Parameterization Study of The Efficiency of a Piezoelectric Flutter Based Harvester

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Abstract

Facing the threats of climate change, innovation in the development of renewable energies has become a major research focus today. One such technology involves the utilisation of piezoelectric transducers to harvest energy from aeroelastic flutter. Such technologies allow for the safety and noise considerations of installing wind turbines in urban centres to be addressed. However, due to the novelty of the concept, the design considerations in building such a harvester are still not fully understood. As such, this project aims to test how different parameters affect the efficiency of such devices by conducting an experimental study within a low speed wind tunnel. The results showed that long thin plates generated higher voltages a low wind speeds but also failed easily. While reinforcement of the plate was able to address the problem of structural failure, it also resulted in the delay of the onset of flutter. It was thus concluded that an optimal length and thickness exists, with support structures to be centred to the centre of mass to reduce their impact on the efficiency of the harvester.

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Chapter 1 Introduction

1.1 Motivation for Research

Innovation in the development of renewable energies has received much attention due to its relevance in addressing climate change, dubbed as the major threat of the 21st century. The impact of the burning of fossil fuels on the environment, depleting fossil fuel reserves, as well as the opportunities in renewable energies are the main drivers behind this wave of innovation.

To begin with, the carbon emissions from the use of fossil fuels is one of the main contributors to climate change. This results in global issues such as extreme weather events and sea level rise, which makes the environmental impacts of fossil fuel use a primary concern [3].

Furthermore, fossil fuels are a limited source of energy, with oil reserves expected to be depleted in 40 years at the rates of consumption seen in 2006 [4]. In particular, the aviation industry is highly vulnerable, with its fuel being nearly exclusively obtained the kerosene fraction of crude oil [5].

On top these worries, the trend of increasing global industrialisation and urbanisation is expected to result in an increased energy demand [6]. Fortunately, wind energy holds promise as a renewable energy source and is estimated to account for 20% of the world’s energy needs in 2020 [7]. There has thus been a great deal of effort in improving the implementation of wind energy harvesting technologies to increase their output in urban environments. Efforts have so far been split between two approaches, locating wind energy farms in the peripheries of urban areas or integrating them within the urban centres [8]. Unfortunately, offsite power generation suffers from power losses of up to two-thirds the generated power due to transmission losses [9, 10]. Resultingly, there has been a push to scale down wind turbines for on-site applications. However, due to their proximity to urban centres, the noise, safety and reliability are the key challenges which require to be addressed [11].

Mechanical energy harvesters utilizing piezoelectric transduction mechanisms are an alternative to traditional wind turbine designs as a means of extracting energy from a flow. Compared to wind turbines, piezoelectric transduction devices can be deployed in small volumes and are able to harvest energy over a large range of frequencies, making them suitable for a wide range of applications from urban deployment to mountings on unmanned aerial vehicles (UAV) [12, 13].

Flutter is an aeroelastic phenomenon, involving the transfer of energy from a fluid flow to a structure within the flow. While it is usually treated as a destructive phenomenon, there is potential to utilize piezoelectric materials to harvest energy from the flow by means of the flutter phenomenon. Given the negative impacts of flutter on the performance of the various structures and its contribution to fatigue damage and even structural failure, there has been extensive work done on flutter control [13]. On the other hand, research done on energy harvesting devices from flow induced vibrations are fairly recent. Therefore this project aims to parameterize the efficiency of flutter-based harvesters, so we may extract power from what is considered an unwanted phenomenon [12].

1.2 Objectives

The objective of this project is to parameterize the efficiency of a flat plate piezoelectric flutter-harvester and to suggest optimal design considerations based on the identified parameters.

1.3 Scope of Work

This project will begin with a literature review of energy harvesting provide the background knowledge required to understand how flutter-based harvesters work and the considerations involved in designing them. The literature review will also cover known factors determining the efficiency of flutter-based harvesters and identify gaps in current research which this report will attempt to answer.

Various samples will be designed to test the factors identified in the literature review, and a set-up will be constructed to secure the airfoil within the wind tunnel, as well as to measure the voltage developed by the structure undergoing aerodynamic responses.

The material used to construct the samples will have to be chosen to allow the sample to act as a model representative of practical applications. It will also have to allow for a short turn-around time in the production of new samples, to allow for flexibility in how a variety of factors can affect the efficiency of the harvester.

The set-up will need to be able to securely position the samples within the low speed wind tunnel as well as mitigate variables such as disruptions in the flow and vibrations in the set-up. A piezoelectric sheet will also have to be chosen to enable energy to be extracted from the device.

The investigation will be conducted in two rounds, first to determine what combination of factors will effectively result in flutter and the second to determine how they contribute to the amount of flutter experienced.

Finally, the results will need to be tabulated and examined to consider how they affect the voltage developed by the set-up.

1.4 Organisation of Report

The report is organised as follows:

Chapter 1, which is this chapter, presents an introduction, including the research motivation, objectives and scope of work to achieve said objectives. It also includes a brief overview of the organisation of the report.

Chapter 2 summarises findings from the literature review as well as the research gaps targeted by this project. It serves to provide insight into the flow conditions where the harvesters will be deployed and the mechanisms in which the flow energy is converted to mechanical and subsequently electrical energy. Subsequently it categories the conclusions made in past works and the research gaps to be tackled by this project.

Chapter 3 describes the experimental setup and rationale behind the choice of materials used in the setup. It also covers the methodology and progress of the experiments, highlighting the parameters being tested for.

Chapter 4 presents the results from the experimental procedures, providing data to describing the energy harvested and behaviour of the experimental setup. Following which it offers an analysis of the results, suggesting conclusions which can be drawn.

Chapter 5 concludes the report, as well as offering suggestions for future research.

Chapter 2 Literature Review

2.1 Urban wind profile

To fully exploit the potential of wind energy in an urban environment, it is essential to first understand the urban wind characteristics. The urban boundary layer (UBL) is a boundary layer above a city centre in which the flow characteristics are heavy influenced by an inhomogeneous roughness, characteristic of the city centre. The UBL is further subdivided into different levels, based upon their relative heights to the height of the buildings. In the bottom layer, known as the surface layer, the flow at a point is highly dependent on its surroundings. Thus, different flow behaviours will be observed depending on the uniformity of building heights, and the building aspect ratio, which is the ratio of the building heights to the street width [14, 15]. Figure 2-1 shows how the aspect ratio affects the flow regime experienced within the canyon. As the building aspect ratio increases from sparsely distributed low lying buildings (a) to densely packed high-rise buildings (c), the aerodynamic effects of the buildings on the flow interfere with each other, resulting in the formation of a vortex in the canyon within the buildings [16].

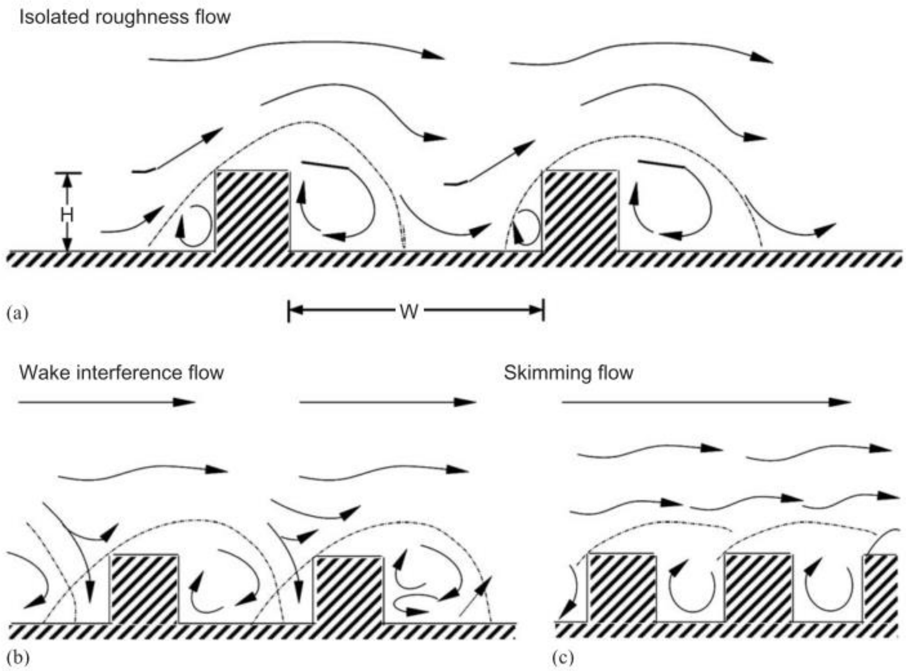

Figure 2-1: Perpendicular flow regimes in urban canyons for different aspect ratios, taken from [17]

On-site surveys provide a clearer picture of the conditions flutter-based harvesters installed in urban areas will experience. They suggest that wind speeds vary between 1 – 10ms^{-1} in urban areas, averaging 4ms^{-1} in city centres and 6ms^{-1} at coastal areas. In addition, turbulence intensities are also known, ranging from 10-22% [11, 18, 19].

2.2 Aeroelastic phenomena exhibited by various structures

Flutter-based harvesters are made possible due to the phenomenon whereby structures placed in a flow experience various aeroelastic responses. These responses depend on the flow about the structure as well as the geometry of said structure. Consequently, the literature for aeroelastic harvesters can be divided by the aeroelastic response of the structure and its associated geometry; flutter in flat plates, vortex induced vibrations (VIV) of cylindrical structures, galloping of prismatic structures and wake induced galloping of structures placed behind a vortex shedding buff body [12]. Of these, the flutter of flat plates is the most suitable for a parameterization study as the other aeroelastic responses are more complicated due to the need to consider the upstream vortex shedding buff body as well as the oscillating system [11, 13].

2.2.1 Flutter

Flutter is a self-induced destructive oscillation, resulting from the interaction of inertial, elastic and aerodynamic forces. Nearing the onset of flutter, the flow will transfer energy to the structure, resulting in a damping effect. Below a certain flow speed, known as the critical flutter wind speed, henceforth to be referred to as the flutter speed, structural vibrations will decay, maintaining the structure in an equilibrium state. However, above the flutter speed, the structure will experience a negative damping effect, causing the oscillations to grow until structural failure occurs [13]. The flutter point refers to the point where the damping provided by the flow results in the overlap of two modes of vibration in the structure. The frequency at which this occurs is the flutter frequency. [20]

Three regimes of flutter were identified by Connell and Yue, fixed point stability, where the initial displacement decays over time, limit-cycle flapping where the displacement results in a stable sinusoidal wave and finally chaotic flapping, characterised by non-periodic behaviour [21].

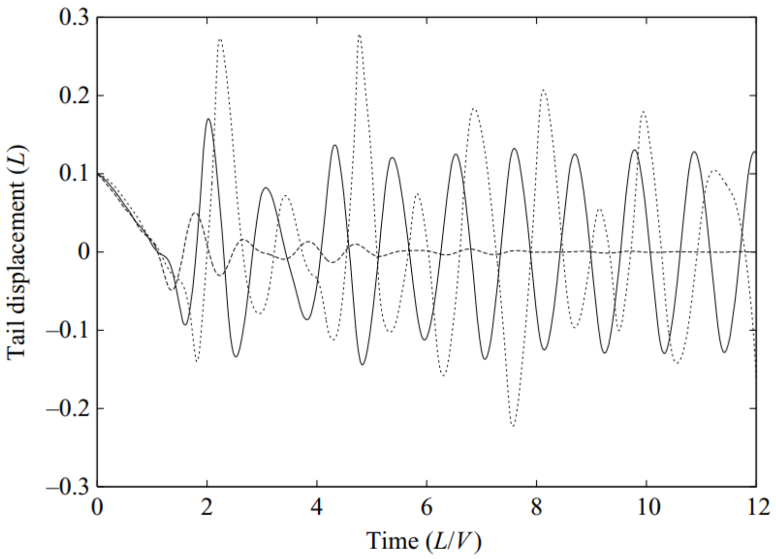

Figure 2-2: Tail displacement plotted against time for 3 regimes of flutter: (I) Fixed point stability (- -), (II) Limit-cycle flapping (--) and (III) Chaotic flapping (…), taken from [21]

Of interest to the design of flutter-based harvesters is the 2nd regime, limit-cycle flapping indicative of limit cycle oscillations (LCOs). LCOs are system responses generated from nonlinearities in a system. In the case of flutter, they result in oscillations with a finite amplitude over a range of wind speeds. As such LCOs must be accessed evaluate the potential and risks of flutter-based harvesters [12]. Consequently, it is insufficient to simply consider the system as a linear one, instead, flutter-based harvester designs must undergo nonlinear analysis to determine their reliability.

Using a numerical analysis, it is possible to determine the flutter speed as well as the frequency of oscillations in a simplified model where the natural frequency of the system is known. In this regard, the work of Theodorsen in explaining flutter through analytical potential flow methods are still widely used today. Figure 2-3 and Figure 2-4 are examples of different models used by studies on flutter based harvesters to which the analysis can be applied to solve for the required values [22, 23].

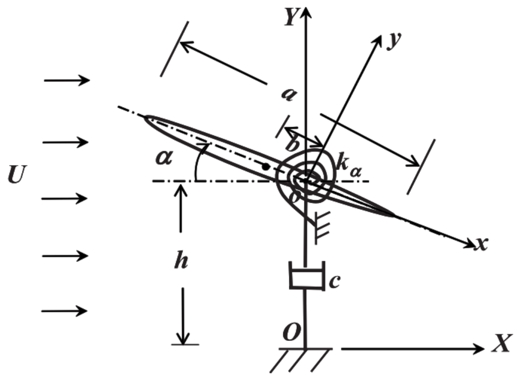

Figure 2-3: Schematic of the flapping foil energy harvester used in [22]

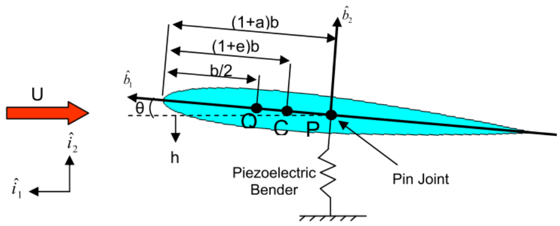

Figure 2-4: Two DOF wing section model with coordinates and physical parameters shown, taken from [23]

2.3 Piezoelectric Effect

Piezoelectric materials can be used to extract the mechanical energy from the structural vibrations due to the piezoelectric effect. The piezoelectric effect is the ability of a material to generate an electrical potential in response to an applied mechanical stress. Materials which exhibit the piezoelectric effect are also able to generate mechanical stresses under the application of an electric field [24].

The piezoelectric effect comes about from a delicate balance of charges within a piezoelectric material on an atomic scale. The atomics in a piezoelectric material are arranged in a repeated manner, such that the material is electrically neutral when undisturbed but charged when deformed. Resultingly, piezoelectric materials possess crystalline structures [25].

2.4 Piezoelectric materials used in flutter harvesters

Due to their unique properties, piezoelectric materials are well suited for electrical generating and sensing applications. Since transducers are devices which convert energy from one form to another, piezoelectric devices used to convert mechanical energy into electrical energy, or vice-versa, are known as piezoelectric transducers [25].

Piezoelectric transducers can be classified into 3 classes, natural piezoelectric substrates such as quartz crystals, piezoelectric ceramics such as lead zirconate-titanate (PZT) and polymer-film piezeoelectrics, such as polyvinylidene fluoride (PVDF). From Table 1, a comparison of commonly used piezoelectric materials, it can be seen that PZT has a high piezoelectric sensitivity reflected by its large piezoelectric constant value, while the PVDF film has the lowest piezoelectric constant.

Table 1: Comparison of piezoelectric materials adapted from [26]

Property	*PVDF Film (at 28 microns)*	*PZT*
Density/ 10^{-3} kgm^{-3}	1.78	7.5
Relative Permittivity/ $Fm^{-3}\mathcal{E}^{-1}$	1200	1700
Piezoelectric Constant/ 10^{-12} CN^{-1}	23	110
Voltage Constant/ 10^{-3} VmN^{-1}	216	10
Electromechanical constant/ % at 1KHz	12	30

2.4.1 PZTs

PZTs are made by heating mixtures of lead, zirconium and titanium oxide powders to 800-1000°C, which are then mixed with a binder and sintered into the desired shape. During the cooling process, the material develops unit cells possessing a permanent dipole. However, overall, the unpoled ceramic has no net polarisation as these domains are randomly orientated. The application of a strong electric field serves to orientate the unit cells, giving PZTs a high piezoelectric sensitivity. However, this manufacturing process also results in the piezoelectric sensitivity degrading over time and with high temperatures. PZTs also possess many of the characteristics of ceramics, having a high elastic modulus, brittleness and low tensile strength.

2.4.2 PVDFs

PVDFs may have a lower piezoelectric sensitivity, however, they possess many characteristics which offset this issue in sensor applications. Due to their low Young’s modulus, roughly 1/12 that of PZTs and aluminium, they possess low stiffness and can be directly attached to structures without too large an influence on the mechanical properties of the structure. In addition, they can be manufactured to suit different stiffness, toughness and shape requirements [11, 26].

2.5 Factors affecting the efficiency of flutter harvesters identified by previous works

The impact of wing geometry was shown by Bryant et. al, who tested a NACA 0012 airfoil against a flat plate, shown in Figure 2-5, with similar parameters in terms of weight and dimensions and found that wing geometry did not have a significant impact on generated energy [23]. It was also found by Abdelkefi et al. that symmetric airfoils are the best configuration for flutter based harvesters as camber at large values of the location had minimal effect on the flutter speed, while for small values of the camber location, an increase in camber led to a decrease in harvested power [27].

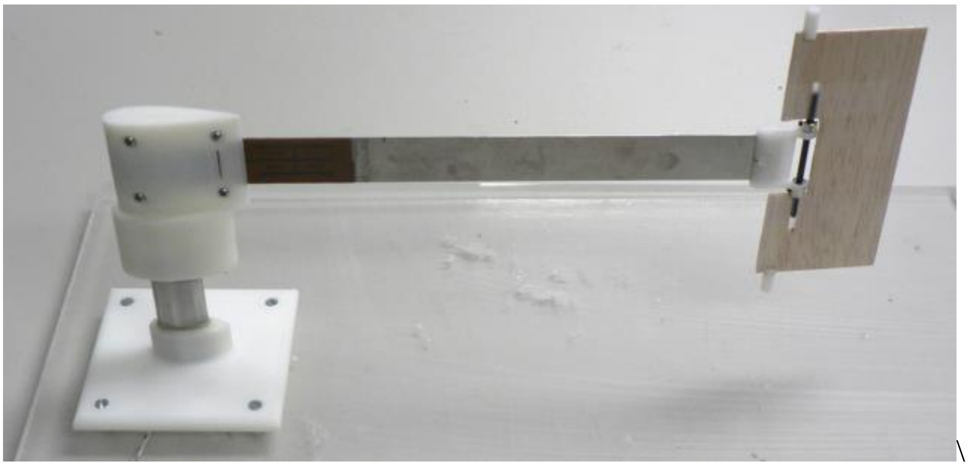

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Figure 2-5: Photograph of the aeroelastic power harvester design used by [23]

The significance of various model parameters was also investigated by Bryant et al., who found that the linear flutter speed is more significantly influenced by the flap mass properties, as compared to the non-rotating beam tip mass, flap hinge natural frequency, chordwise flap centre of mass (CoM) location and chordwise flap hinge location. The flap mass properties included the flap centre of mass location, the flap mass moment of inertia, and the flap mass, labelled in Figure 2-6 which were suggested to be tuned to achieve the desired flutter speed [2]. Abdelkefi et al. reported that by selecting for small eccentricity between the gravity axis and elastic axis, thereby reducing the distribution of energy between the pitch and plunge motions, the harvested power could be significantly increased [28]. It is known and has been proven experimentally that the stiffness of a structure results in decreased flutter when placed in a flow [29].

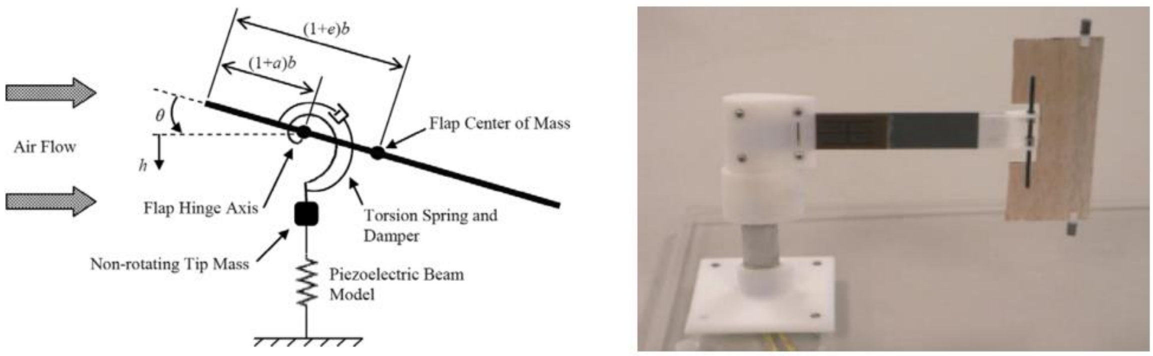

Figure 2-6: Model and experimental setup used in [2]

It was also found that the electrical properties of the harvesting circuit can affect the efficiency of the harvester. Elvin et al. performed an electromechanical analysis on a cantilevered pipe and showed that the electric properties of the harvester have a coupled effect with the mechanical stiffness of the setup, affecting the flutter speed. In particular the resistance of the load of the load could be varied to allow the system to possess varied stiffness values to match the requirements at different times, such as allowing for energy generation at lower flutter speeds and then increasing stiffness when sufficient energy has been generated to restore the stability of the system [30].

Additionally, there exist external factors which can increase the effectiveness of the system. Bibo et al. suggested combining base vibrations with the aerodynamic flutter based harvesters and found that there was a significant improvement in the level of harvested power in their model as compared to the two separate models [31]. Zhu and his co-workers found by theoretical and experimental study that the performance of the harvester could be enhanced by the presence of solid ground [22].

2.6 Research Gap

Many works have focused on the linear characteristics of flutter harvesters, focusing on design perspectives to reduce the linear flutter speed. Yet there are many conclusions that can be drawn by examining its non-linear responses such as limit cycle oscillations [12]. In addition, the focus on theoretical models outweighs the data recorded from experimental procedures. A number of works have expressed the possibility of future work in further experimental investigations [2, 30]. Hence this work will focus on the experimental parametrisation of nonlinear properties of the fluttering plate system.

Chapter 3 Methodology

3.1 Experimental setup

Experiments were conducted in the open loop wind tunnel, Figure: 3-1, with a test section of dimensions width, 1.1m, height, 0.9m length, 2.0m and test speeds 3 – 30 ms^{-1}.

Figure: 3-1 Open Loop Wind Tunnel

Samples were prepared by securing a balsa wood sheet to a piezoelectric stalk, Figure 3-2, by means of screws. The samples were then mounted in the test section with a retort stand, ensuring the balsa wood plate was within the test section. The retort stand was additionally weighted with a 10kg weight to secure it, as seen in Figure 3-3.

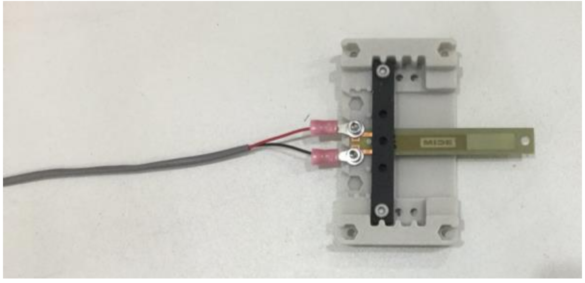

Figure 3-2: Piezoelectric mounting

Figure 3-3: Setup placed within the wind tunnel

The first series of tests conducted in the wind tunnel involved the qualitative determination of flutter in balsa sheets of different size, thickness, shape and grain. The first set of samples were triangular in shape inspired by the piezoelectric tree design in Figure 3-4 by Dickson, with varying chords and spans, while maintaining the surface area, illustrated in Figure 3-5 as conducted by Arvind [32]. The cutting of the balsa wood relative to the grain was also varied to examine how the stiffness varied. However, no vibrations were observed in any of the triangularly shaped samples. Instead, a large deflection was seen at high wind speeds. Thus, a rectangular shaped flat plate was attempted, as seen in Figure 3-6, which possessed a larger surface area at lengths further from the piezoelectric stem. As this sample showed small vibrations approaching $10ms^{-1}$, subsequent tests were done maintaining the rectangular shape while varying size and mounting positions.

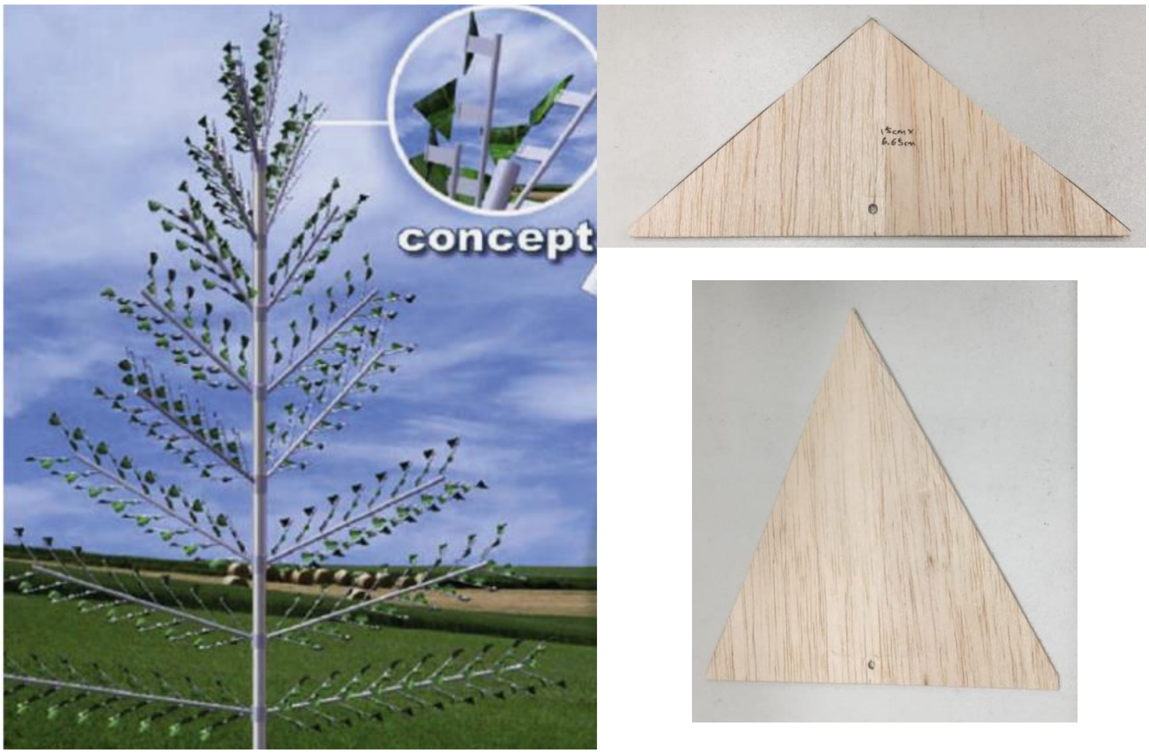

Figure 3-4 Triangular plates (right) inspired by the piezoelectric tree concept by [1]

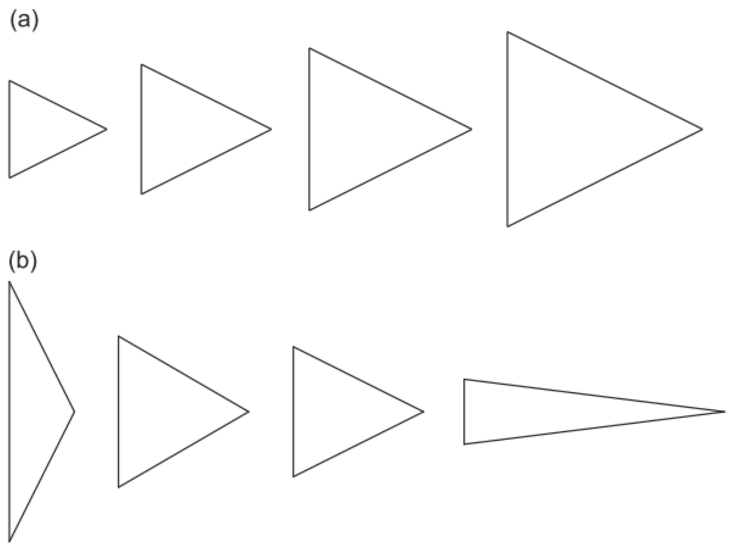

Figure 3-5: Triangular shapes of (a) varying area and (b) aspect ratio

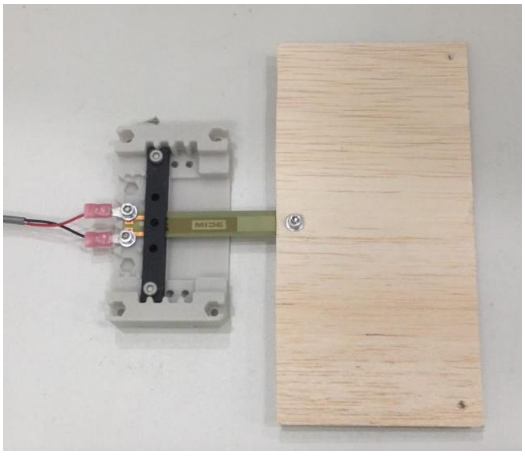

Figure 3-6: Rectangular flat plate

The second round of tests were conducted qualitatively to determine how the efficiency of the harvester varied with wind speed for each combination of sample parameters. The sample was prepared according to the parameters to be tested and placed in the test section. After which, the wind speed was brought up to 3ms^{-1} and the variation of voltage with time was recorded from the oscilloscope. The wind speed was increased by 0.5ms^{-1} intervals and the voltage recorded until the flutter speed was reached. Above the flutter speed, the wind speed was increased by $0.25ms^{-1}$ and data was only recorded when the system reached equilibrium, so the voltage produced and frequency domain of the LCO could be recorded. Under the same conditions, a fast Fourier transform (FFT) was also performed on the signal. This was repeated until one of 3 end conditions, divergent amplitudes were observed, excessive vibration by the support structure or structural failure of the sample.

3.2 Choice of materials for setup

Balsa wood was chosen as the material for the flat plates due to its prevalence of use in previous works [2, 23] to reduce the weight and stiffness of the setup. Additionally, balsa wood was an easy material to work with, allowing new samples to be prepared on the spot to allow different parameters to be quickly tested.

The piezoelectric used was a PPA-1021 as shown in Figure 3-7, with a voltage range of 200V, maximum peak to peak deflection of 12.0mm and effective stiffness of 211.60N/m when secured at clamp -6. Due to its high length to width ratio, its effective stiffness was lower than comparable piezoelectrics, hence it was chosen to reduce the stiffness of the setup. Another important consideration was how the piezo output varied with frequency. For the selected piezoelectric, the output voltage was fairly constant for frequencies below 120Hz and small amplitude deviations, as seen in Figure 3-8.

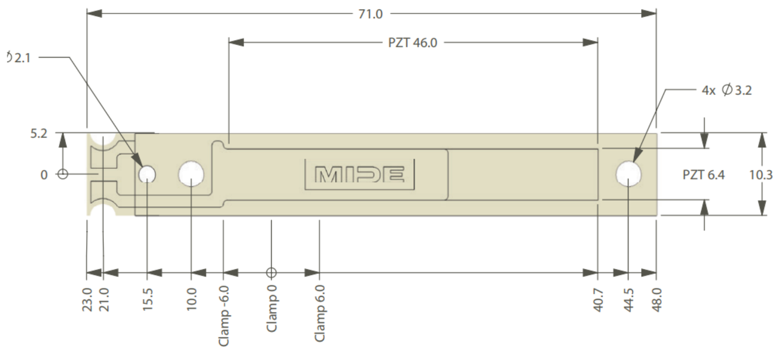

Figure 3-7: Piezoelectric dimensions

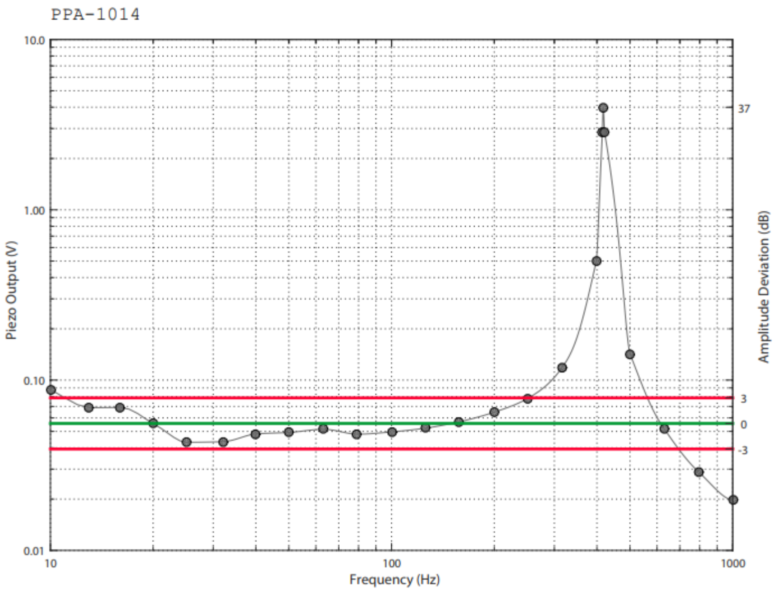

Figure 3-8: Piezo Output against Frequency

3.3 Optimisation of design

The first round of tests allowed for the identification of an appropriate shape and mounting position relative to the flow to achieve flutter at realistic wind speeds of <10ms^{-1}. It also provided the basis for how the samples were to be prepared from the balsa wood planks. However, the following round of tests were dependent on the continuous update of system parameters to increase the efficiency of the harvester. Henceforth this section will describe the parameters varied with each trail and how they were changed.

To begin with, it was sought to identify an ideal length, thickness and orientation to achieve stable LCOs at the desired wind speeds of ~4ms^{-1}. To do so, sheets of 1/16 inch thick balsa wood were cut to lengths of 20cm, 30cm and 40cm. Each sheet was secured to the setup and the voltage produced at varying wind speeds recorded. The tests were performed in a horizontal and vertical orientation of the harvester as seen in Figure 3-9. Finally, the tests were repeated for 1/32-inch-thick balsa sheets.

Figure 3-9: Balsa sheets in a horizontal orientation (left) and vertical orientation (right)

After determining a suitable length and thickness for the sample, it was desired to investigate how the characteristics of the flat plate, such as the weight distribution, would affect harvester efficiency. To do so, markings were made every 5cm from the tip of the sample to allow for measured weights to be distributed evenly as required. The locations of the markings, together with a set of weights placed 30cm from the tip placed chordwise can be seen in Figure 3-10. Following which, the distribution of weights spanwise, also shown in Figure 3-10 was also be varied. The orientation chosen was vertical to improve stability and prevent the weights from causing excessive sagging.

Figure 3-10: Locations for weight adjustment on sample with weights placed chordwise (left) and spanwise (right)

Furthermore, to reduce accumulated fatigue on the sample across multiple tests, reinforcements were added to the base as seen in Figure 3-11. The reinforcements served to distribute the load at the point of connection across the width of the balsa sheet, as well as to reduce damage caused by the screws. A control was also conducted with the reinforcements removed to compare the effects of the reinforcements on the effectiveness of the harvester.

Figure 3-11: Reinforcement at point of attachment

3.4 Independent Parameters

This project aims to determine how the characteristics of the harvester will affect the performance of a flutter-based harvester. As such, the characteristics were broken down into the various dimensions and adjustable parameters of the flat plate. These parameters were tested individually at a range of wind speeds. A table summarising the parameters has been included as Table 2.

Table 2: List of parameters studied

Independent parameters
Wind speed
Plate thickness
Plate length
Sample orientation
Weight distribution (Chordwise)
Weight distribution (Spanwise)

First to be investigated were the dimensions of the flat plate, affected by the choice of wood the plate was cut from and how it was cut. Next was how the orientation of the plate would affect the behaviour of the harvester such that a choice could be made. Finally, the weight distribution on the plate was adjusted using measured 1x1cm squares of blu tack cut from a fresh sheet.

3.5 Dependent Parameters

Based on the independent parameters, different modes of vibrations were observed at varying wind speeds in the wind tunnel. The vibrations were parameterised by the frequency of vibration as well as the amplitude of the vibration, measured as the voltage produced by the piezoelectric stalk.

Chapter 4 Results

4.1 Overview of Results

4.1.1 Voltage produced

The voltage-time graph produced by each sample at different wind speeds was recorded, from the root-mean squared value of the voltage (V_{rms}) was calculated and subsequently plotted in the graphs below.

Figure 4-1 presents the V_{rms} against wind speed of lengths of balsa wood of 1/16 inch thickness placed in a horizontal and vertical orientation. Firstly, it can be observed that the longer plates were able to manifest flutter at lower wind speeds, with about a $2ms^{-1}$ difference from the 30cm plates to the 20cm plates and $3ms^{-1}$ from the 30cm plates to the 40cm plates. Secondly, the vertical orientation was also noted to achieve flutter at a lower speed by about $1.5ms^{-1}$ for the 20cm and 30 cm sheets. For the 40cm sheet, flutter set in in the horizontal orientation before the vertical orientation. However, this resulted in the balsa sheet undergoing structural failure at $3.5ms^{-1}$.

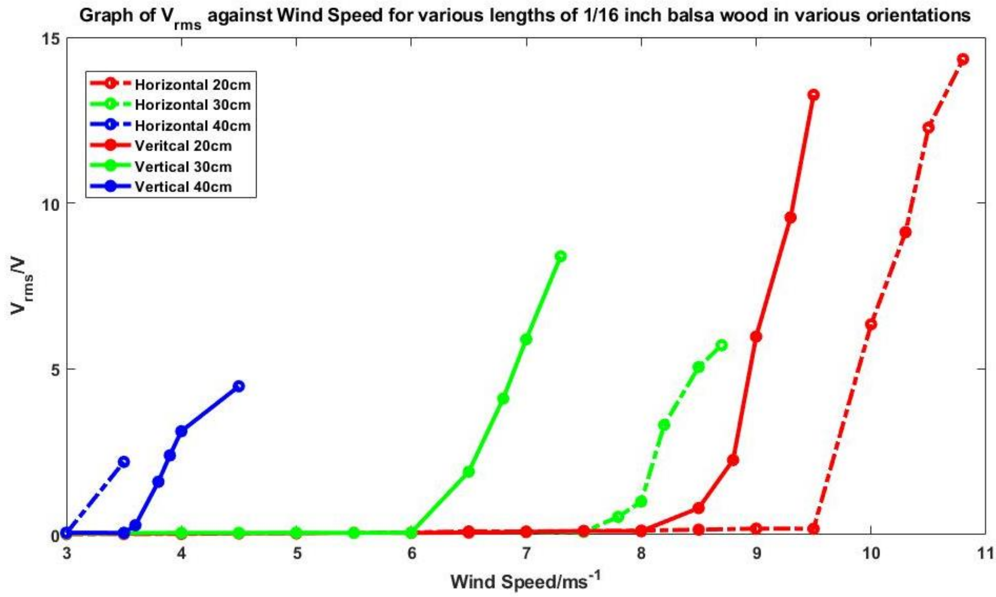

Figure 4-1: V_{rms} against wind speed for various lengths of 1/16 inch balsa wood in various orientations

Similarly, Figure 4-2 presents the V_{rms} against wind speed of various lengths of 1/32 inch balsa plates in various orientations. Overall the thinner plates displayed flutter at lower wind speeds with the minimum flutter speed for the 30cm plate dropping 2ms^{-1} and that for the 20cm^{-1} dropping 3ms^{-1}. Again, the vertical orientations were able to achieve flutter at lower wind speeds for the 20cm and 30cm plates, with a reduction of 0. 5ms^{-1} and 1.5ms^{-1} for the 20 and 30cm plates respectively. While the 40 cm sheet in the vertical orientation had flutter set in later, it was also more stable than the sheet in the horizontal orientation which was unable to support itself in the flow at 3ms^{-1}.

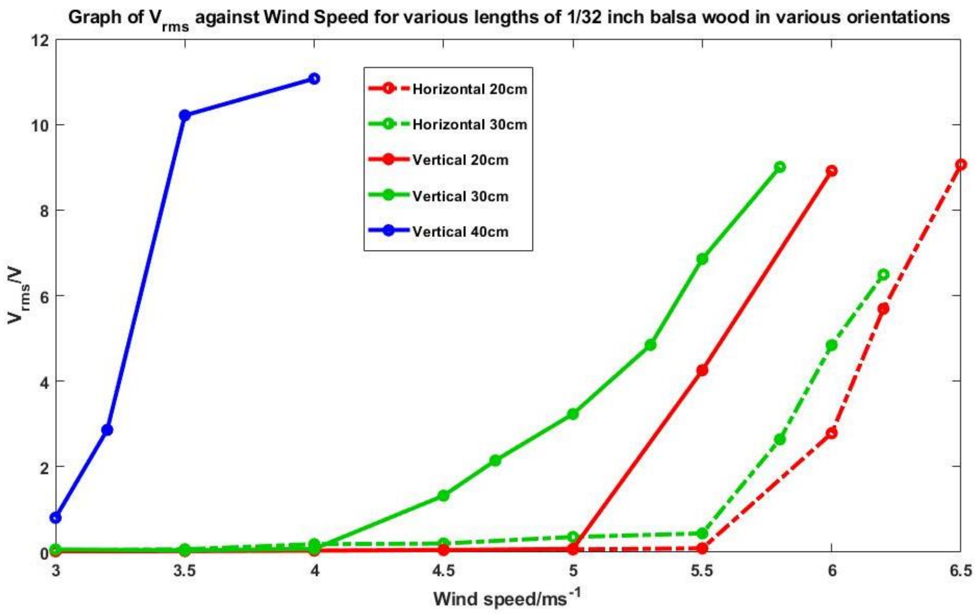

Figure 4-2: V_{rms} against wind speed for various lengths of 1/32 inch balsa wood in various orientations

Figure 4-3 shows the variation of V_{rms} with wind speed for sheets with weights placed along the chord at different lengths from the edge. Overall there was no significant improvement for any of the locations, with each plate having a flutter speed of 4-4.25ms^{-1}. The exception was the plate weighted at 30cm from the free end, which experienced a slightly delayed onset of flutter at 4.5ms^{-1} and a more gradual increase in power harvested with wind speed.

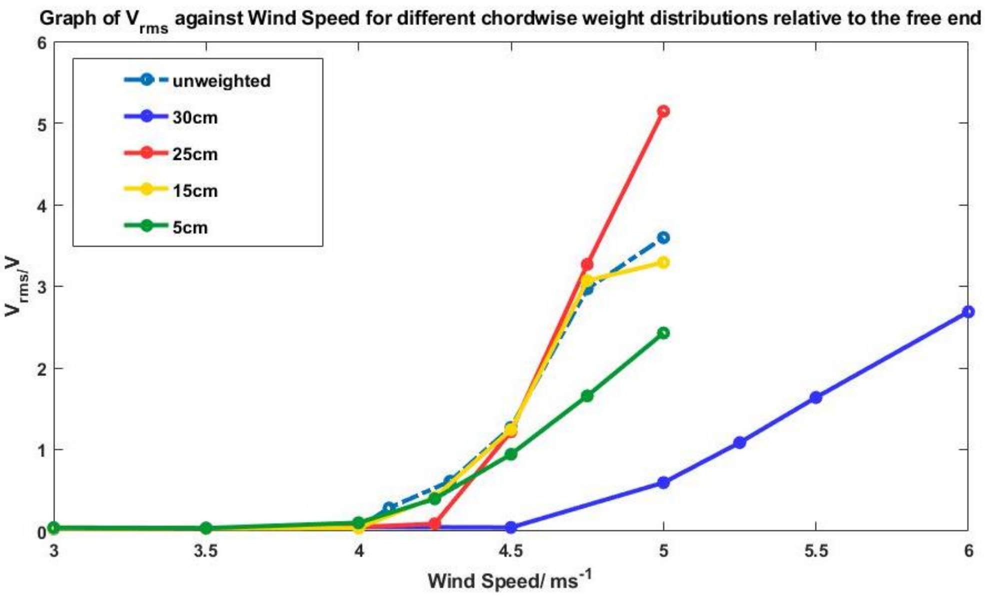

Figure 4-3: V_{rms} against wind speed for different chordwise weight distributions

Figure 4-4 shows how the V_{rms} curves varies with the distribution of weights along the span of the balsa plates. While there is little divergence for the weights placed along the leading edge, the sheet with weights placed along the trailing edge experienced the onset of flutter at $3ms^{-1}$ compared to $4ms^{-1}$ and reached a maximum of 6V at $5ms^{-1}$, about twice that of the other samples.

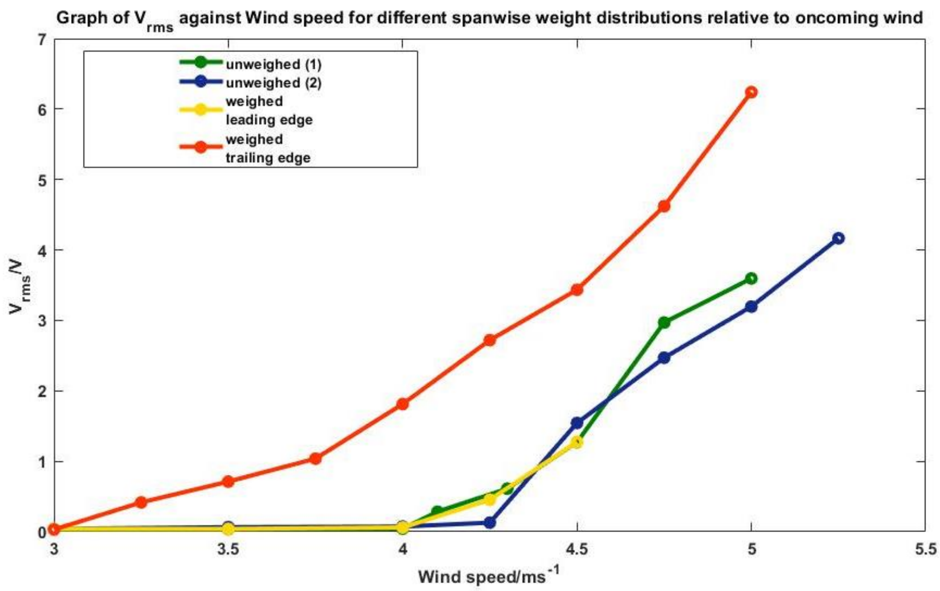

Figure 4-4: V_{rms} against wind speed for different spanwise weight distributions

Figure 4-5 presents the V_{rms} against wind speed of various configurations where the weights were placed close to or along the centre of mass of the plate, along its chord and span. Again, the weights placed along the chord had little effect on the onset of flutter. Placing the weights along the span in the middle of the balsa sheet however, did slightly improve the efficiency of the harvester at wind speeds $1ms^{-1}$ lower. Finally, removing the reinforcements allowed the balsa sheet to demonstrate flutter at much lower wind speeds at the cost of early structural failure, which set in at about $3.5ms^{-1}$.

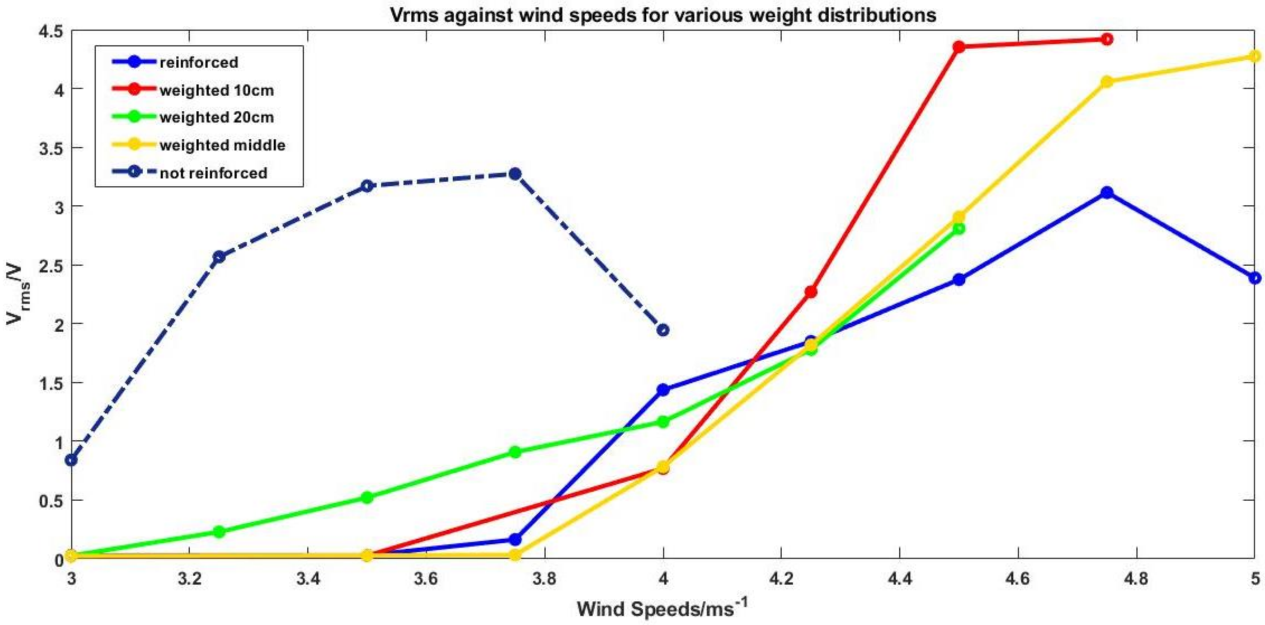

Figure 4-5: Vrms against wind speed for different weight distributions around the CoM

4.1.2 Frequency of oscillations

The various frequencies of the oscillations were recorded as the FFT of the voltage-time graph of the oscillations. As the FFT showed multiple peaks at multiple frequencies which were approximately integer multiples of each other, the dominant frequency at each wind speed was identified and plotted in the graphs below. For most of the cases, the dominant frequency was the base frequency of about 5-15Hz.

For the non-reinforced 35cm and 33cm plates, the dominant frequency followed a downwards trend of about 4Hz per 1ms^{-1} in Figure 4-6, Figure 4-7 and Figure 4-8. For the reinforced 33cm plate, the dominant frequency was much higher at about 11Hz compared to 5Hz in the non-reinforced case at 4ms^{-1}. In addition, it increased by 1Hz with a 1ms^{-1} increase.

The plates with weights added chordwise, generally followed a downwards trend with the expectation of the 30cm case in Figure 4-15 instead displaying an upwards trend. The rate of change was noted to be larger for the 5cm, 10cm and 20cm cases, with Figure 4-10, Figure 4-11 and Figure 4-13 having a downwards gradient of about 3Hz/ms^{-1}. In the 25cm case it was lower, with Figure 4-14 having a gradient of 2Hz/ms^{-1}. Following which the 30cm case in Figure 4-15 had a gradual upwards gradient of 2Hz/ms^{-1}. Finally, the frequency was relatively constant for the 15cm case in Figure 4-12 where it had an overall decrease of 1Hz over 1ms^{-1}.

Finally, for the plates with weights added spanwise, the weights on the trailing edge had a gradual upwards gradient of 2Hz/ms^{-1} in Figure 4-16 while the weights added to the middle resulted in a downwards gradient of 3Hz/ms^{-1} in Figure 4-17.

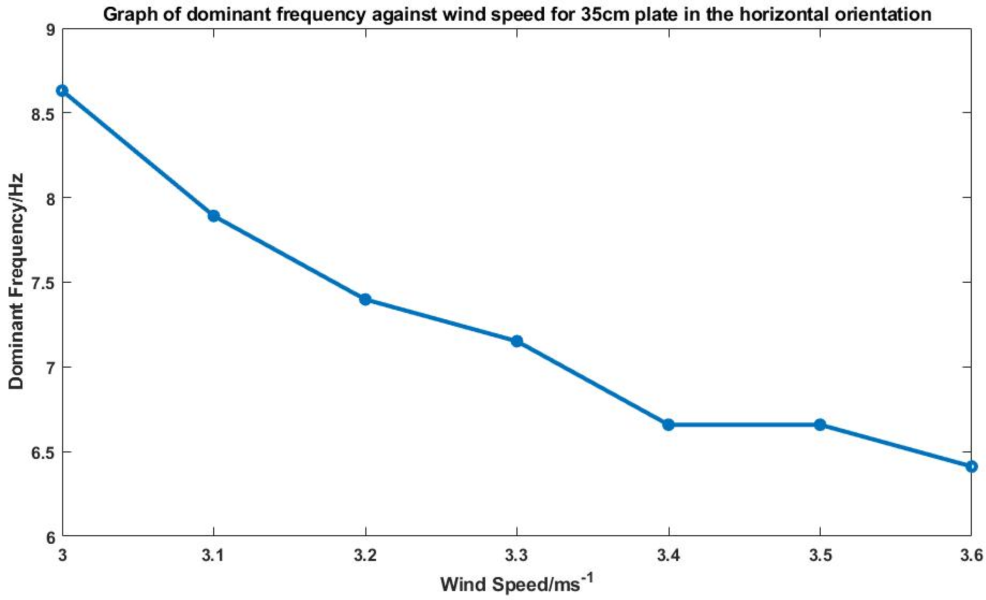

Figure 4-6: Dominant Frequency against wind speed for 35cm plate in the horizontal orientation

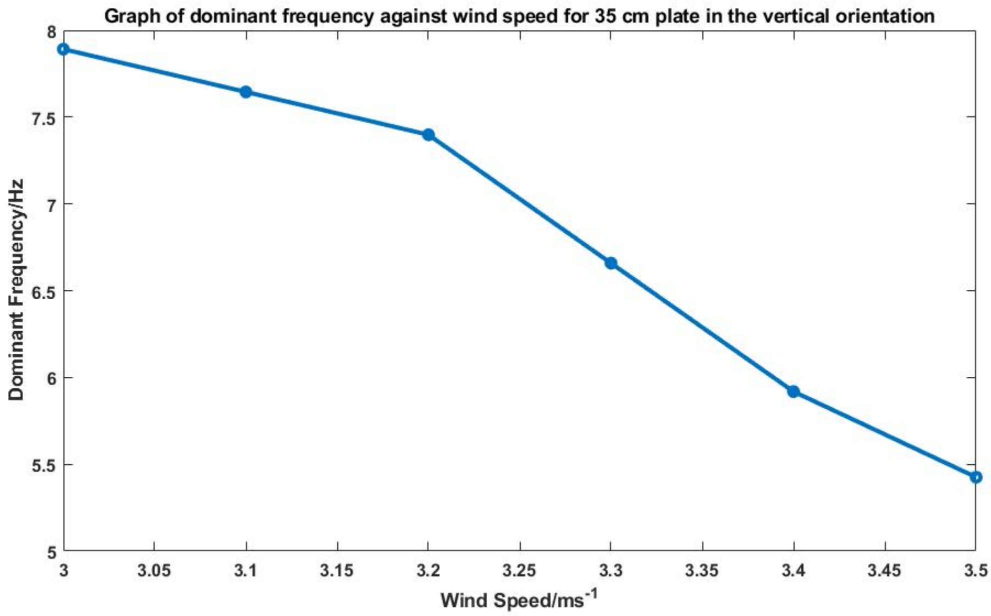

Figure 4-7: Dominant Frequency against wind speed for 35cm plate in the vertical orientation

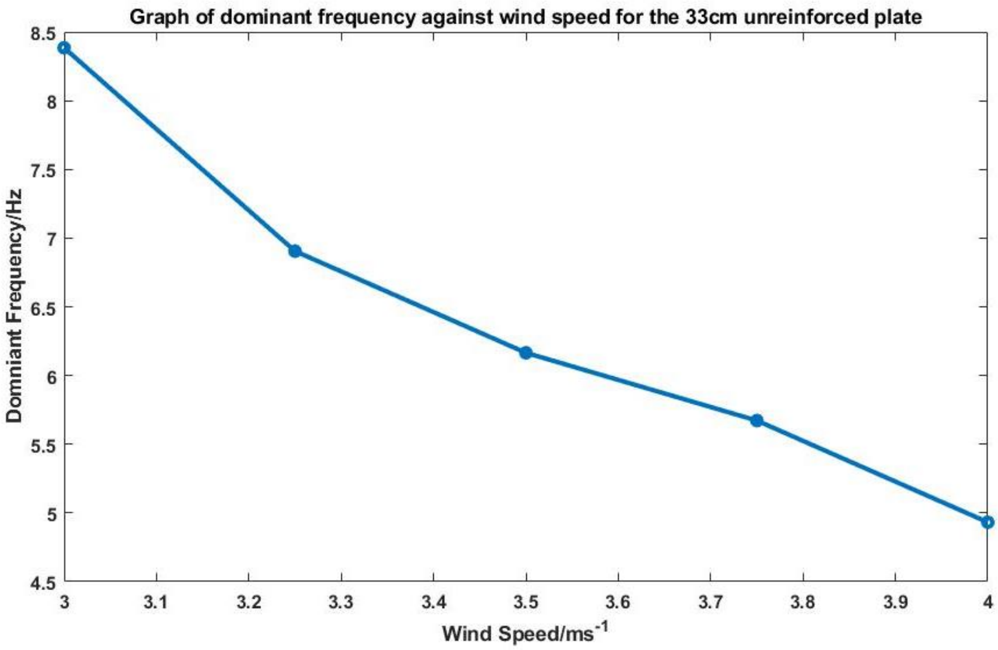

Figure 4-8: Dominant Frequency against wind speed for 33cm unreinforced plate

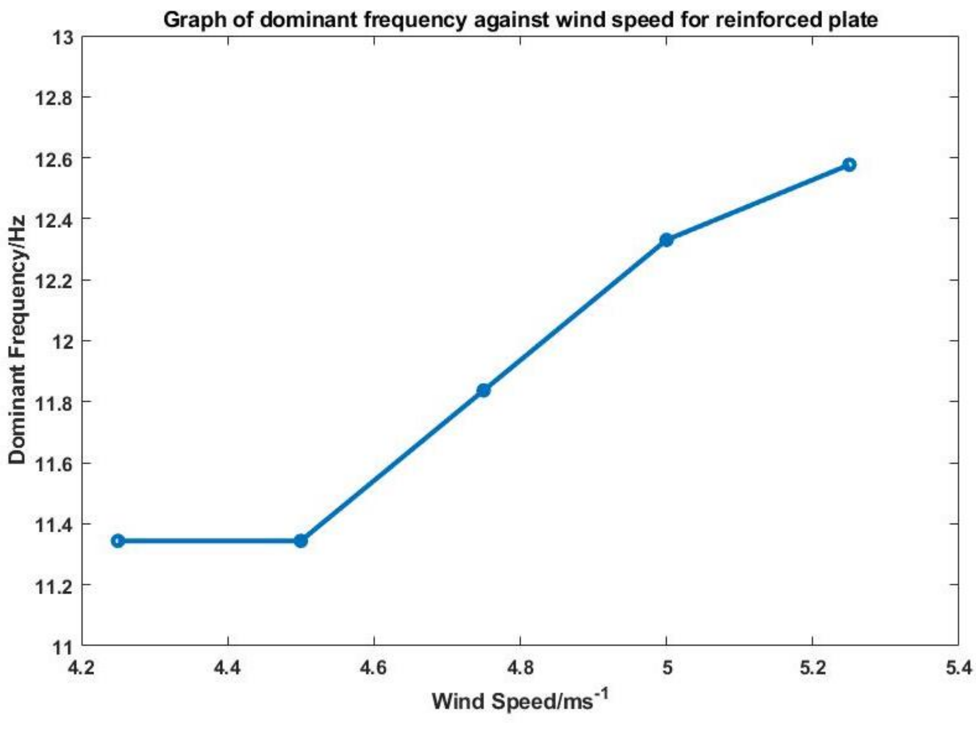

Figure 4-9: Dominant Frequency against wind speed for 33cm reinforced plate

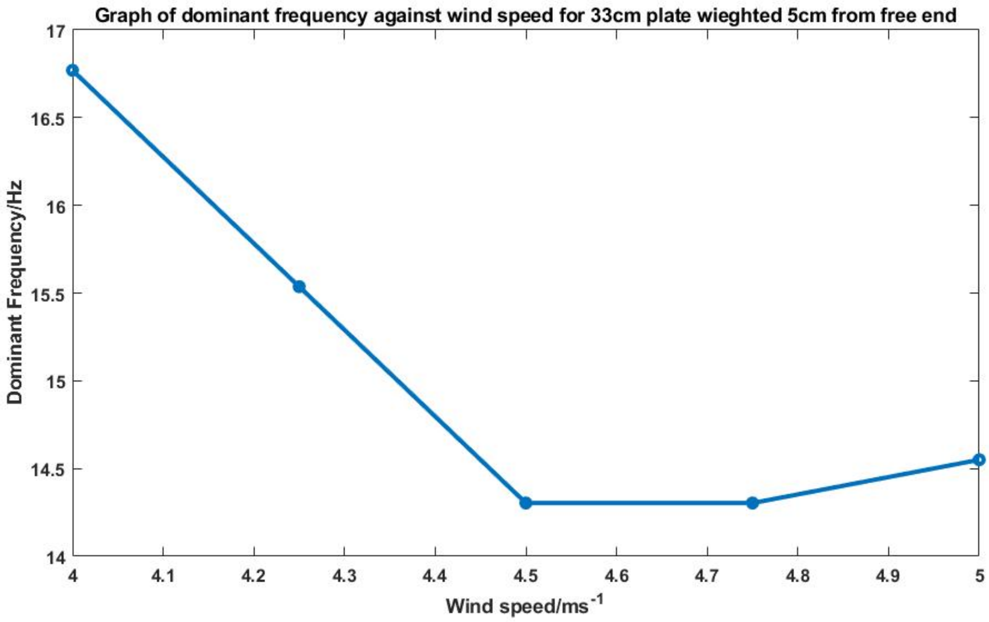

Figure 4-10: Dominant frequency against wind speed for chordwise weights placed 5 cm from the free end

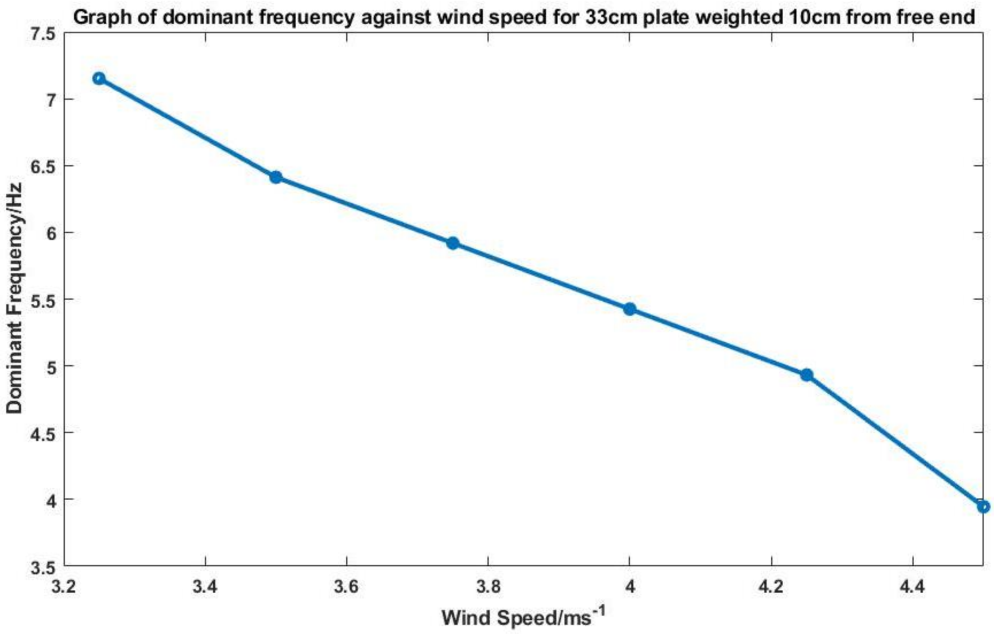

Figure 4-11: Dominant frequency against wind speed for chordwise weights placed 10 cm from the free end

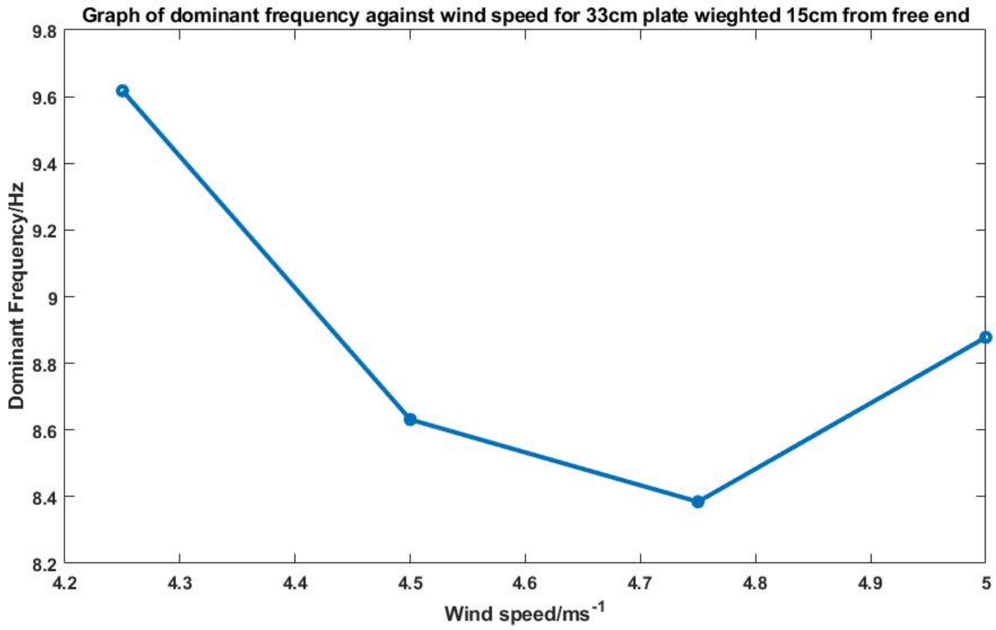

Figure 4-12: Dominant frequency against wind speed for chordwise weights placed 15 cm from the free end

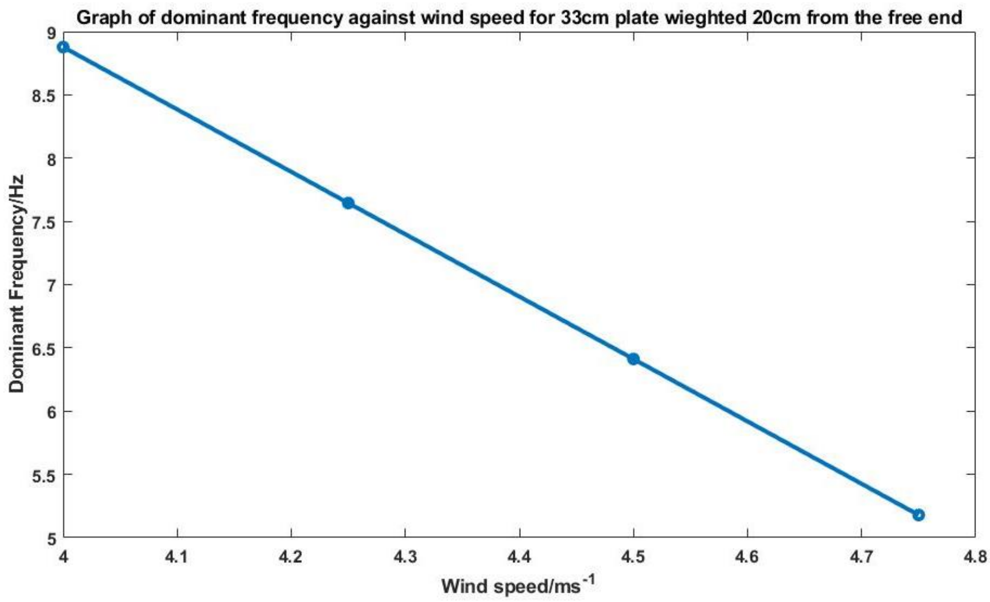

Figure 4-13: Dominant frequency against wind speed for chordwise weights placed 20 cm from the free end

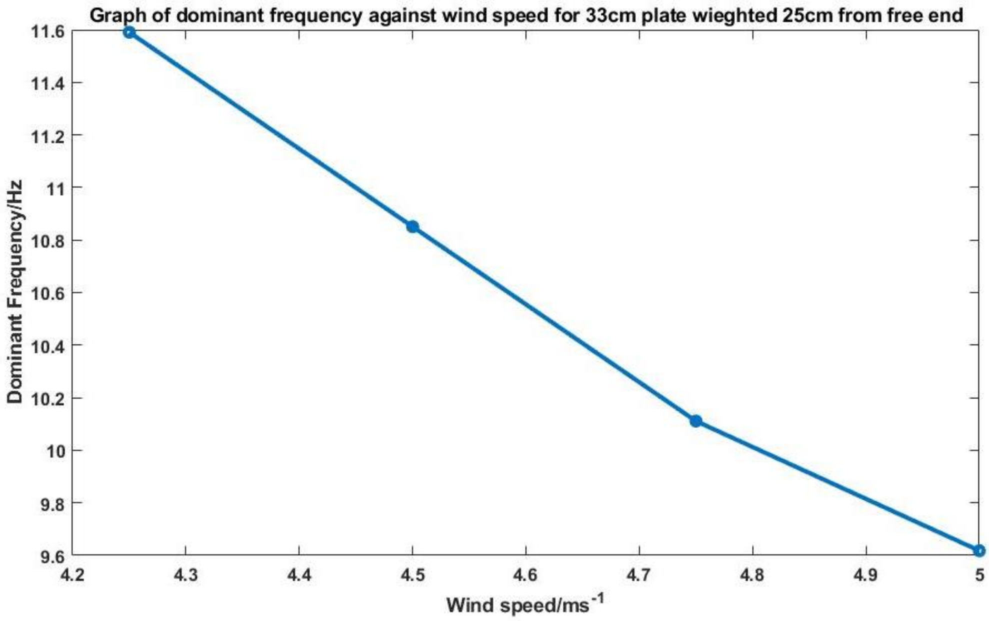

Figure 4-14: Dominant frequency against wind speed for chordwise weights placed 25 cm from the free end

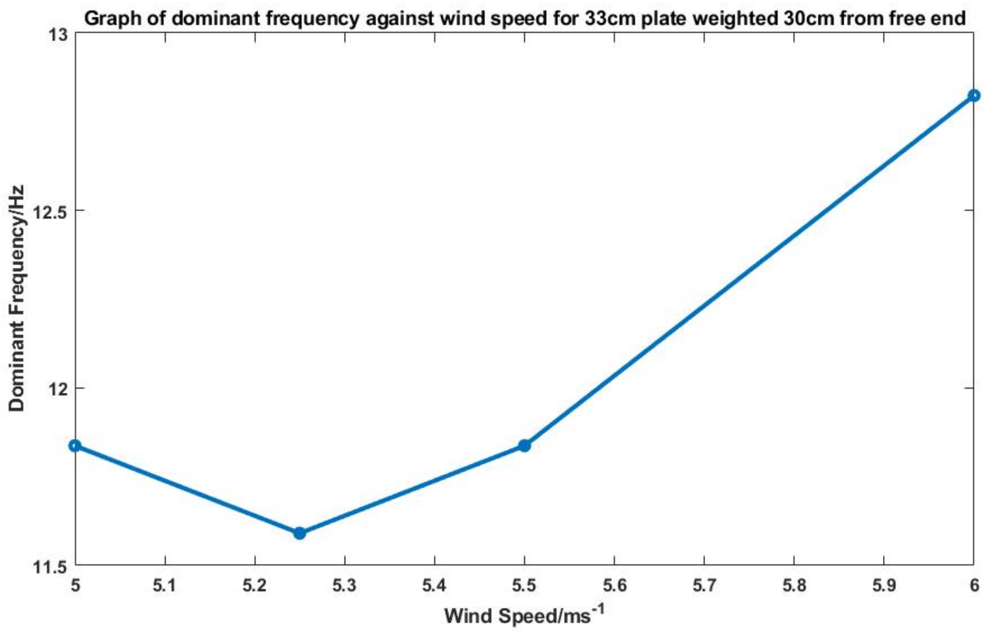

Figure 4-15: Dominant frequency against wind speed for chordwise weights placed 30 cm from the free end

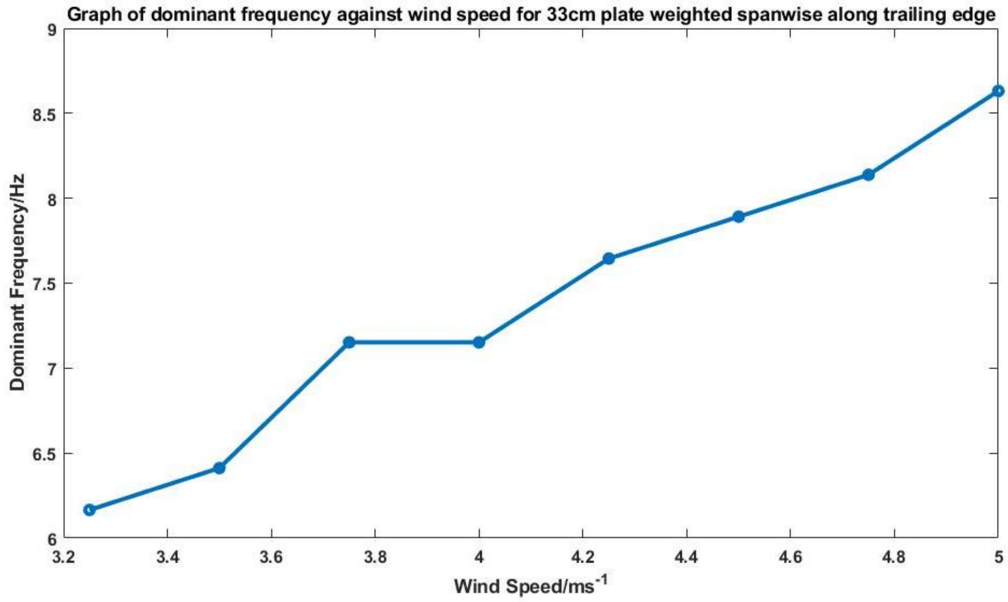

Figure 4-16: Dominant frequency against wind speed for spanwise weights placed along the trailing end

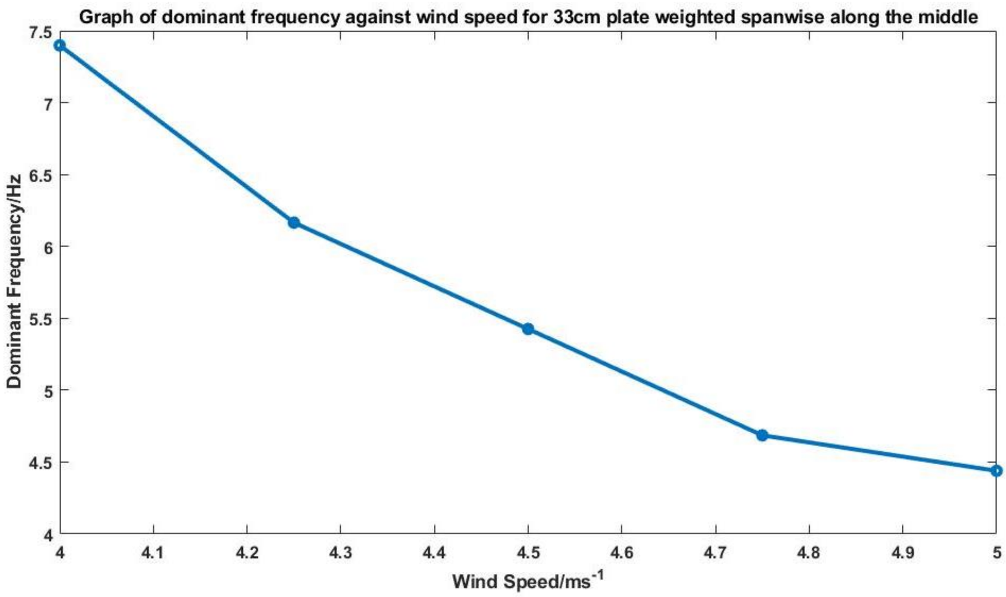

Figure 4-17: Dominant frequency against wind speed for spanwise weights placed along the middle

4.2 Discussion

Before analysing the results, the limitations of the experimental setup should be addressed. Firstly, while the samples were prepared in the same manner to maintain a level of consistency, there still exist differences inherent in the balsa wood planks. To mitigate errors arising from such differences, a control was run for each sample so that subsequent tests could be compared against it. Secondly, the weighted retort stand introduced extra degrees of freedom to the oscillating system due to vibrations in the stand. Therefore, there was a need to omit data points where these vibrations were large, which generally occurred at higher wind speeds or when the oscillations of the sample itself were large. The impact was likely to be more significant for the FFTs which resulted in large variances in the data.

Regardless, the results clearly show a reduced flutter speed as the thickness, and hence stiffness of the balsa sheet was reduced. Similarly, there was a clear trend between the length of the balsa sheet and the flutter speed, with longer sheets displaying flutter at lower wind speeds. This was likely due to the reduced stiffness of the harvester, resulting in a larger structural response to the flow. The length of the balsa wood also likely increased the magnitude of the aerodynamic forces on the harvester, leading to greater deformations.

However, the longer sheets were also quicker to break, again, likely due to the increased weight and aerodynamic forces experienced. Hence there exists a balance between a low flutter speed and sufficient structural strength to ensure the reliability of the harvester. On a similar note, the vertical orientation was also observed to result in more controlled oscillations, likely due to the weight acting through the elastic axis which resulted in reduced eccentricity of the oscillations, as compared to the horizontal orientation where the weighted acted against the aerodynamic lift and at some distance from the elastic axis, affecting the torsional responses of the harvester.

Changing the weight distribution of the harvester did not result in a decrease in flutter speed or increase in voltage at each wind speed. Instead, weights being placed away from the centre of mass resulted in dampened oscillations, which was most distinct when the weights were placed 30cm from the free end. An exception was with weights placed spanwise at the trailing edge, which increased the efficiency of the harvester in terms of decreased flutter speed and increased voltages at higher wind speeds. For this case, the trailing edge was seen to be more stable while the leading edge had a greater amplitude of oscillation. This behaviour could have led to increased overall stability while the leading-edge vibrations extracted energy from the flow.

Comparing the controlled, non-reinforced sample to the unweighted sample, it was observed that there was a large increase in flutter speed. This was likely due to increased stiffness of the plate due resulting from the reinforcement. However, just as importantly, it distributed the strain from the point of attachment, which greatly reduced structural damage. This allowed the harvester to operate at higher wind speeds with greater reliability.

Considering that weights along the span in the middle of the sheet did not have a significant impact on the effectiveness of the harvester, it is possible that reinforcing the spine would have a reduced impact as compared to reinforcing the entire structure, especially considering the increased stiffness that would result from it.

Purely observing the trends shown by how the dominant frequency changed with wind speed, a plausible explanation can be drawn. It is known that flutter results from the coupling of various vibrational modes of the structure which respond differently to the dampening caused by the flow. Thus, it is possible that the changing weight distribution had an impact on the torsional and pitching moments, resulting in a different contribution from each. From the literature review, it is likely that by balancing the pitch and plunge axis it is possible to increase the efficiency of the harvester. This would correspond to weights placed close to the centre of mass, as in the case where they were placed 15cm from the free end. However, more precise equipment would be required to draw any further conclusions.

From the above discussion, the stiffness of the harvester as a whole should be reduced to increase the efficiency of the harvester at low urban wind speeds. To compensate for the low structural strength, reinforcements could be added from the root spanwise, as this would have a reduced impact on lowering the harvester's efficiency. Chordwise supports could also be added to provide greater structural integrity as well as balance the axis of pitch and plunge to maximise efficiency. From the above, this paper suggests a rectangular leaf design, with a thicker main stalk as well as thinner support veins extending chordwise.

Chapter 5 Conclusions and Recommendations

5.1 Conclusions

Harvesting energy from flutter is a delicate balance between ensuring structural strength while reducing the weight and stiffness of the structure. This is especially so due to the destructive nature of aeroelastic flutter, which causes fatigue damage due to the constant deformation of the material. From the results outlined above, structural support can be provided along the span of the harvester either along the leading edge or in the middle of sheet. Stresses on the structure can also be avoided by placing the harvester in a vertical orientation, thus eliminating the stresses brought about by the weight of the structure.

All in all, flutter-based harvesters are a small and adaptable alternative to traditional wind turbines. Their size makes them more suitable to be deployed in urban centres due to their increased safety and lower impacts to the surroundings. In addition, their ability to harvest energy even at low wind speeds makes them highly adaptable to different scenarios.

5.2 Recommendations for Future Work

Three main directions were identified for future work, namely, improving on the design suggested in this report, investigating the electromechanical properties of the system and evaluating the considerations for the deployment of the harvesters.

Firstly, different materials could be considered for the construction of the harvester. While balsa wood proved to be a lightweight and easy material to work with, allowing flutter to be observed at low wind speeds, as well as for samples to be produced with relative ease, there were also concerns regarding the strength of the material. Future works may include cured wood, or other materials which may trade the quick production time in exchange for sturdier samples. Given that it is likely the stiffness of the harvester may increase with the increased strength, numerical investigations could be performed to determine how to scale the current design with different materials. With the design less likely to undergo major changes, a more permanent fixture for the mounting of the samples would allow for more accurate measurements to be taken. Additional data could also be obtained, such as the lift characteristics of the harvester, to better parametrize the efficiency of the harvester. This would allow for the design of the harvester to be better calibrated based on factors such as the material chosen for the harvester.

Secondly, the electromechanical aspects of the system were kept constant in this study to better understand how the design considerations of the flat plate would affect the efficiency of the harvester. Given that the electrical characteristics of the system, such as the electrical load connected to the harvester and piezoelectric chosen can have significant impacts on the mechanical responses and thus the harvester efficiency [30].

Finally, to isolate the various parameters chosen in this report, the experiments comprised of a single flat plate harvester placed in a uniform flow. However, flutter based harvesters stand to benefit from being in the wake of another harvester, resulting in potential harvester designs being an array of flat plates [11]. As such it is worth optimising for a configuration to maximise the generated power of a harvester system based on the proposed design. For harvesters meant to be installed in urban centres, vertical surfaces or roofs are likely sites for deployment. In such deployments there may be limitations to how the harvesters may be positioned, such that ground effect, boundary layer flow or different orientations for the harvesters will have to be considered. Also, the window of wind speeds optimised for was roughly $4ms^{-1}$, typical for urban centres. Should the harvesters prove to be able to be deployed in different conditions such as rural areas, on board large ships or other varied locations, then adaptations to the design would have to be considered.

List of References

1. Dickson, R., *New Concepts in Renewable Energy.* 2008.
2. Matthew, B., Eric, W., and Ephrahim, G., *Aeroelastic flutter energy harvester design: the sensitivity of the driving instability to system parameters.* Smart Materials and Structures, 2011. **20**(12): p. 125017.
3. Panwar, N.L., Kaushik, S.C., and Kothari, S., *Role of renewable energy sources in environmental protection: A review.* Renewable and Sustainable Energy Reviews, 2011. **15**(3): p. 1513-1524.
4. Shafiee, S. and Topal, E., *When will fossil fuel reserves be diminished?* Energy Policy, 2009. **37**(1): p. 181-189.
5. Nygren, E., Aleklett, K., and Höök, M., *Aviation fuel and future oil production scenarios.* Energy Policy, 2009. **37**(10): p. 4003-4010.
6. Jones, D.W., *How urbanization affects energy-use in developing countries.* Energy Policy, 1991. **19**(7): p. 621-630.
7. Tripanagnostopoulos, Y., Christodoulou, A., Tselepis, S., Souliotis, M., and K. Tonui, J., *Practical aspects for small wind turbine applications*. 2014.
8. Ishugah, T.F., Li, Y., Wang, R.Z., and Kiplagat, J.K., *Advances in wind energy resource exploitation in urban environment: A review.* Renewable and Sustainable Energy Reviews, 2014. **37**: p. 613-626.
9. Zeng, H., *Integration of renewable energy with urban design : based on the examples of the solar photovoltaics and micro wind turbines.* 2011.
10. Allen, S.R., Hammond, G.P., and McManus, M.C., *Prospects for and barriers to domestic micro-generation: A United Kingdom perspective.* Applied Energy, 2008. **85**(6): p. 528-544.
11. McCarthy, J.M., Watkins, S., Deivasigamani, A., and John, S.J., *Fluttering energy harvesters in the wind: A review.* Journal of Sound and Vibration, 2016. **361**: p. 355-377.
12. Abdelkefi, A., *Aeroelastic energy harvesting: A review.* International Journal of Engineering Science, 2016. **100**: p. 112-135.
13. Li, D., Wu, Y., Da Ronch, A., and Xiang, J., *Energy harvesting by means of flow-induced vibrations on aerospace vehicles.* Progress in Aerospace Sciences, 2016. **86**: p. 28-62.
14. Ricciardelli, F. and Polimeno, S., *Some characteristics of the wind flow in the lower Urban Boundary Layer.* Journal of Wind Engineering and Industrial Aerodynamics, 2006. **94**(11): p. 815-832.
15. Abd Razak, A., Hagishima, A., Ikegaya, N., and Tanimoto, J., *Analysis of airflow over building arrays for assessment of urban wind environment.* Building and Environment, 2013. **59**: p. 56-65.
16. Ahmad, K., Khare, M., and Chaudhry, K.K., *Wind tunnel simulation studies on dispersion at urban street canyons and intersections—a review.* Journal of Wind Engineering and Industrial Aerodynamics, 2005. **93**(9): p. 697-717.
17. Oke, T.R., *Street design and urban canopy layer climate.* Energy and Buildings, 1988. **11**(1): p. 103-113.

18. Georgakis, C. and Santamouris, M., *Experimental investigation of air flow and temperature distribution in deep urban canyons for natural ventilation purposes.* Energy and Buildings, 2006. **38**(4): p. 367-376.
19. Emejeamara, F.C., Tomlin, A.S., and Millward-Hopkins, J.T., *Urban wind: Characterisation of useful gust and energy capture.* Renewable Energy, 2015. **81**: p. 162-172.
20. Chinmaya, P. and Venkatasubramani, S.R.P. *Aeroelasticity - In General and Flutter Phenomenon*. in *2009 Second International Conference on Emerging Trends in Engineering & Technology*. 2009.
21. Connell, B.S.H. and Yue, D.K.P., *Flapping dynamics of a flag in a uniform stream.* Journal of Fluid Mechanics, 2007. **581**: p. 33-67.
22. Peng, Z. and Zhu, Q., *Energy harvesting through flow-induced oscillations of a foil.* Physics of Fluids, 2009. **21**(12): p. 123602.
23. Bryant, M. and Garcia, E. *Energy harvesting: a key to wireless sensor nodes*. in *Second International Conference on Smart Materials and Nanotechnology in Engineering*. 2009. SPIE.
24. *The Piezoelectric Effect*. Available from: http://www.nanomotion.com/piezo-ceramic-motor-technology/piezoelectric-effect/.
25. Woodford, C. *Piezoelectricity*. August 11, 2017; Available from: http://www.explainthatstuff.com/piezoelectricity.html.
26. Pye, A. *Piezoelectric Materials*. 2015; Available from: https://knowledge.ulprospector.com/2689/pe-piezoelectric-materials/.
27. Abdessattar, A. and Abdullah, O.N., *Modeling and performance analysis of cambered wing-based piezoaeroelastic energy harvesters.* Smart Materials and Structures, 2013. **22**(9): p. 095029.
28. Abdelkefi, A., Nayfeh, A.H., and Hajj, M.R., *Enhancement of power harvesting from piezoaeroelastic systems.* Nonlinear Dynamics, 2012. **68**(4): p. 531-541.
29. Huang, L., *Flutter of Cantilevered Plates in Axial Flow.* Journal of Fluids and Structures, 1995. **9**(2): p. 127-147.
30. Elvin, N.G. and Elvin, A.A., *The Flutter Response of a Piezoelectrically Damped Cantilever Pipe.* Journal of Intelligent Material Systems and Structures, 2009. **20**(16): p. 2017-2026.
31. Bibo, A. and Daqaq, M.F., *Energy harvesting under combined aerodynamic and base excitations.* Journal of Sound and Vibration, 2013. **332**(20): p. 5086-5102.
32. Deivasigamani, A., *Piezoelectric energy harvesting from wind-induced flutter.* 2014.