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Development of A Small-Scale Vortex-Induced Wind Turbine

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Abstract: Over the last several years, there has been a significant and encouraging interest in the generation of power from wind. However, a massive wind turbine can only operate in a high wind speed condition. The vortex bladeless wind turbine is a completely new idea in wind turbines with a different mode of operation. It is designed to operate in low wind conditions, making it an ideal choice for areas with such conditions, such as Malaysia. This study aims to develop and evaluate a functional prototype of a vortex bladeless wind turbine that can be used to harvest wind energy in a low wind speed condition. A vortex bladeless wind turbine is fabricated based on existing research on the principle of the vortex shedding phenomenon. It is built in a cylindrical shape with an approximately 2 m height measuring from the base to the top of the mast and 0.2 m in diameter. The structure of a bladeless wind turbine is a flexible cylindrical mast over the setup that captures potential forms of energy from moving airstreams and uses a vortex induced vibration (VIV) mechanism to produce vibration in the structure. The testing was done by using a wind tunnel's exhaust that produced 1 m/s to 10 m/s of air flow, which simulates a low-to-medium wind speed condition. The vibration is turned into electrical energy, using a power generating system like an electromagnetic induction mechanism. The analysis of the results is based on numerous data points gathered during the testing, including the frequency of oscillation, vortex shedding, natural frequency, and resonance parameter. Through the investigation, the results show that the phenomena of induced vibration were working at even critically low speeds, which starts at 3.3 m/s, where standard and conventional wind turbines may fail to produce the desired outcomes as they are outside of their operating windspeed. The frequency of vortex shedding increases with windspeed, from 0.94 Hz at 1 m/s to 9.39 Hz at 10 m/s. On this basis, it is confirmed that the prototype of the vortex bladeless wind turbine is working properly in harvesting wind energy, though several improvements need to be made.

Keywords: Vortex shedding, resonance, wind energy, wind turbine, bladeless

1. Introduction

In this modern era, electricity significantly impacts our day-to-day activities. Electrical power is used in several locations during our daily routines, whether it be at home, school, the local shopping mall, or our office. In our contemporary lives, such as our everyday lives at home and industry and communication as in the form of radio, television, email, the Internet, etc., electricity is incredibly vital. People have begun to generate electricity from renewable resources, based on appropriate site geometry and environmental conditions. Wind energy was one of the most common types of renewable resources harvested. Currently, massive wind turbines are used to harvest wind energy. A wind turbine was invented to convert wind's kinetic energy into electrical energy by using aerodynamic force from the blades. To efficiently capture high wind velocity, the size of the blades is usually massive, and the standard wind turbine height is usually around 40 to 90 meters tall [1]. An enormous wind turbine will be rendered useless in a low wind speed condition. Thus, a smaller wind turbine is needed to harvest wind energy at low wind speeds efficiently. One of the smaller wind

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turbine innovations was the vortex bladeless wind turbine. In this project, a working prototype of a wind turbine without blades that can collect energy from the wind at low to medium wind speeds was made and tested.

2. Literature Review

The Vortex bladeless wind turbine (VBWT) is an entirely new type of wind turbine that operates differently. It was intended to function at low wind speeds, making it a better choice for areas with such conditions. The vortex shedding phenomenon is used to power a vortex bladeless wind turbine. A bladeless wind turbine's structure gathers potential forms of energy from flowing airstreams and produces vibration in the structure using a vortex-induced vibration (VIV) principle.

2.1 Concept of Vortex-Induced Vibration (VIV)

Vortex induced vibration (VIV) results from a phenomenon called vortex shedding, which happens most frequently when a solid body is immersed in a fluid. The flow's fluctuating pressure difference results in a lift force perpendicular to the flow direction. The alternating lift force is what causes the body to vibrate.

As the fluid travels around the cylindrical body's circumference, the pressure in the fluid rises to the stagnation pressure, which is different from the steam pressure. The pressure at low flow speeds on both sides stays symmetrical, and hence there was no sign of turbulence. As the flow velocity approaches the critical value, the pressure on both sides of the body becomes unstable, resulting in the formation of a novel vortex pattern known as Karman Vortex Street [2]. Fig. 1 shows the pattern of vortex shedding when a high velocity wind collides with a blunt body.

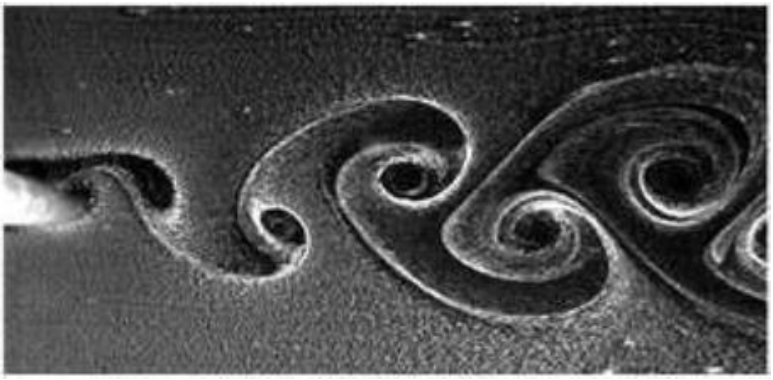


Fig. 1 - The pattern of vortex shedding

In a situation when the wind is blowing at a high velocity, the fluid will separate from the surface of a blunt body. This phenomenon is referred to as flow separation. Several factors will determine the separation point, including the roughness of the surface, degree of free stream, pressure gradients, and the Reynolds number [3]. Separation often happens along blunt or sharp edges, referred to as a "positive pressure gradient zone," because it tends to retard the flow. Continuation of flow retardation will cause the wall shear stress to be reduced to zero, separating the flow from the solid body. As the wall shear stress approaches zero, a zone of recirculation flow emerges since the flow is reversed. A separate region was created due to the low-pressure region behind the body where backflow and recirculation occur [2].

2.1.1 Resonance

One famous incident related to resonance was the collapse of the Tacoma Narrows bridges [4]. When an oscillation is enhanced by regular movement, the resonance phenomenon occurs. In aeroelasticity, the air can make a body move in an oscillating way if its natural resonance frequency and the wake frequency of vortex shedding are the same. The vibrations caused by vortices in a body are referred to as VIV phenomena [5]. The inherent resonance frequency or the natural frequency is given as:

$$\omega_n = \sqrt{\frac{(K.L^2 - 2Mc.gL)/4}{I}} \tag{1}$$

where *K* is the spring stiffness, *L* is the length of mast and *Mc* represent the center of mass of cylinder.

The Strouhal Number, *St* relates the wake frequency of the vortex shedding to the characteristic dimension of the body:

$$St = Fs.\frac{D}{U} \tag{2}$$

where, *Fs* is defined as vortex shedding frequency, *D* is the diameter of mast and *U* is the velocity of the fluid.

2.2 Electromagnetic Induction

The process of electromagnetic induction occurs when a conductor was placed in a certain position, and a changing or stationary magnetic field maintains this conductor in place. The electrical conductor gets a voltage or an EMF (Electromotive Force) across it. The Law of Induction was discovered by Michael Faraday in 1830 [6]. A broad number of practical applications are associated with the discovery of electromagnetic induction.

3. Methodology

3.1 Design Modelling

The design models for this study were created using the SolidWorks 2019 software. The Vortex bladeless wind turbine consists of several parts. The basic shape of the turbine is a slender flexible cylinder mounted on a solid base or surface. Fig. 2 shows the isometric view of the full assembly of the design.

Fig. 2 - Isometric view of vortex bladeless wind turbine

3.2 Parts and Material

Several materials are needed to begin the process of fabrication. Table 1 shows the material used for every component:

Table 1 - List of component's material

Material	Item	Part
PVC	8-inch diameter pipe	• Mast and base cover
	26mm diameter pipe	• Fixed and flexible rods
Plywood	3mm Plywood	• Base Plate
PLA Plastic	3D Printed part	• Mast cover • Base top cover • Magnet holder • Magnet holder cap • Outer magnet ring • Inner magnet ring • Copper coil holder
ABS Plastic	3D Printed part	• Mast-rod connector
Concrete	-	• Base

3.3 Electric Generation Mechanism

An electric current will be generated if the magnet moves with the mast and allows the copper coils to cut the magnetic flux of the magnet. This will enable the wind turbine to operate either at a high wind speed or a low wind speed, as both situations will cause oscillation of the mast. As for the amount of electric current produced, it will generate more current per oscillation than the piezo element compared to electromagnetic induction. The amount of the current produced depends on several factors, such as the number of coils turned, the strength of the magnet and the speed of cutting of magnetic flux. With the number of coils turning and the magnet's strength remaining constant, the amount of electric current produced will depend on oscillation speed. To put it simply, the higher the wind speed, the faster the oscillation of the mast and the higher the current that will be generated and vice versa.

3.4 Assembly

After all the components and parts are fabricated, the system needs to be assembled. The assembly process is vital because any final adjustments need to be made before securing all the components and parts together. The fully assembled model is as shown in Fig. 3.

3.5 Testing

A wind tunnel was required to test the VBWT in a controlled environment. The testing was done using a wind tunnel in UTHM's aerodynamic laboratory. Unfortunately, the testing area was very small compared to the prototype, so the wind tunnel exhaust was used instead. The wind produced by the exhaust is suitable for the test run because it almost resembles natural wind in terms of the type of airflow, which is turbulent. It is also easier to collect the data as the wind speed can be kept constant while running the air through the VBWT. Fig. 4 shows the vortex bladeless wind turbine tested by using the wind tunnel exhaust varying from 1 m/s to 10 m/s.

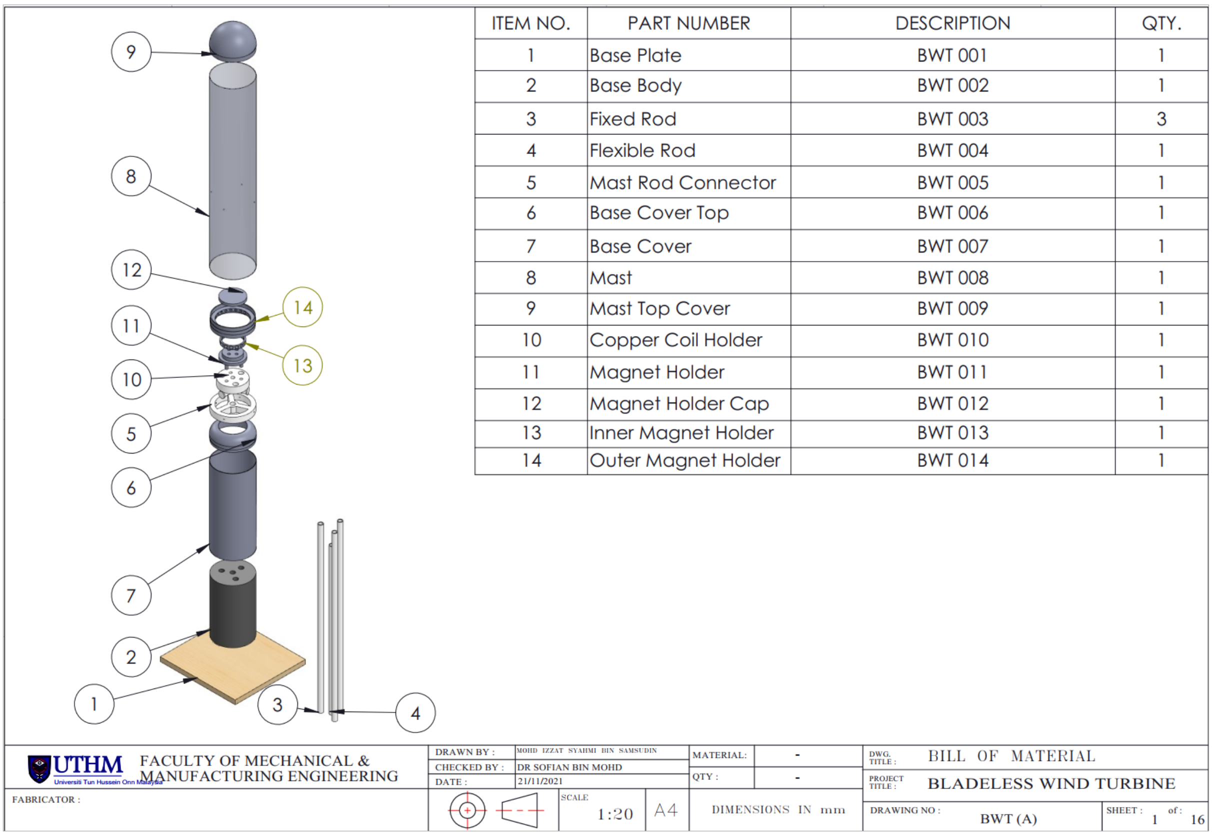
Fig. 3 - Full assembly of VBWT

Fig. 4 - Testing of VBWT on Different Windspeed

4. Results and Discussion

4.1 The Prototype of a Small-Scale Vortex Bladeless Wind Turbine (VBWT)

A prototype of a small-scale VBWT has been successfully fabricated after a series of calculations and designs have been done. The initial design of the wind turbine consists of the usage of fiberglass as the main body or mast of the wind turbine. After several considerations, the mast's material has been changed to PVC plastic. Nevertheless, the initial design does not undergo any changes except for the material. However, the electrical generation mechanism undergoes several changes after consulting electrical experts, though it still needs some improvements to work properly. Fig. 5 shows each of the components of the finalized product, the complete assembly, and the fabricated product.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Base Plate	BWT 001	1
2	Base Body	BWT 002	1
3	Fixed Rod	BWT 003	3
4	Flexible Rod	BWT 004	1
5	Mast Rod Connector	BWT 005	1
6	Base Cover Top	BWT 006	1
7	Base Cover	BWT 007	1
8	Mast	BWT 008	1
9	Mast Top Cover	BWT 009	1
10	Copper Coil Holder	BWT 010	1
11	Magnet Holder	BWT 011	1
12	Magnet Holder Cap	BWT 012	1
13	Inner Magnet Holder	BWT 013	1
14	Outer Magnet Holder	BWT 014	1

Fig. 5 - (a) Exploded view of final VBWT design

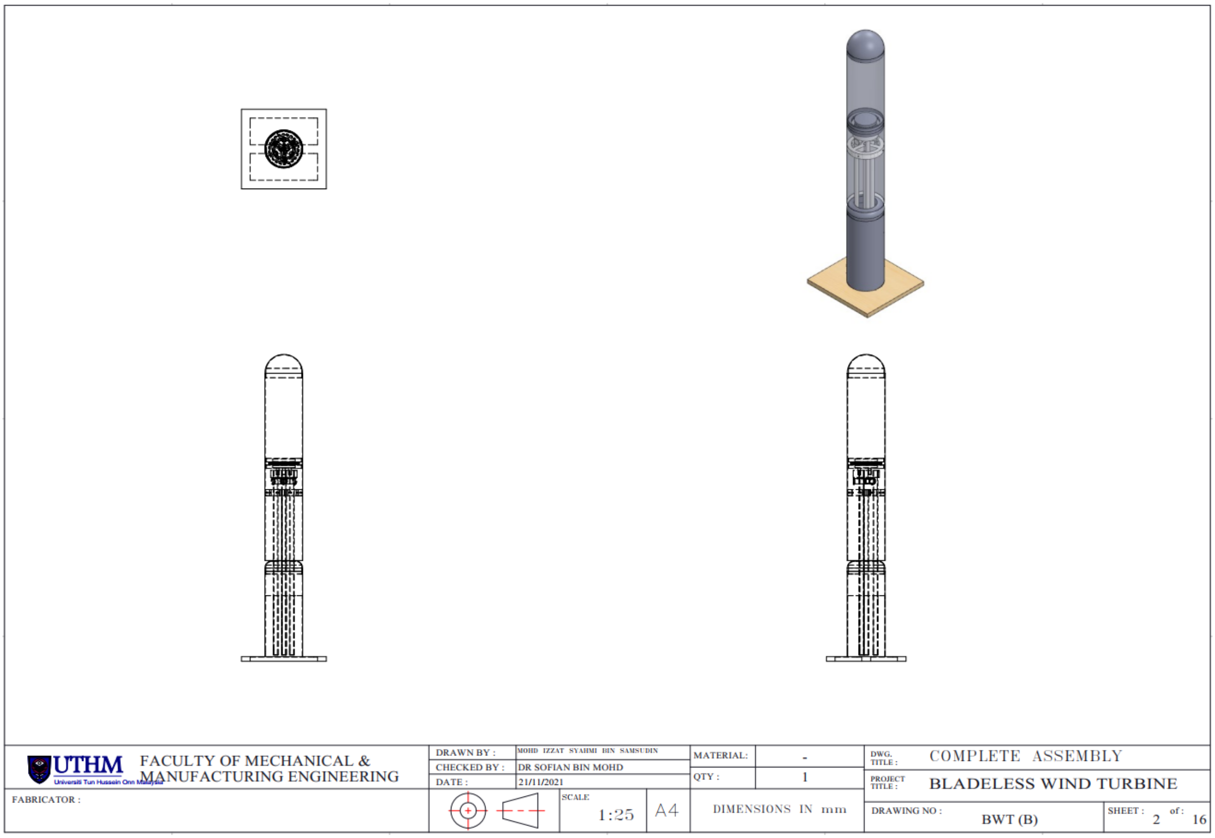


Fig. 5 - (b) Complete assembly of VBWT

The small-scale bladeless wind turbine fabrication is based on the design above. To fabricate complex-shaped components, the use of 3D printing is necessary. More than 50% of the components are fabricated by using this method.

The rest of the components are manually done by woodwork, cutting, measuring, and fitting. With that, the fabrication of the prototype of VBWT was successful, and the final product is shown in Fig. 6.

Fig. 6 - Prototype of VBWT

4.2 Analysis of Wind Turbine Parameter

4.2.1 The Frequency of Oscillation Vs Windspeed

The oscillation count data was collected and tabulated, as shown in Table 2. To see the trend more clearly, the data was plotted into a graph to better view the result.

Table 2 - Experimental data

Wind Speed (m/s)	No. of Oscillation				Time Taken (s)	Frequency of Oscillation (Hz)
	1st	2nd	3rd	Average		
1	23	20	24	22,33	20	1.12
2	24	26	25	25,00		1,25
3	26	25	25	25.33		1.27
4	24	23	26	24.33		1.22
5	25	26	24	25.00		1.25
6	26	25	26	25.67		1.28
7	27	26	27	26.33		1.32
8	23	24	27	24.67		1.23
9	24	24	24	24.00		1.20
10	25	24	23	24.00		1.20

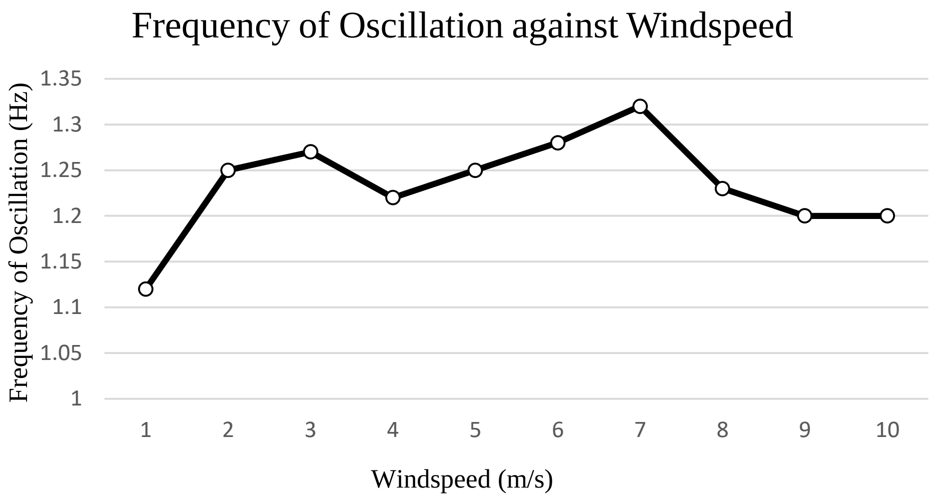


Fig. 7 - Graph of Frequency of Oscillation against Windspeed

Fig. 7 shows a steady increment of oscillation frequency up to the wind speed of 7 m/s, though there is a slight downtrend at 4 m/s. The oscillation frequency starts to show a steady downtrend starting at 8 m/s. This is due to the braking system being engaged during high wind speed conditions. The braking system is engaged when the oscillation displacement is big enough to almost cause a collision between the internal components. This ensures that the system is not exposed to any unnecessary vibration or knocking that will reduce the life expectancy of the VBWT's components. The trend also shows that the above hypothesis is true: the oscillation will get stronger as the wind speed goes up.

4.2.2 Natural Frequency and Vortex Shedding Frequency

For resonance to occur, the vortex shedding frequency must be the same as the natural frequency of the mast. Resonance is not a mandatory parameter for the VBWT to operate, but it will help the mast produce a forced oscillation. This is important because the vortex shedding phenomenon will not likely occur in low wind speed conditions. To overcome that limitation, resonance and forced oscillation are needed to kickstart the mast's oscillation. Before that, Equation 1 needs to be used to figure out the mast's natural frequency with the following information: The Young's modulus of the flexible rod is E = 3.27 GPa (PVC Hard Plastic), the length of the rod, L = 0.95 m, and the diameter of the rod, D = 0.027 m. The mast's natural frequency can be established as follows:

$$\omega_n = \sqrt{\frac{[(99.49)(0.95)^2 - 2(0.148)(9.81)(1.075)]/4}{0.057}} = 19.50\, rad/s$$

$$f_n = \frac{19.50\, rad/s}{2\pi} = 3.10\, Hz$$

The vortex shedding frequency is also calculated from Equation 2, and the values are tabulated according to their individual wind speeds.

Table 3 - Vortex shedding frequency vs windspeed

Wind Speed (m/s)	**Vortex Shedding Frequency (Hz)**
1	0.94
2	1.88
3	**2.82**
4	**3.76**
5	4.69
6	5.63
7	6.57
8	7.51
9	8.45
10	9.39

Table 3 shows the mast's natural frequency, which is 3.10 Hz, is close to the vortex shedding frequency at the windspeed of between 3 m/s and 4 m/s, which has a frequency of 2.82 Hz and 3.76 Hz, respectively. So, resonance is most likely to occur in the said windspeed range.

4.2.3 Resonance and Frequency of Oscillation

To see the effect of resonance on the system more clearly, the frequency of oscillation and the resonance's windspeed range need to be compared side by side. To find the exact wind speed where resonance occurred, interpolation needs to be done.

Table 4 - Interpolation

Wind Speed (m/s)	Vortex Shedding Frequency (Hz)
3	2.82
3.3	**3.10**
4	3.76

Table 4 shows the result of the interpolation of windspeed for the vortex shedding frequency of 3.10 Hz. The vortex shedding frequency of 3.10 Hz occurred at a windspeed of 3.3 m/s. By making an intersection line at a windspeed of 3.3 m/s in the frequency of oscillation graph, the effect can be seen based on the oscillation frequency trend in the graph.

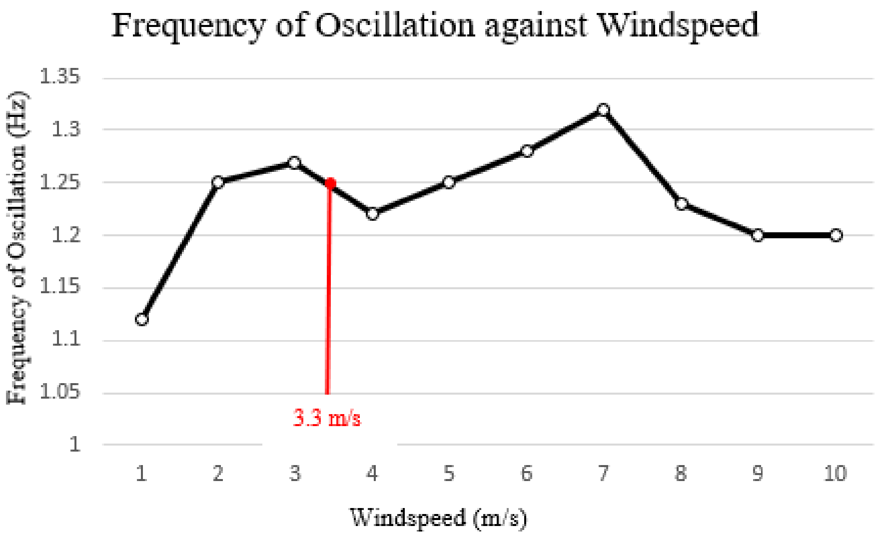


Fig. 8 - Intersection of resonance windspeed and oscillation frequency

Fig. 8 shows the trend where resonance occurs. The red line represents the wind speed at which resonance occurred. The graph shows a downtrend when resonance takes place. This downtrend may be caused by the forced oscillation cancelling out the oscillation produced by the vortex shedding phenomenon. Nevertheless, the graph begins showing an uptrend after 4 m/s. This indicates that resonance should not occur while the vortex shedding phenomenon is in action, as it will reduce the ability of VBWT to harvest wind energy. As said before, resonance is needed to kickstart the oscillation before the vortex shedding phenomenon can occur; hence, it must be aimed to take effect at a lower frequency. This can be done by changing the material of the mast, which can contribute to lowering the natural frequency value to ensure resonance will occur only at low wind speed conditions.

5. Conclusion

In conclusion, the prototype of the VBWT has been successfully built. Based on the testing done, the VBWT can harvest wind energy and convert it into kinetic energy. The tuning and braking systems are also working, as we can see from the data provided. According to the data collected, we know that wind speed is one of the parameters affecting the wind turbine. The higher the wind speed, the higher the frequency of oscillation. Next, we can also conclude that the natural frequency of the mast and vortex shedding frequency is critical in producing resonance and forced oscillation. According to the calculation, to change the resonance's wind speed zone into the intended target, we can either alter the natural frequency of the mast by changing the materials used or alter the vortex shedding frequency by changing the diameter of the mast. Nevertheless, the fabrication of VBWT still needs improvements and minor changes in design for it to operate as intended. As this is the first prototype made, it also serves as a reference for future research and developments.

Based on the findings and conclusions presented in this study, the following recommendations are suggested to improve. First, the flexible rod should be changed with a lower Young's modulus material to reduce the mast's natural frequency. Reducing the natural frequency makes it easier to match the vortex shedding frequency in low wind speed conditions to produce resonance and forced oscillation. Another method is by increasing the diameter of the mast to reduce the overall vortex shedding frequency. This ensures that both frequencies will be equal at a lower value. Consequently, this makes it possible for resonance to occur at a lower wind speed. Next, the design of the copper coil holder should be changed. The design must allow the copper to be coiled around the holder. It is also preferable to have a slot where a ready-made copper coil can just be slotted in. The copper wire for the coils also needs to be smaller in diameter. This is to ensure that more turns can be made, thus increasing the performance of electromagnetic induction. The stronger magnet will also contribute positively to this aspect. Lastly, to better understand the vortex shedding phenomenon, a simulation should be done using software such as Ansys. This will ensure that the best parameters can be chosen before the 3D modelling design and fabrication process.

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