IOP Conference Series: Earth and
Environmental Science

PURPOSE-LED
PUBLISHING™

PAPER • **OPEN ACCESS**

Parametric optimisation of a dual cantilever flutter for electromagnetic wind energy harvesting

To cite this article: V R Velusamy *et al* 2023 *IOP Conf. Ser.: Earth Environ. Sci.* **1281** 012015

Parametric optimisation of a dual cantilever flutter for electromagnetic wind energy harvesting

V R Velusamy[1], **F M Foong**[*,1], **N A R Nik Mohd**[1] **and C K Thein**[2]

[1]UTM Aerolab, Institute for Vehicle Systems & Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor, Malaysia
[2]School of Aerospace, University of Nottingham Ningbo China, Ningbo 315100, PR China

*Corresponding author email: faruqfoong@utm.my

Abstract. This paper investigates the parametric optimisation of dual cantilever flutter (DCF) beams for electromagnetic wind energy harvesting application. When two cantilever beams are placed side by side facing the direction of the wind flow, both beams would oscillate in an anti-phase motion once the critical flutter speed has been achieved. This arrangement is known as the DCF and it represents an ideal situation for energy harvesting through electromagnetic induction due to its anti-phase motion. Experimental results showed that the optimum load resistance value for the device is equivalent to a single-degree-of-freedom vibration energy harvester for low electromagnetic coupling case, despite the difference in the type of oscillations. Further analysis showed that there among the two possible arrangements for the magnets one arrangement results in a 51.5% larger magnetic flux density. It was seen that reducing the length of the electromagnetic DCF by 41.2% can increase the power output of the device by approximately six times, although the critical flutter speed also increased by 125.0%. Finally, some suggestions were provided on how to further improve the device.

1. Introduction

Vibration related phenomena such as resonance, vortex induced vibration and flutter are often undesirable in many engineering applications as they can cause structural failures [1]. However, the opposite case is viewed in energy harvesting practices as these phenomena encourages the generation of electrical power. Although vibrations are usually related to contacts between solid objects, they can also be induced from fluid-structure interactions due to aerodynamic forces. Some researchers take advantage of the oscillations generated by fluid-structures interactions to harvest renewable energy from low wind speeds because at this range, these methods are deemed more effective than wind turbines [2-5]. The power obtained from these energy harvesting methods are usually small but they provide a good alternative for batteries in low-powered electronics. Nevertheless, many researchers have attempted to increase the performance of energy harvesters using various methods.

While resonance and vortex induced vibrations experience significant oscillations within a limited range of wind speeds, flutter on the other hand can occur over a larger range of wind speeds due to its self-sustained behavior [6], making it a promising choice for energy harvesting. Several designs have previously been proposed to harvest wind energy from flutter oscillations using membranes [7], cantilever beams [8] or flags [9] but the one that stands out is the dual cantilever flutter (DCF) design by Hobeck et al. [10,11] due to its unique characteristics. The DCF design consist of two vertical cantilever beams that are placed side by side separated by a small gap and facing the direction of the wind flow. When exposed to the wind flow with speeds larger than the critical flutter speed (minimum wind speed for flutter to occur), the beams oscillate in an anti-phase manner with respect to each other.

This study aims to optimize an electromagnetic DCF for wind energy harvesting applications. If designed properly, the anti-phase motion from the DCF may be used to increase the relative velocity between the conductor and the permanent magnet which in turn can quadruple the power output [12]. Several parameters such as the load resistance, magnet arrangement and beam dimension were analyzed through experiment and simulation. The power output of the final optimum device was then tested experimentally and compared to the initial design, emphasizing the improvements obtained. Finally, several suggestions were highlighted for further improvements of the device.

2. Theoretical modelling of and experimental setup

Assuming that both cantilever beams can be represented by a single degree of freedom (SDOF) system under forced excitation,

$$M\ddot{x}_i + C\dot{x}_i + Kx_i = F_i \qquad i = 1,2 \tag{1}$$

where x, $\dot{x}$ and $\ddot{x}$ are the beam's displacement, velocity and acceleration response whereas M, C and K are the equivalent mass, damping and stiffness of the beam. F is the excitation force and the subscript i are indicators to differentiate the two beams. Considering the fluid forcing terms [11], equation (1) can be re-defined as:

$$M\ddot{x}_i + C\dot{x}_i + Kx_i = \frac{\gamma(\dot{x}_i-\dot{x}_j)|\dot{x}_1-\dot{x}_2|}{[1+(x_1-x_2)^2]^\alpha} + \frac{1}{2}\rho_a A_i C_{D,i}(U^2 - \dot{x}_i^2) + \beta M(\varepsilon^2 - x_i{}^2)\dot{x}_i \qquad i = 1,2 \;\; j = 2,1 \tag{2}$$

where γ, α and ε are constants, ρ_a, C_D and U are the density, drag coefficient and velocity of the air flow A is the area of the beam exposed to the airflow, otherwise known as the wetted area and β = 10000 $m^{-1}s^{-1}$. Subscript j indicates the other beam in conjunction with subscript i. Considering the region after the critical flutter speed and assuming that both beams flutter with the same speed but in an anti-phase motion, the voltage output generated at the load resistance (connected in parallel) is

$$V_L = 2Kx_i\omega_i \frac{R_L}{R_c+R_L} \qquad i = 1,2 \tag{3}$$

where V_L is the voltage output at the load resistance, $K$is the electromagnetic coupling coefficient, ω is the flutter frequency of the beams and R_c and R_L are the coil and load resistance respectively. The power output can then be calculated as

$$P = \frac{V_L{}^2}{R_L} \tag{4}$$

In this study, an experiment was conducted to verify the optimization. Two cantilever beams measuring 229.5 mm × 20.0 mm × 0.5 mm (length × width × thickness) were clamped side by side into the test section of a low-speed wind tunnel. The beams were oriented so that they are perpendicular to the incoming air flow, hence forming the DCF. A pair of neodymium magnets of grade N35 was attached onto one of the beams and two identical wounded coils were attached onto the other beam as seen in Figure 1. Some proof mass was added to the coil to tune its frequency to be similar to the magnet-holding beam. The two beams were placed close to one another to maximise the electromagnetic coupling factor, with the centre of the coil being approximately 7.0 mm away from the surface of the magnets. At this distance, the electromagnetic coupling factor was measured to be around $K = 0.14$ Tm.

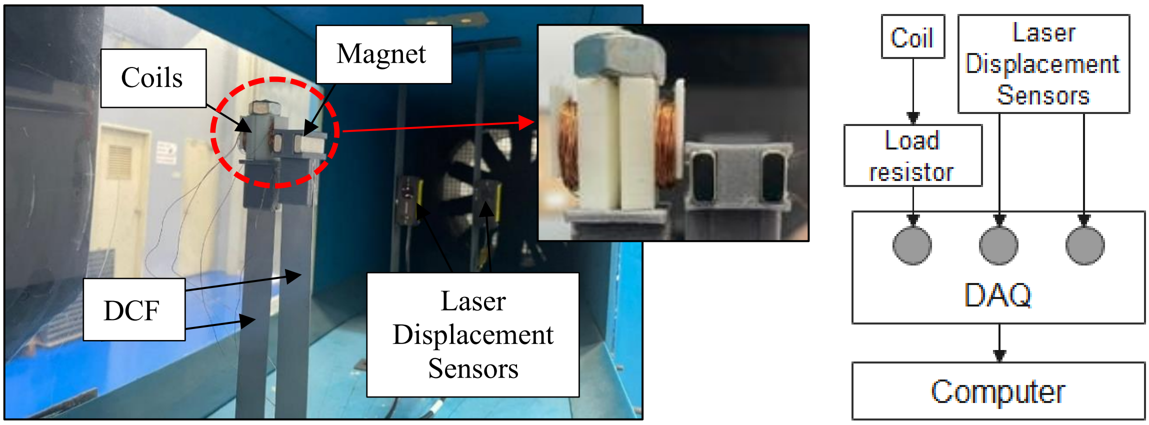

Figure 1. Experiment setup for an electromagnetic DCF energy harvester.

Two laser displacement sensors were used to capture the free-end oscillations of the beams. The coil was connected in parallel to a variable load resistor and the responses of the sensors and the coil were transferred to a computer through data acquisition device (DAQ). Note that only the output from a single coil was measured from the device, which is the coil closest to the permanent magnet. The DCF was then tested at different wind speeds ranging from 2.0 ms^{-1} to 15.0 ms^{-1}.

3. Results and Optimization

This section presents the results and parametric optimisation conducted on the electromagnetic DCF energy harvester, as well as suggestions for further improvements.

3.1. Optimisation of the load resistance

The device in Figure 1 was tested until significant oscillations were observed, indicating the occurrence of flutter. It was found that even at a low wind speed of 4.0 ms^{-1}, the electromagnetic DCF has already achieved flutter. Afterwards, the resistance value of the variable load resistor was varied between 0.0 Ω to 20.0 Ω to determine the optimum load resistance, which is the load resistance corresponding to the maximum power output, while maintaining the same wind speed of 4.0 ms^{-1}. Figure 2 demonstrates the oscillations recorded by the laser displacement sensors at a wind speed of 4.0 ms^{-1} and the variation of power output (calculated using equation (4)) against load resistance for the electromagnetic DCF. Beam 1 and Beam 2 in Figure 2 refer to the two beams of the DCF.

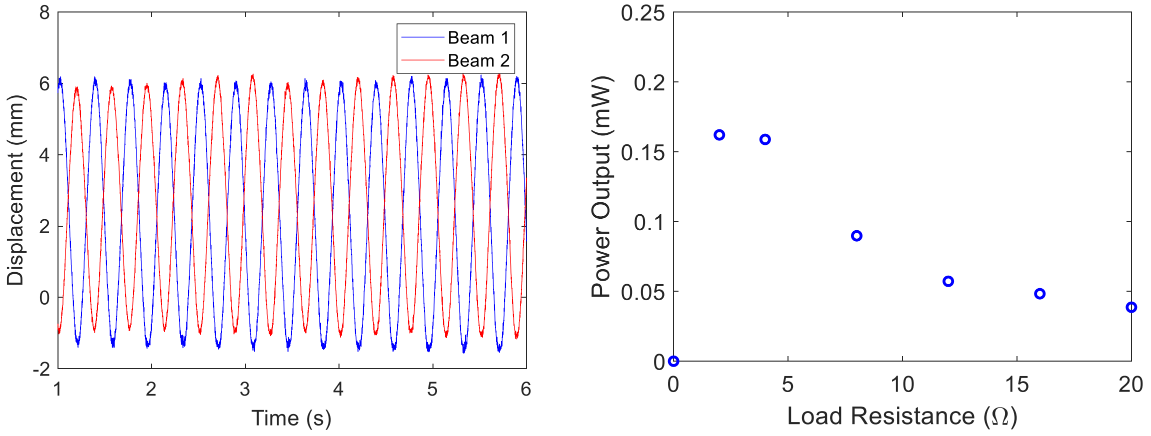

Figure 2. Recorded beam displacements at 4.0 ms^{-1} wind speed (left) and power output against load resistance (right).

Figure 2 shows that both beams recorded an anti-phase motion relative to each other, which is the ideal scenario for electromagnetic energy harvesting. The optimum load resistance value is seen to lie somewhere between 2.0 Ω and 4.0 Ω. The internal resistance of the coil was measured to be 2.7 Ω, which lies within the said optimum range. This means that the optimum load resistance for an electromagnetic DCF can be considered similar to that of a conventional SDOF vibration energy harvester for low coupling cases, where the optimum value is about equal to the coil resistance [13].

3.2. Optimisation of the magnet arrangement

The pair of magnets for the electromagnetic DCF harvester have two possible arrangements. Either both magnets have the same poles facing outwards or both magnets have opposite poles facing outwards. The current setup in Figure 1 has the latter arrangement. A two-dimensional simulation was conducted using Finite Element Method Magnetics software to explore which arrangement is more favourable for the device as seen in Figure 3. In this case, the more favourable one would be the arrangement that outputs a larger magnetic flux density as this parameter is directly proportional to the electromagnetic coupling coefficient, K. Both magnets measure 25.0 mm × 10.0 mm × 5.0 mm and are spaced 8.0 mm away from each other and are attached to a non-magnetic material (plastic).

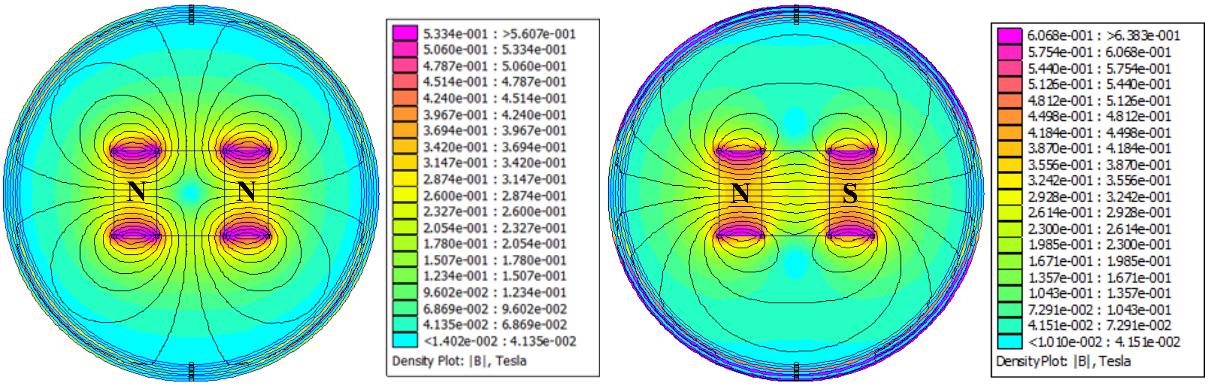

Figure 3. Permanent magnet simulation for two different arrangements with outward facing poles inscribed onto the magnets.

Taking the average magnetic flux density at a distance of 7.0 mm from the surface of the magnets, the arrangement where two alike poles are facing outwards recorded a flux density of 0.066 T whereas the other arrangement recorded a flux density of 0.100 T. This shows that the latter arrangement is more ideal for the DCF device.

3.3. Optimisation of the cantilever beam length

The power output at the optimum load resistance shown in Figure 2 is relatively low and may not be useful for practical applications, despite having the ideal magnet arrangement. One of the main reasons for this is that despite the high amplitude oscillations, the flutter frequency recorded was only 2.8 Hz. According to equations (3) and (4), the power output of the device is highly dependent on the product of amplitude and frequency. Hence, the length of the cantilever beam was reduced to 135.0 mm in an attempt to increase the flutter frequency. This beam was then tested using the favourable magnet arrangement and under the optimum load resistance, with the results presented in Figure 4. Like in Figure 2, the power output here was calculated using equation (4).

The first observation one may notice is that the theoretical model agrees well with the experimental results. It is seen that the optimised DCF has a larger critical flutter speed at approximately 8.8 ms^{-1} compared to the initial DCF. Nevertheless, this is still considered within the range of low wind speeds [10]. Consequently, the DCF now vibrates at a much higher frequency of 6.2 Hz, resulting in a significantly larger power output of nearly 1.0 mW at a wind speed of 14.6 ms^{-1}. This represents an approximately six times increase in power generated compared to the initial device. While the power generated is still quite low, it is now sufficient for small electronics such as wireless sensor nodes.

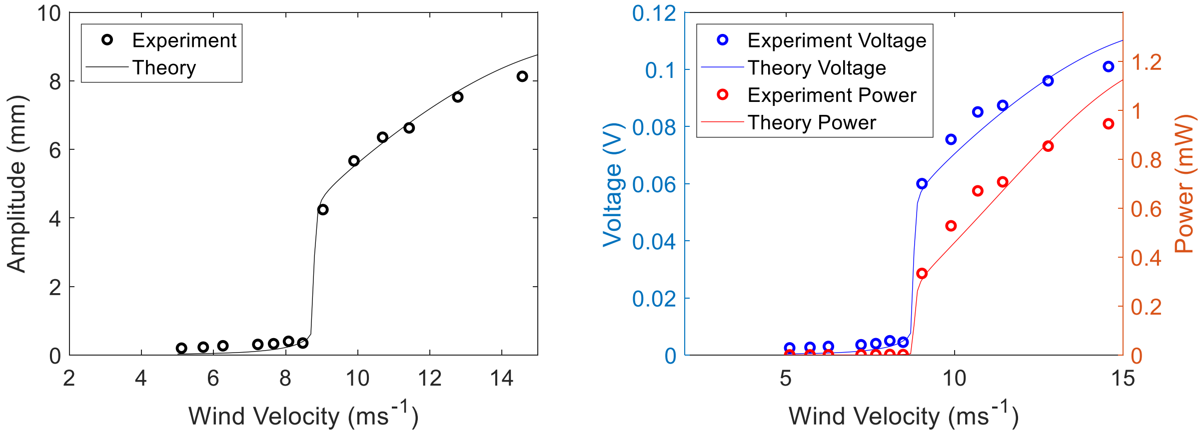

Figure 4. Amplitude response, voltage and power output of the optimized electromagnetic DCF energy harvester.

3.4. *Suggestions for further improvements*

Although the optimization results presented here so far has demonstrated a significant improvement in terms of power output, it is still possible to increase the performance of the device. For example, instead of being separated by a non-magnetic material, a soft magnetic material like iron can be used instead to connect the pair of permanent magnets. Additionally, it would be possible to reduce the distance between the magnet and the coil so that the coil is exposed to a larger magnetic flux density. The magnets used in the experiments were neodymium magnets of grade N35. If a higher-grade magnet was used, the performance of the device can be further increased.

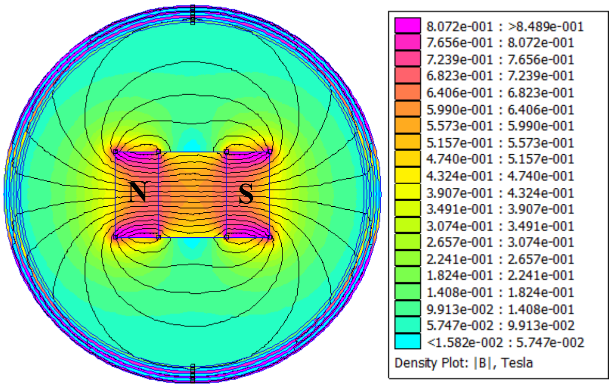

Figure 5. Permanent magnet simulation for newly suggested considerations to further improve the performance of the electromagnetic DCF energy harvester.

Consider the case where neodymium magnets of grade N52 were used instead and that these magnets are separated by a soft magnetic material like iron instead of plastic. Next, consider that the distance between the coil and the magnets were reduced to 5.0 mm. Repeating the magnetic simulation from Figure 3 using these new considerations results in a much stronger magnetic flux density as shown in Figure 5. The measured magnetic flux density in Figure 5 is 0.206 T which is around twice as large as the ideal arrangement measure in Figure 3. Theoretically, this will result in a four times larger power output that what was obtained in Figure 4.

4. Conclusion

This study presents a parametric optimization for an electromagnetic DCF energy harvester. Experimental results showed that the optimum load resistance value for the device is approximately equal to the internal resistance of the coil, which is identical to a SDOF vibration energy harvester with low electromagnetic coupling coefficients. It was then demonstrated through simulation that if the permanent magnets were arranged in a way that opposite poles are facing outwards, the magnetic flux density produced would be 51.5% than if the magnets were oriented so that alike poles are facing outwards. Reducing the length of the DCF beams by 94.5 mm resulted in six times increase in power output, although the critical wind speed also rose by 125.0%. Finally, based on the suggestions made to increase the magnetic flux density, it was shown that the power output of the device can be further improved by approximately four times more. As a continuation of this work, it would be interesting to explore the possibility of using more cantilever beams to create an array of electromagnetic DCF energy harvesters.

5. References

[1] Liu C, Xu H, Chai X and Gao Y 2021 *Liutex and Its Applications in Turbulence Research* (London: Academic Press–Elsevier)

[2] Lee Y J, Qi Y, Zhou G and Lua K B 2019 Vortex-induced vibration wind energy harvesting by piezoelectric MEMS device in formation *Sci. Rep.* **9** 20404

[3] Tang B, Fan X, Wang J and Tan W 2022 Energy harvesting from flow-induced vibrations enhanced by meta-surface structure under elastic interference Int. J. Mech. Sci. **236** 107749

[4] Nan W, Yuncheng H and Jiyang F 2021 Bistable energy harvester using easy snap-through performance to increase output power *Energy* **226** 120414

[5] Zhao D, Hu X, Tan T, Yan Z and Zhang W Piezoelectric galloping energy harvesting enhanced by topological equivalent aerodynamic design *Energy Conv. Manage.* **222** 113260

[6] Chen Y, Mu X, Wang T, Ren W, Yang Y, Wang Z L, Sun C and Gu A Y 2016 Flutter Phenomenon in Flow Driven Energy Harvester–A Unified Theoretical Model for “Stiff” and “Flexible” Materials *Sci. Rep.* **6** 35180

[7] Dou Z, Rips A, Jacob L and Mittal R 2019 Experimental Characterization of the Flow-Induced Flutter of a Suspended Elastic Membrane *AIAA J.* 058600

[8] Z Lu, Q Wen, X He and Zhiyu Wen 2019 A Flutter-Based Electromagnetic Wind Energy Harvester: Theory and Experiments *Appl. Sci.* **9**(22) 4823

[9] Orrego S, Shoele K, Ruas A, Doran K, Caggiano B, Mittal R and Kang S H 2017 Harvesting ambient wind energy with an inverted piezoelectric flag *Appl. Energy* **194** 212–222.

[10] Hobeck J D, Geslain D and Inman D J 2014 The Dual Cantilever Flutter Phenomenon: A Novel Energy Harvesting Method *Sens. Smart Struct. Tech. Civ. Mech. Aero. Syst.* Proc. SPIE **9061** 906113

[11] Hobeck J D and Inman D J 2015 The Jd number: An empirical constant for predicting dual cantilever flutter velocity *App. Phys. Lett.* **106** 244103

[12] Foong F M, Thein C K, Ooi B L and Yurchenko D 2019 Increased power output of an electromagnetic vibration energy harvester through anti-phase resonance, *Mech. Syst. Signal Process* **116** 129–145

[13] Foong F M, Thein C K and Aziz A R A 2018 *2nd Int. Conf. on Smart Grid and Smart Cities* (Kuala Lumpur: Malaysia) pp 127-132

Acknowledgement

This work was supported by the Fundamental Research Grant Scheme (FRGS) from the Ministry of Higher Education (MOHE) Malaysia, Grant No: FRGS/1/2021/TK0/UTM/02/3.