy harvesting for power supply to low power hardware, like sensors in inaccessible environments, has garnered sustained interest over the last two decades. Common sources of ambient energy include vehicle vibrations and natural fluid flow. The latter is also proposed as a possible quiet alternative to conventional renewable energy systems like horizontal and vertical axis wind turbines. Various forms of flexible structures have been proposed and tested over years and found to be comparable to conventional systems on an energy density basis. These harvesters often rely on instability of the fluid-structure coupled system at increasing flow velocities. Thus, the design of these harvesters requires an understanding of the complex fluid-structure interaction inherent in them, which may include nonlinear effects. The inclusion of an electric circuit to scavenge the vibratory energy further transforms it into a three-way coupling problem. Despite laboratory scale verification of the potential of these systems, practical deployment has been deterred by the fluctuating nature of the natural fluid flows. Recent researches have sought to develop adaptive harvesters for such scenarios. Some progress has also been made in exploiting the spatio-temporal flow fluctuations beneficially for enhancing harvested power. This chapter summarizes the state-of-the-art in this regard and classifies the various approaches to tackling flow fluctuations.

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10.1 Introduction

The rapid growth of electricity consumption over the last few decades and concurrent rapid depletion of non-renewable resources for power generation have stimulated widespread research efforts into renewable energy technologies. While solar and wind energy production has progressively improved in terms of yield and efficiency, such sources are not useful in all scenarios of power consumption. For example, the ubiquitous use of small sized sensors across critical infrastructure, urban monitoring systems, aerospace applications have necessitated development of reliable ultra low power (ULP) sources. In many cases, like structural health monitoring of bridges, the sensors operate in remote locations and are wireless (Park et al. 2008). The difficulty in providing sustained power from ground station over time has motivated standalone energy harvesters tapping abundantantly available ambient energy in the environment. Further, portable electronic systems like sensors are often small in size, i.e., centimeter-scale to micro-scale. Ambient energy harvesters help replace batteries as power sources for such systems since batteries are often of unwieldy size and require repeated maintenance. Prominent sources of ambient energy are base excitation as in an oscillator placed on a bridge or a moving vehicle, acoustic energy and energy from fluid flows.

Various vibration based energy harvesters (VEH) exploiting base excitation and external forcing have been developed over the past few decades (Pellegrini et al. 2013; Williams and Yates 1996; Stephen 2006). Early models of VEH considered linear oscillators which would undergo substantial vibration due to resonant conditions. Optimal energy harvesting would then require that the VEH was tuned to resonate with the ambient energy source. However, this imparted a restriction on the practical use of such harvesters as the ambient energy source could have varying frequencies over time and space. In other words, the ambient source is characterized by a wide frequency spectra. Linear harvesters perform poorly away from the resonant frequency, even for small mistuning. While automated tuning of VEH has been attempted with some success, a better solution to this problem exists in the form of nonlinear energy harvesting. As nonlinear systems possess multiple equilibria-both stationary and oscillatory- rich dynamical behaviour ranging from inter-well oscillations in systems with double well potential to limit cycle oscillations can be expected. Since the nonlinear systems permitted significant oscillation even in non-resonant conditions, along with the emergence of superharmonic and subharmonic frequencies in the response due to nonlinearity, it improves the frequency range over which substantial energy can be harvested. Most nonlinear harvesters, like those of the double well potential type, typically are designed to operate in noisy or random environment conditions. The interaction of noise and nonlinearity has been found to widen the frequency band suitable for energy harvesting, leading to what is known as broadband energy harvesting.

Broadband energy harvesting has been applied to both linear and nonlinear systems. Adhikari et al. (2009) studied a stack based base-excited energy harvester with a stationary Gaussian white noise energy source. Stochastic differential equations based on a single degree-of-freedom model for the harvester were obtained and solved using theory of linear random vibrations. Optimal values of mechanical damping, electromechanical coupling and natural frequency of the electrical circuits were obtained. Kim et al. (2011) studied a proof mass attached to two cantilever beams. While their numerical model was linear and yielded broadband harvesting, the experiments revealed that the bandwidth was enhanced by presence of nonlinearities. A similar improvement in energy harvesting performance was observed in a bistable inertial harvester comprising of two permanent magnets and a piezo-electric cantilever beam by Stanton et al. (2009). Daqaq (2012) studied the effect of stiffness nonlinearities on monostable or bi-stable piezoelectric Duffing-type harvesters subjected to white Gaussian noise. Conditions for optimal performance of harvester were derived and contrasted with the performance of linear harvesters. Further, He and Daqaq (2014) studied nonlinear energy harvesters with asymmetric potential functions and excited by white noise. It was noticed that the asymmetry leads to degradation of performance for low and moderate noise intensities. For higher noise intensities, it seemed that the effects of asymmetry were marginal. Tang et al. (2010) discuss multiple strategies to increase the bandwidth of energy harvesting for both linear and nonlinear harvesters.

Atmospheric wind flow is one of the prominent and virtually limitless sources of broadband energy. In many systems, like unmanned air vehicles (Anton and Inman 2008), micro-air-vehicles and morphing wings (Erturk and Inman 2008; Abdelkefi and Ghommem 2013), flow induced vibrations may also be the only mechanisms available for energy harvesting. The possibility of harnessing energy from flow induced vibrations in such cases has stimulated numerous investigations into the same (Young et al. 2014; Xiao and Zhu 2014; Abdelkefi 2016). These systems attempt to harvest the enormous untapped energy available in wind flows and are easily extended to energy harvesting from other fluid flows, for example, oceanic flows. Early implementation of flow energy harvesters assumed a steady freestream flow, often causing an oscillatory instability in a flexible structure. A common structure which has been considered for such a harvester is the oscillating or ‘flapping foil’ (Young et al. 2014). Periodic oscillations obtained in such a system for a range of flow velocities have been found to be suitable for energy harvesting (Peng and Zhu 2009). Such flapping foils may be ‘passive’, i.e. oscillating purely due to the fluid forces acting on them, or ‘active’ when a pitching or heaving motion is externally imparted to the airfoil (Zhu and Peng 2009). An early implementation of flapping foil harvester was by McKinney and DeLaurier (1981), taking inspiration from fish motion. The pitching-heaving airfoil was termed ‘oscillating wingmill’ and the average power and efficiency were found to be peak with an optimal phase difference between the two oscillations. Jones et al. (1999) showed, through numerical experiments, that the efficiency of these harvesters can be improved further through a proper choice of their configurations.

Thus, the flutter or instability based harvesters involve oscillation of elastic structures under fluid forces. Energy harvesters exploiting flow induced vibrations require these vibrations to be augmented to yield reasonable quantity of power. The oscillations could be self-excited, as in the case of an elastically mounted cylinders

(Mehmood et al. 2013), airfoils (Xiao and Zhu 2014), or flat plates (Tang et al. 2009; Jamshidi et al. 2015; Onoue et al. 2014). In other cases, the oscillations of the harvester could be due to unsteady flow caused by an upstream bluff body (Allen and Smits 2001; Akaydın et al. 2010; Shi et al. 2013). Comprehensive reviews of general flow energy harvesters can be found in Young et al. (2014), Abdelkefi (2016), Xiao and Zhu (2014).

Most of the harvesters discussed hitherto assume a steady freestream flow. However, realistic flows are more often unsteady, turbulent and hence, timevarying. A classic example is the case of flexible plate or airfoil placed in the wake of a bluff body, as in Allen and Smits (2001), Akaydın et al. (2013), Shi et al. (2013). At higher Reynolds numbers, the flow behind a bluff body is turbulent. Thus, a flexible foil harvester placed in the wake of bluff body encounters unsteady upstream flow. For the standalone-foil-harvesters placed in atmospheric boundary layer, i.e. close to earth surface, the freestream flow itself is turbulent. Similarly harvesters placed over buildings in urban environment are likely to be impinged by turbulent freestream flow due to interfering buildings. In fact, most real life flows are time-varying and fluctuating, if not turbulent. Thus, fluctuating flows are both realistic as well as advantageous for robust flow energy harvesting. The rest of the chapter presents a brief review of the state of the art in different kinds of fluctuating flow energy harvesters. A cursory summary of the modelling of wind fluctuations is elucidated, followed by a review of different classes of energy harvesters based on fluctuating flow.

10.2 Aeroelastic Flow Fluctuations

Typically, turbulence is characterised by a broad frequency spectrum, comprising of a range of spatial and temporal scales, and can serve as a broadband power source. Fluctuating flows are ubiquitous in nature. The atmospheric flow closer to earth's surface is largely fluctuating, and the fluctuations are often considered simply as horizontal and vertical components. In aerospace parlance, velocity fluctuations in these components are called gusts. Real life fluid flows possess gusts of different temporal and spatial scales. Typically, in fluid-elastic problems, the fluctuations are modelled as discrete gusts- i.e., discrete impulses for computation of design loads. However, a continuous type of fluctuations is preferred when the interaction between nonlinearity and fluctuations are studied from a dynamics perspective (Poirel and Price 1997). Further, the freestream fluctuations are generally considered to be independant of structural deformations, since these do not originate from the flexible-body motion and are often called "external noise" in physics literature. Hence, the flow fluctuations are modelled in this study as a purely temporal irregular fluctuations, i.e., a stochastic process, under the assumption of isotropy, stationarity and homogeneity (Poirel and Price 1997). This implicitly assumes chordwise uniformity of the flow fluctuations. As the responses of elastic systems are often dominated by a long time scale or low frequencies in a fluctuating flow, such an assumption is found permissible (Poirel and Price 1997). Further, atmospheric fluctuating flows have often been found to conform to a Gaussian distribution (Taylor 1965; Rice 1944). Even in the presence of non-Gaussian or even non-stationary components of fluctuations, existence of a Gaussian continuous fluctuation background has been found to be reasonable (Hoblit 1988), especially when the fluctuations are strong. The frequency spectra for such a Gaussian process is often based on the Dryden spectrum or the Von-Kárman spectrum, which can essentially be treated as filtered Gaussian noise (Hoblit 1988). Common aero-elastic fluctuation spectra have predominant low frequencies, with most energy transferred between the fluid and the solid at such frequencies (Taylor 1965). Further insights on modelling turbulent flows, for energy harvesting as well as other aero-elastic applications, can be obtained from elsewhere (Hoblit 1988; Poirel and Price 1997). In addition to turbulent flows, periodic flow fluctuations have also been exploited for low power energy extraction. Real life periodic flows include fluctuations behind a bluff body for Reynolds numbers lower than the turbulent-critical value and airflow across rotor blades. A plain sinusoidal fluctuation model often suffices for such flow fluctuations. The rest of the chapter provides a short summary of energy harvesters based on fluctuating flows. The list of harvesters described here are only representative of diverse efforts in the literature towards energy harvesting from fluctuating flows and not exhaustive. Comprehensive reviews of aeroelastic harvesters, including some of the harvesters based on fluctuating flows can be found in Young et al. (2014), Xiao and Zhu (2014).

10.3 Bluff Body and Tandem Harvesters

A well known source of turbulence, studied extensively by fluid mechanicians, is the turbulence caused by obstruction of a fluid flow by a 'bluff' body. The flow past a bluff body, which is laminar for low fluid velocities, turns turbulent at higher velocities. Large eddies or coherent structures are formed behind the bluff body. The fluctuating wake has been identified as a suitable source of energy. For example, a flexible foil placed in the wake of a bluff body undergoes oscillations at lower velocities than the critical velocity at which standalone foil would exhibit substantial vibrations. The vibration of the harvester could then be considered to be a result of a combination of movement induced instability and an extraneously induced instability (Allen and Smits 2001; Naudascher and Rockwell 2012). The downstream flexible harvesters are usually called membranes or foils, and oscillate due to the unsteady fluid forcing acting on them. When the foil motion is well coupled to the vortex shedding, characterised by the foil oscillating at the frequency corresponding to Strouhal number, remarkable oscillations happen facilitating power extraction (Allen and Smits 2001).

Taylor et al. (2001) developed energy harvesting eel using a PVDF bimorph made to undergo a wavy vibration due to upstream bluff body. When flapping frequency matched the shedding frequency, maximum power output was obtained. The electric subsystem was optimised and upto 37% conversion from mechanical to electrical energy was achieved. Allen and Smits (2001) experimentally studied the flutter

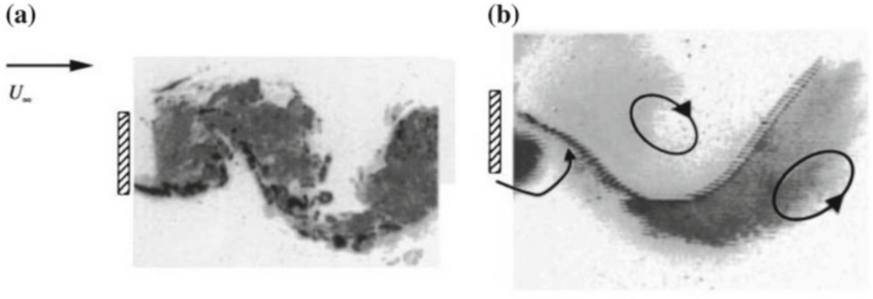


Fig. 10.1 **a** Particle image velocimetry results from the experiments in Allen and Smits (2001), which show the interaction between alternating wake coherent structures and the flexible foil; **b** Clockwise and counter-clockwise coherent structures highlighted. Reproduced with permission from Allen and Smits (2001)

characteristics of this system in detail (see Fig. 10.1). Results from particle image velocimetry showed the interaction between the flexible harvester and the coherent structures in the wake. One of the key parameters, the ratio of gap s between the bluff body and foil and the length scale D of the bluff body was fixed to be 1. Later investigations have shown that the gap plays a crucial role in the wake-foil interaction and optimal values have to be identified for efficient energy harvesting Lau et al. (2004), Kumar et al. (2017).

Pobering and Schwesinger (2004) conducted experiments on two models: PVDF flag placed behind a rectangular cylinder and a cantilever bimorph. The PVDF flag exhibited substantial energy harvesting potential and possessed an energy density of 11–32 W/m^2. It was noted that a large scale array of generators can exhibit 68 W/m^2 power compared to 34 W/m^2 of wind turbines, and could be developed as a hydro power plant. However proximity effects or mutual interaction of harvesters were ignored. It must be noted that in these harvesters, the upstream body remained static under the action of fluid forces. Alternate systems, where the upstream body can also contribute to energy output, have also been developed in the form of tandem harvesters. Depending on the freestream flow velocity, the wake of an upstream vibrating harvester can possess strong flow fluctuations, periodic or turbulent. Taking inspiration from fish shoal and bird flock motion, it has long been expected that the downstream harvesters can improve their aero-elastic performance in the presence of an upstream fluctuating harvester. Bryant and Garcia (2011) studied tandem operation of two airfoil-beam-flap harvesters. The upstream harvester performance was found to be unaffected by the downstream one. However, for the downstream harvester, presence of upstream counterpart improved performance by 30%. Streamwise gap was found to be optimal at twice the length scale of upstream harvester but the cross stream separation was found to have no effect. Four tandem harvesters were also tested with a zero gap and were found to yield more power than the individual cases. The harvesters flapped at the same frequency. The wake interaction in the tandem

Fig. 10.2 Tandem harvesters comprising of flexible beams with a tip flap tested in Bryant et al. (2012). Reproduced with permission from Bryant et al. (2012)

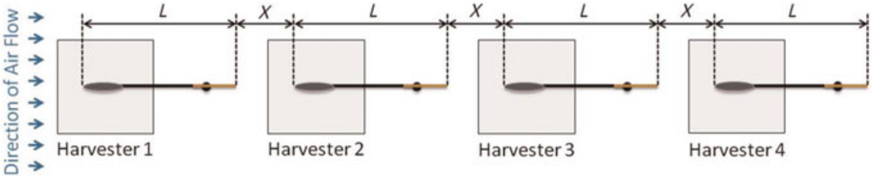


Fig. 10.3 Tandem harvesters comprising of four flexible beams with a tip flap tested in Bryant et al. (2012). Here, *X* refers to the streamwise gap between harvesters and *L* refers to the length of the harvesters. Reproduced with permission from Bryant et al. (2012)

airfoil harvester scheme was further studied by Bryant et al. (2012) (see Figs. 10.2 and 10.3). The results indicated that the tandem scheme with closely spaced array of harvesters outperformed the performance of independant harvesters. The turbulent wake structure, dependent on the streamwise and cross-stream separation of the harvesters, was found to have significant effect on the power output of the system. Optimal separation distances along cross-stream and streamwise directions were identified and frequency locking between the harvesters was observed for harvesters with identical flutter frequency.

Similarly, Abdelkefi et al. (2014) studied a cantilever beam with a rectangular tip mass placed in a fluctuating flow (see Fig. 10.4). Two cases were studied: the harvester placed in the wake of another harvester and a single harvester placed in a grid-generated freestream turbulence. Optimal spacing for the tandem harvester case and optimal turbulence scales for the grid-generated turbulence were identified and the harvesters showed power enhancement over the steady flow. Note that the bluff body-wake foil harvesters and tandem foil harvesters do not require the freestream to be fluctuating. As a corollary, the effects of freestream flow fluctuations on the

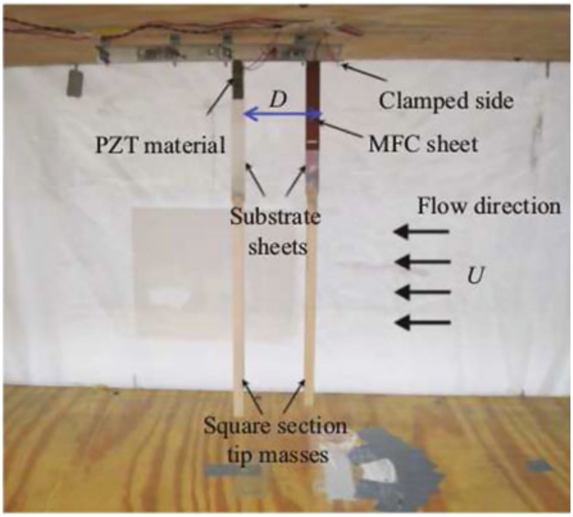


Fig. 10.4 Tandem cantilever beams with rectangular tip masses studied in Abdelkefi et al. (2014). Reproduced with permission from Abdelkefi et al. (2014)

harvesting performance of these multi-body harvesters are less known. Since real wind flows often possess substantial freestream turbulence, significant efforts have been made over years towards harvesting energy directly from it.

10.4 Freestream Pulsating Flow

The effect of upstream flow fluctuations on aero-elastic systems attracted significant interest in the early days of manned flight. Often, the focus was limited to vertical or cross-stream fluctuations, though sporadic efforts on streamwise or horizontal flow fluctuations have been made from time to time. In recent times, the development of Micro-air-vehicles (MAVs) and the need to control their flight as well as to provide persistent source of power has motivated the study of upstream flow effects at this size scale. Micro-air-vehicles are generally operated at low altitudes, in atmospheric boundary layer (Lundström and Krus 2012). Additionally, use of MAVs in urban surroundings necessitates the consideration of turbulence. Thus, substantial efforts have been made by the aero-elastic community over the last century to understand energy extraction from flow fluctuations. The first part of the review presented next deals with the pulsating or periodic flows often considered to model freestream fluctuations. The second part discusses energy harvesting research considering continuous freestream turbulence.

Katzmayr (1922) conducted one of the earliest investigations into energy extraction during aircraft flight in pulsating flow. It was shown through wind tunnel experiments that a pulsating flow caused reduction in both drag and lift for thin airfoils. On the contrary, for thick airfoils, a negative drag with positive lift was observed indicating a forward ascending flight. This is often known as the ‘Katzmayr effect’. It was also noted that the aircraft performance improved with increase in the amplitude of the pulsating flow. The frequency of the pulsating flow was seen to have a less significant effect, though an optimal low frequency was also reported for certain airfoil sections. Phillips (1975) developed a simple analysis of the propulsive effect caused by gusts encountered by aircraft. A Dryden spectrum based model of vertical gusts was used, along with assumptions of constant airspeed and constant pitch angle. It was shown that the thrust improvements were insignificant for aircrafts, for example soaring gliders, fighters, transport and light airplanes, encountering moderate turbulence. Langelaan (2009) proposed the biomemetic exploitation of short duration gusts by aircrafts for performance enhancement, in comparison to earlier efforts to exploit long duration vertical air motions, thermals and dynamic soaring. The study noted that such gusty flows are highly probable in urban environments and may provide performance benefits at the size-scale of micro-air-vehicles, which operate in such environments. A closed loop control architecture was developed for energy extraction and the gust-soaring controller was shown to have advantages over a constant-air-speed controller. Cutler et al. (2010) investigated the flight performance of UAVs using ridge lift based energy harvesting, enabling persistent imaging of a stationary target. The flow past the ridge and the closed loop trajectory of the UAV effectively causes a periodically fluctuating flow. Optimal position and trajectory of the UAV for low use of external supplied power were identified.

Pozzi et al. (2012) investigated the strain levels in an aircraft wing with a piezoelectric skin caused during and after a gust event. The gust was modelled using 1-Cosine profile and a range of gust frequencies were studied to yield insight into realistic air turbulence. It was found through finite-element based numerical simulations that the energy generation was higher when the gust frequency was closer to the natural frequency of the wing. In general, higher gust frequencies yielded better energy output than lower frequencies. Also, large and thin PZT patches were seen to improve energy output. The gust based harvesting technique was also noted to be useful during taxiing of aircrafts and during long flights.

Bruni et al. (2014) studied the response of three wing models to discrete gust loads for the purpose of gust alleviation and energy harvesting. Three different gust models were employed- sinusoidal, constant and linear. The numerical simulations suggested that significant energy output could be harvested from the gusts and was preferable to flutter based energy harvesting due to the fatigue effects caused by the latter.

Chen et al. (2017) examined the effects of a sinusoidal gust on the energy harvesting performance of NACA0012 airfoil with imposed heaving and pitching motions (see Figs. 10.5 and 10.6). It was observed that the energy harvesting efficiency varies with the phase difference between the gust and airfoil pitching motions and peaked at optimal values of phase difference. Energy efficiency was found to be less sensitive to changes in gust frequency. However the sensitivity of energy efficiency towards gust amplitude was found to depend on the gust frequency. At lower gust frequencies, monotonic decrease in efficiency with increase in gust amplitude was

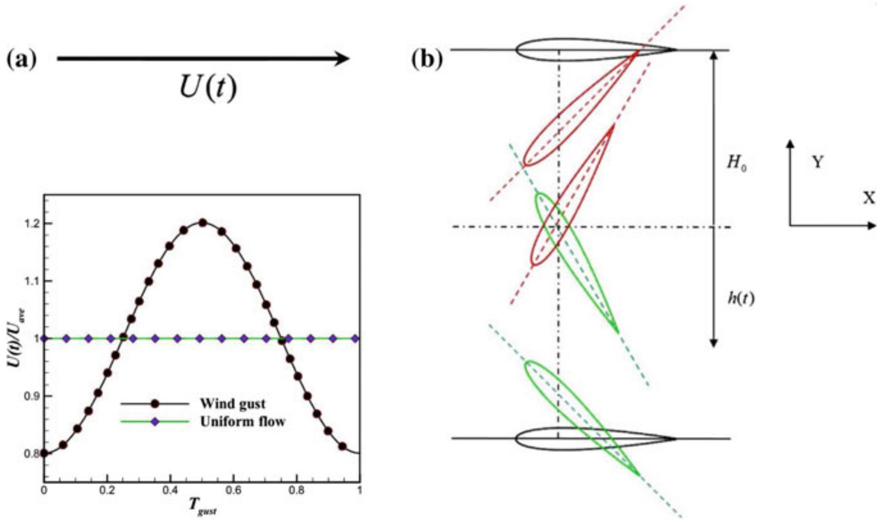
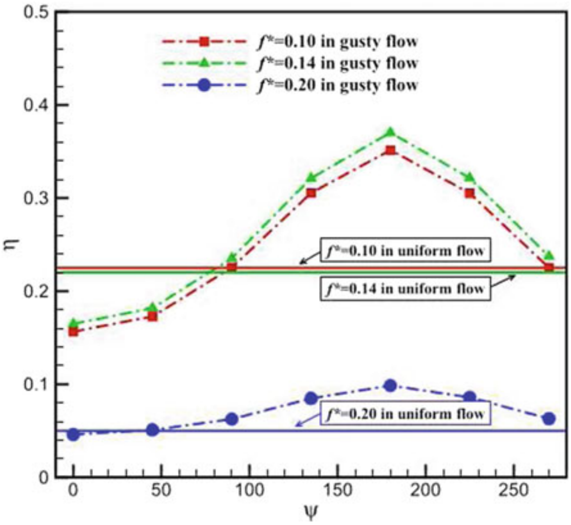


Fig. 10.5 **a** Sinusoidal flow fluctuations and **b** the kinematics of pitching-heaving airfoil in Chen et al. (2017). Reproduced with permission from Chen et al. (2017)

Fig. 10.6 Variation of harvester efficiency η with variation in the phase difference Ψ between the gust and the pitch Chen et al. (2017). Reproduced with permission from Chen et al. (2017)



observed. In contrast, at higher frequencies, the efficiency has a peak value at an optimal amplitude.

Xiang et al. (2015) studied aeroelastic energy harvesting from a piezo-electric wing under a 1-Cosine discrete gust through a coupled aero-electro-elastic model. They optimized the energy harvester for a given gust through a parametric study for energy efficiency and energy output density. It was noted that maximum efficiency and maximum output density occur at different optimal size of transducers. Bruni et al. (2017) note that in the pre-flutter regime, flutter based harvesters are typically subjected to unsteady and time-varying fluid forces. These are similar to broadband and impulsive excitations studied for general vibration based energy harvesters. They considered 1-Cosine and square gusts as idealization of continuous vertical turbulence. The gusts were deemed to be comparable if they had equal area under the curve defining the gust profiles. It was found that the square gust acted like a step input to the system and the response was transient decay of oscillations during and after the active period of the gust. For the 1-Cosine gust, the scenario was different. During the active period of the gust, the response had the same cosine profile as the gust, except for a time-lag. Beyond this period, the response was found to be transient decay. It was found that the power generated during the cosine gust was lesser than that generated from the transient decay after the gust. The power from the transient decay was also found to be dependant on the value of response at the termination of the gust. Both the gust profiles were found to produce more power after the gust than during it. The power generated during the square gust was found to be higher than that during the 1-Cosine gust. Note that the gust, being a cross-stream fluctuation acts akin to an external forcing on the system. The interesting observation of this study was that the power generated after the termination of the forcing was higher than that during the forcing. Since the discrete gust profiles themselves are idealizations of continuous turbulence, it is unclear how these insights would translate for continuous gust. In such a case, the transient decay would not be largely existent and the increased power expected could be absent (Fig. 10.7).

Bruni et al. (2017) also studied the variation in the power output with variation in the gust gradient. It was observed that during the square gust, the peak power increased with increase in gust gradient. In contrast, a decrease in peak power was observed with increase in gust gradient for the 1-Cosine gust. Likewise, the average power output after the termination of the gust was found to increase with increase in the gust gradient for the square gust. However, for post-termination response corresponding to the 1-Cosine gust, an optimal gradient existed beyond which both the peak instantaneous power and the average power decreased with increase in gust gradient. Additionally, it was found that for both the gust profiles, an optimal electrical resistance of the harvesting circuit existed beyond which the gust seemed to

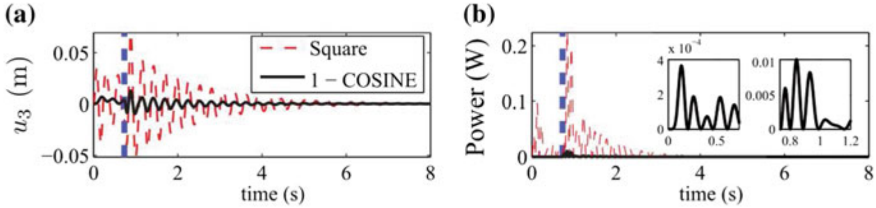


Fig. 10.7 **a** Displacement and **b** instantaneous power output of the harvester for square and cosine gust studied in Bruni et al. (2017). The blue dashed line marks the end of the active period of the gust. Reproduced with permission from Bruni et al. (2017)

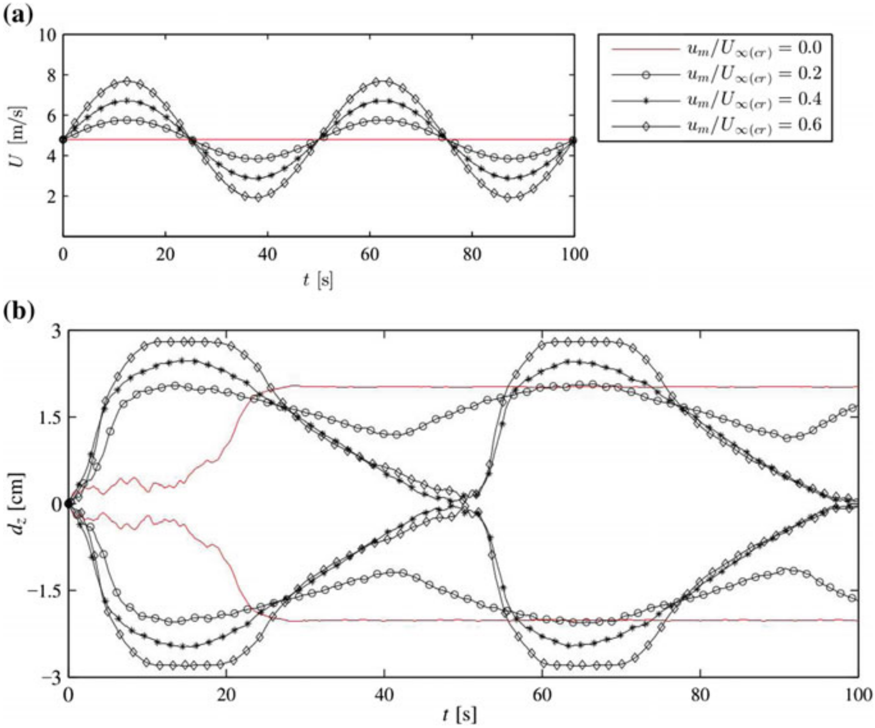


Fig. 10.8 Flow velocity fluctuations and displacment time histories for different non-dimensional amplitude of imposed fluctuations in Chawdhury et al. (2018). Reproduced with permission from Chawdhury et al. (2018)

have no effect on the wing. Chawdhury et al. (2018) numerically studied the effect of a pulsating flow on a T-shaped flutter based energy harvester through a single degree of freedom model coupled with a vortex particle method based fluid solver (see Fig. 10.8). Periodic streamwise flow velocity fluctuations were superimposed on a mean flow. The fluctuations were chosen to have low frequency for computational convenience as well as to model larger eddies present in natural fluid flows. They noted that the flow fluctuations caused a change in the onset of flutter. An early commencement of unstable motion was observed, though amplitude of the resulting oscillations was observed to be smaller than the corresponding steady flow case. These two effects were attributed to effective negative aerodynamic damping occurring when instantaneous flow velocity was lesser than the mean velocity and effective positive aerodynamic damping when it was otherwise. They compared the two damping effects using flutter derivatives and concluded that the net effect was effectively that of a negative damping. However the study was restricted to modelling of fluid-structure interaction and the effects of pulsating flow on the power output wasn't investigated.

10.5 Freestream Turbulence

Though the 1-Cosine pulses and periodic streamwise flows enable easy exploration of effects of freestream flow fluctuations, they do not capture the complete effects of turbulence. For instance, these models do not account for the co-existence of different spatial and temporal scales in turbulent flows and their simultaneous interaction with the harvester. This necessitates the need to study realistic turbulence and its effects on the flow energy harvesters. A short summary of recent research on this front is presented next. Fei et al. (2012) proposed a wind belt based harvester designed to operate under low mean-wind-speed random flow conditions. The harvester performed better under higher mean velocities when the spring constant was higher, enabling better aero-elastic coupling. A peak output of 7mW at mean flow velocity of 2m/s was observed. Such randomly fluctuating flows can result from boundary layers of objects or inherent turbulence in the freestreamflow. Andreopoulos et al. (2015) investigated the effect of size and strength of turbulent eddies on energy harvesters (see Figs. 10.9 and 10.10). Two scenarios were experimentally studied- an inhomogenous turbulent field in a boundary layer and a homogenous grid-generated turbulence. They noted that turbulent flow degraded the performance of resonance based energy harvesting. It was found that the power harvested varied nonlinearly with change in turbulence length scales.

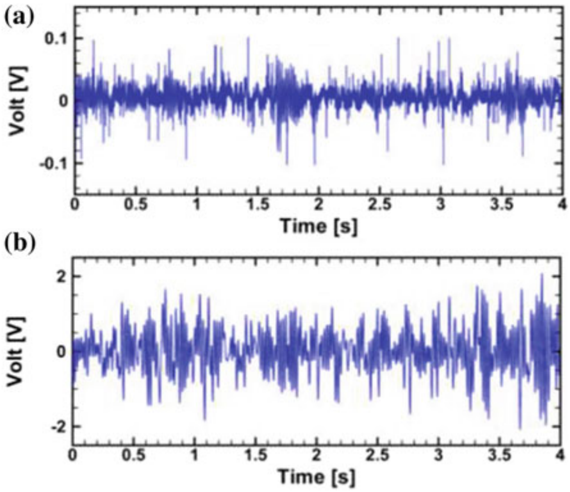


Fig. 10.9 Votage time histories for **a** boundary layer turbulence and **b** grid-generated turbulence for the harvester in Andreopoulos et al. (2015). Reproduced with permission from Andreopoulos et al. (2015)

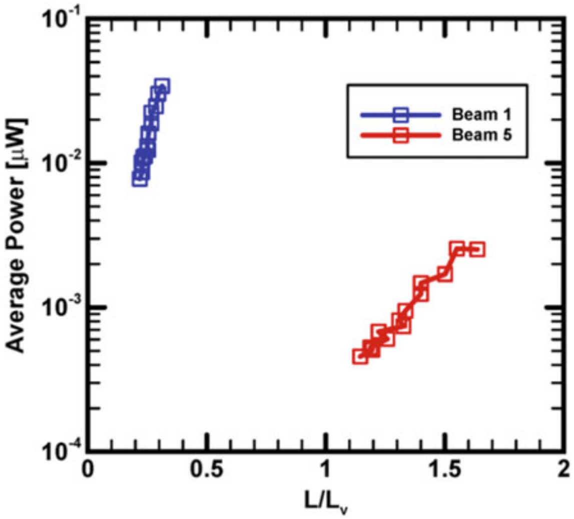


Fig. 10.10 Variation of average power output with the length scale of turbulence for the harvester studied in Andreopoulos et al. (2015). Reproduced with permission from Andreopoulos et al. (2015)

St. Clair et al. (2010) used the pressure fluctuation in a cavity to harvest energy from a piezo-electric beam (see Fig. 10.11). The design was inspired from air-flow induced oscillations inside harmonicas. A supercritical Hopf bifurcation was found to occur and limit cycle oscillations yielded sustained power output of the range 0.1–0.8 mW in the flow velocity range of 7.5–12.5 m/s. An electro-mechanical model and a Galerkin discretization based reduced order model for the harvester was later developed by Bibo et al. (2011). Akaydın et al. (2010) tested a harvester under pure freestream turbulence and obtained 0.06 μW at 11 m/s. This was lesser than 4 μW obtained at 11 m/s behind a cylinder. Hobeck and Inman (2012) studied inverted/vertical cantilever beam arrays, termed as 'piezo-electric grass' (Figs. 10.12 and 10.13). They attempted to harvest energy from low velocity high turbulence flows as in rivers. The experiments used a bluff body upstream with mean freestream velocity of 7 m/s and turbulence intensity of 25% impinging on the 'grass'. A power output of 1 mW was observed for PVDF patch and PZT Quickpacks(TM).

Lundström and Krus (2012) performed a flight testing of a MAV in real turbulent atmospheric flow. Effect of turbulence on the performance of MAV was found to be negligible, though the MAV flight itself was heavily disturbed by the unsteady effects caused by turbulence. However it was noted that turbulence seemed to offset drag increase due to yaw oscillations expected for a steady aerodynamics. Similar investigations have also been carried out by Emmanuel Bénard's group (Bonnin et al. 2015; Gavrilovic et al. 2017, 2018, 2019). Zhu (2012) performed numerical simulations of a flapping foil placed in a shear flow. The foil was found to undergo sustained periodic oscillations for low shear rates and optimal parameter values for energy harvesting were identified. The region in the parameter space over which

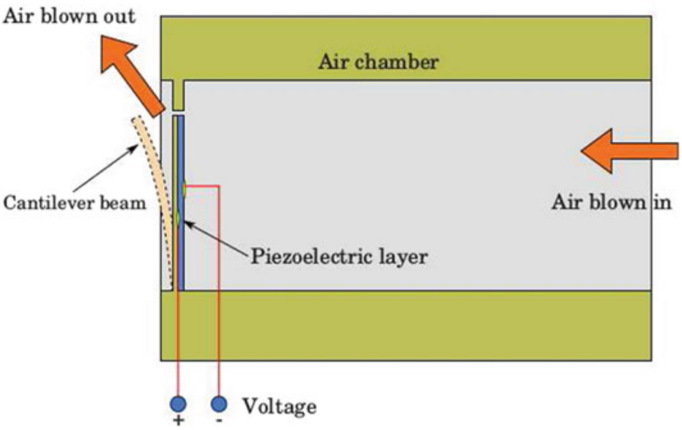
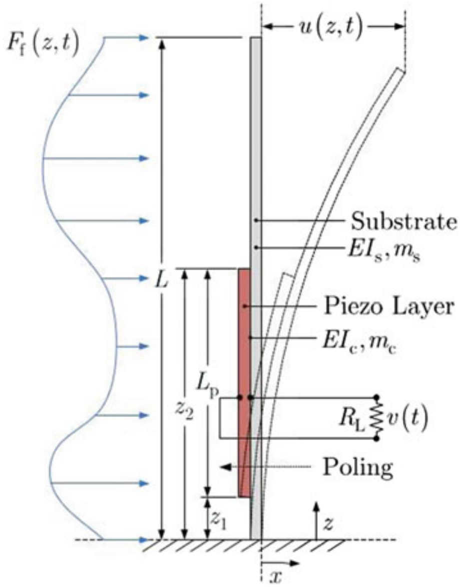


Fig. 10.11 A schematic of the cavity based harvester in St. Clair et al. (2010). Reproduced with permission from St. Clair et al. (2010)

Fig. 10.12 A schematic of harvester studied in Hobeck and Inman (2012). Reproduced with permission from Hobeck and Inman (2012)



periodic oscillations occurred were observed to be bigger than that for uniform flows. However, for large shear rates, such regions completely disappeared and irregular oscillations less suitable for energy harvesting were also observed. Kwuimy et al. (2012) explored energy harvesting from a magneto-piezo-elastic Duffing oscillator placed in a turbulent flow (see Figs. 10.14 and 10.15). A periodic forcing with a Gaussian distributed random phase was used to simulate turbulent airflow. The energy output, from inter-well oscillations that occur once the potential barrier was

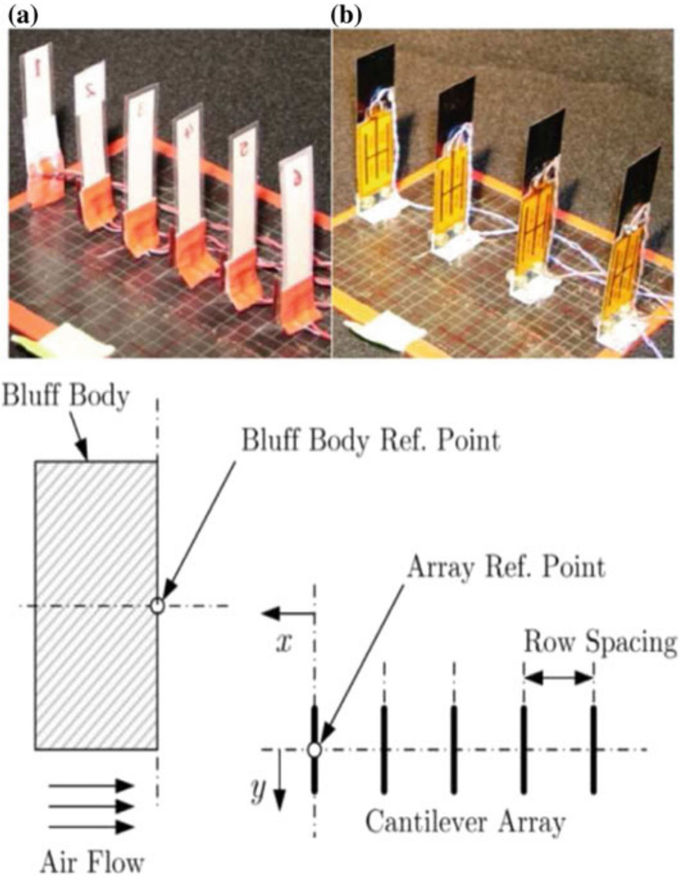


Fig. 10.13 Array of harvestors forming the piezo-electric 'grass' proposed in Hobeck and Inman (2012): **a** using PVDF patches and **b** using PZT Quickpacks. (**c**) Schematic of the placement of the harvesters. Reproduced with permission from Hobeck and Inman (2012)

overcome, were maximum when the noise intensity was such that the system was closer to stochastic resonance.

Wang and Inman (2013a, b) designed a multi-functional wing spar for energy harvesting and gust alleviation in UAV flight. They considered a filtered Gaussian noise with a Dryden PSD spectrum. Variation of gust scale length was imparted by using a gust gain factor in the frequency domain. The model was supposed to mimic clear sky flight with cumulus cloud gusts. Their theoretical and numerical investigations indicated that active gust alleviation was feasible through self-powered piezoelectric wafers. The harvested power was observed to be higher for longer active length of the spar. McCarthy et al. (2015) studied a triangular polymeric leaf attached through a hinge to a PVDF stalk which itself is fixed to a cylindrical base (see Figs. 10.16 and 10.17). In wind tunnels experiments, they replicated atmospheric

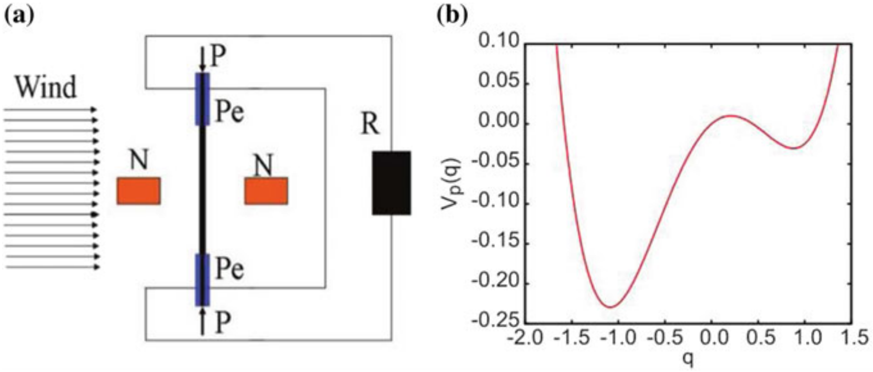


Fig. 10.14 **a** Schematic of harvesters studied in Kwuimy et al. (2012) and **b** the corresponding potential well. Reproduced with permission from Kwuimy et al. (2012)

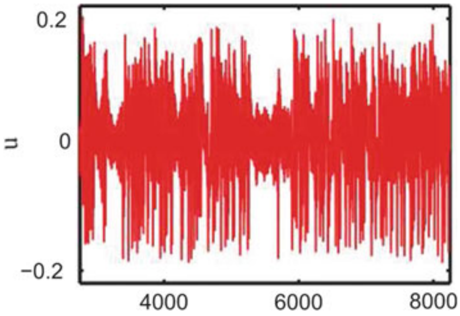


Fig. 10.15 Harvester response near stochastic resonance with prominent inter-well oscillations for the harvester in Kwuimy et al. (2012). Reproduced with permission from Kwuimy et al. (2012)

boundary layer flow using an upstream grid and placed the harvester at sufficient distance downstream to cause a well mixed turbulence. They found that turbulence is generally detrimental to energy harvesting for bluff body- wake foil harvesters. However at high incidence angles of the harvesters, turbulence improved the power output. Increase in power was noted to be possibly due to increased higher frequency contributions. In contrast, at small pitch and yaw angles, turbulence in the flow was noted to dampen the harvester response and acted as a dynamic damping mechanism. Goushcha et al. (2015) experimentally tested the energy harvesting potential of thin flexible cantilever beam piezo-electric harvesters placed in a turbulent boundary layer (see Fig. 10.18). It was seen that the power output increased with higher mean horizontal flow velocity and the optimal position was a region close to the wall.

These studies indicate that both periodic and turbulent fluctuations in fluid flows possess ample potential for energy harvesting. However, it must be noted that the efforts towards a practical flow fluctuation energy harvester is still in nascent stages. Note that significant focus along these ideas have occurred only over the last decade, in contrast to four decades of flow energy harvesting. In addition to the inherent complexity of the flow fluctuations, issues in appropriately modelling and testing them respectively through numerical models and experiments aggravate the slow pace of

Fig. 10.16 Setup for grid turbulence and test rig for the harvester studied in McCarthy et al. (2015). Reproduced with permission from McCarthy et al. (2015)

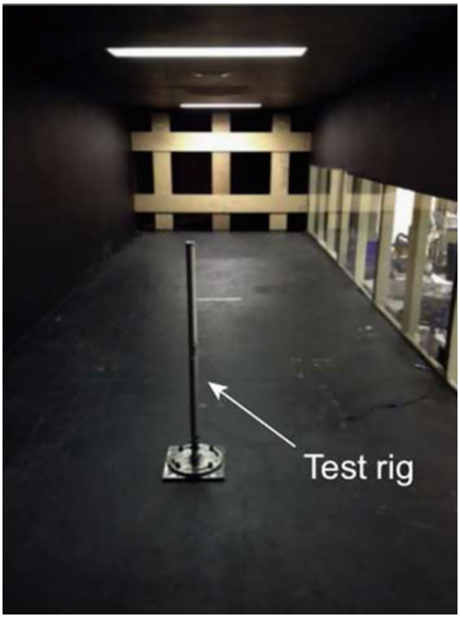


Fig. 10.17 A close view of the piezo-electric leaf harvester in McCarthy et al. (2015). Reproduced with permission from McCarthy et al. (2015)

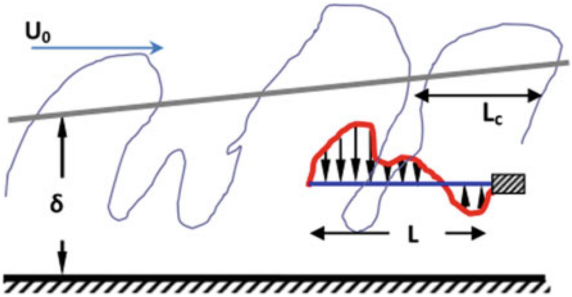


Fig. 10.18 Schematic of harvester in boundary layer turbulence in Goushcha et al. (2015). Reproduced with permission from Goushcha et al. (2015)

progress. Despite four decades of research, hardly any low power flow energy harvester has successfully been commercialised. Flow fluctuations based energy harvesting presents a possible solution to this conundrum, and also significant research challeges.

10.6 Conclusion

This chapter provided a brief background of flow energy harvesting and the necessity and use of considering the fluctuations inherent in the flow. A cursory description on modelling of flow fluctuations has been provided. The chronological development of research on energy extraction from pulsating, periodic and turbulent flow has been provided. Significant emphasis has been given to recent developments in this regard. While a significant body of research has emerged on energy harvesting from flow fluctuations, many aspects of the problem are still scantily explored. While most studies have focussed on effects of fluctuations on a particular harvester configuration, more generic studies akin to fundamental studies on generic nonlinear broadband harvesters need to be conducted. Likewise, little attention has been paid on suitably designing the electrical subsystem of the harvester which needs to be resilient to the irregular or fluctuating nature of the power generated in most of these harvesters. As natural fluid flows are often fluctuating, investing research effort along these lines can be extremely rewarding as the field of flow energy harvesting matures further.

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