Vertical-Axis Wind Turbines Using Permanent Magnet Attractive Type Passive Magnetic Bearings

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***Abstract*— This paper presents a novel design of a vertical axis wind turbine (VAWT) for power generation purposes. Using the effects of magnetic suspension, wind generator will be suspended on permanent magnets (PMs) as a replacement for ball bearings, which are normally used on conventional wind turbines. The features of this system are effective for saving energy, avoiding heat generation and preventing mechanical contact. Electrical power will then be generated with an axial flux generator, which incorporates the use of permanent magnets and a set of coils. The proposed VAWT model has the ability to achieve stability at different wind speeds in both the axial and radial direction. Moreover, the proposed model has a novel advantage consisting in adjustability of the axial and radial stiffness and ability to avoid critical speed reducing the vibration during the rotation of the wind turbine. The proposed model is characterized by simple structure and low-cost design. Finally, the effectiveness of the model is verified by the experimental results.**

I. INTRODUCTION

Nowadays, renewable energy sources are becoming increasingly popular as it represents a cheap and environmental-friendly alternative to the traditional energy sources [1]. Wind energy is considered to be one of the renewable energy sources that is rich, available in many countries and has a great potential in the development of many countries [2]. There are two types of wind turbines: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). VAWTs have many advantages such as low cost, simply structured blades and have the ability to utilize wind from all directions without the need for a steering mechanism. However, the traditional vertical axis wind turbines have some drawbacks such as mechanical friction between the bearing and the rotor and they could not start up if the wind speed is not high enough. So reducing starting torque is necessary to start the operation of the wind turbine at low speeds and improves the utilization of the wind energy [3].

The application of magnetic levitation (Maglev) to wind turbines has two main advantages [4]:

1. Starting wind speed is reduced by magnetic suspension due to reduced bearing friction and power output of wind turbine is increased for the same wind speed.
2. The magnetic suspension not only reduces the cost of the bearings and their maintenance but also reduces the downtime of the wind turbine and therefore, improves the overall efficiency of the system.

Up to date, wind Maglev systems use uncontrollable passive magnetic [5] or active magnetic suspensions/bearings [4-6]. These approaches are limited by their working conditions at different wind speeds and high-energy losses. The main challenge of this research is to design novel magnetic suspension system for the VAWT to obtain the ability to operate in both high and low wind speeds. Different wind speeds represent high-fluctuated forces that should be absorbed to keep Maglev working stably and safely in both axial and radial direction.

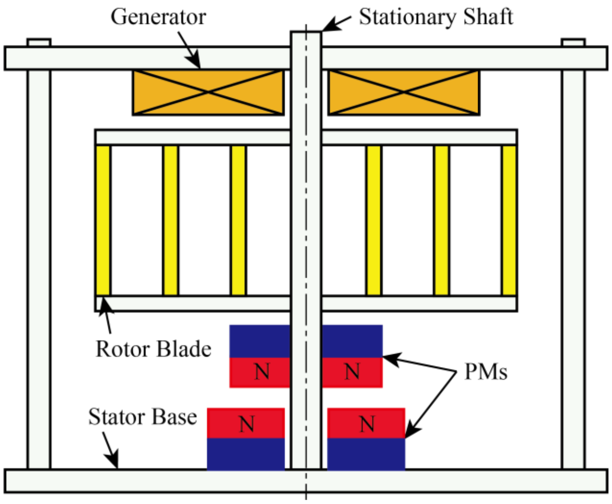


Figure 1. Maglev VAWT using permanent magnet repulsive type.

Although many studies were conducted on the HAWTs [7] [8] and VAWTs [9] [10], most of Maglev wind turbines use a complex structure with high-cost design. Global Wind Energy Technology Company Ltd in Los Angeles has developed a magnetic vertical axis wind turbine [11]. But the small wind turbine with low-cost design and simple structure has not reached to the practical stage yet. Some researchers use a pair of the permanent magnet (repulsive type) to levitate the rotor because it has a simple structure as shown in Fig. 1, however, this system has some drawbacks such as cogging, the effect of the pull force [12] and no stability on the radial direction. Therefore, it is expected that the system will have large vibrations and it could not operate at different wind speeds.

For all the above-mentioned, a novel Maglev VAWT which uses a magnetic suspension system is introduced in this paper to achieve stability in both axial and radial directions and can be operated at different wind speeds with a simple structure and low-cost design.

The rest of the paper is organized as follows: In section II, the proposed model of VAWT is explained in details and the concept of the model is verified using magnetic simulation. While section III analyzes the mathematical formulas of the axial and radial force between two permanent magnets and how the forces change with the air gap, section IV describes the mathematical model and control system to linearize the model around the levitation point. Before introducing the results that prove the ability to obtain the stability in both axial and radial direction in section VI, the details of the test machine and parameters used in the experiment explained in section V.

II. PROPOSED VAWT

In this research, permanent magnet (PM) attractive type passive magnetic bearings (PMBs) is adopted for the suspension of the radial motions of the rotor. A PM attractive type PMB has a simple rotor structure, allowing for the easy design of the rotor, blades and generator system. Moreover, the radial stiffness can be adjusted by changing the air gap between the rotor shaft and permanent magnet, consequently, the critical speed of the rotor can be controlled. This allows VAWT to operate at different rotation speeds.

The proposed VAWT system is shown in Fig. 2. Passive magnetic bearings consist of a button-shaped PM and an iron shaft, where PMs are located over and under the shaft. Because the PMB is unstable for the axial direction, an axial position control coil and displacement sensors are installed. In addition, an electromagnet is installed to change the air gap between the permanent magnets and the shaft.

Figure 3 shows magnetic field simulation for the proposed VAWT model. The rotor will be levitated under the effect of the forces of the upper and lower permanent magnets. The axial coil keeps the shaft stable around the operating point (levitation point). Moreover, the magnetic flux lines created by the air gap control coil will adjust the position of the leaf spring which will change the total air gap between the permanent magnet and the rotor. If the air gap is changed, the radial and axial stiffness will change as illustrated in the next section.

III. MAGNETIC FORCE AND STIFFNESS ANALYSIS

Consider a permanent magnet and iron shaft separated with an air gap. Then a radial force and axial force are discussed when the shaft radially displaced with respect to the permanent magnet as shown in Fig.4. The magnetic attractive force between the shaft and PM can be represented by

$$F_m = \frac{K}{(d_0 + d)^2} \tag{1}$$

where K is the coefficient of magnetic force, d_0 is equivalent air gap of PM and shaft and d is the distance between the shaft and PM and expressed by

$$d = \sqrt{(g_0 + z)^2 + r^2} \tag{2}$$

where g_0 is the air gap between the shaft and PM, and z is the axial displacement of the shaft. The axial and radial forces can be represented by

$$F_a = F_m \cos\theta = -F_m \frac{g}{d} \tag{3}$$

$$F_r = F_m \sin\theta = -F_m \frac{r}{d} \tag{4}$$

Taking Tayler expansion around $z = 0$ and $r = 0$, we have

$$F_a \approx -\frac{K}{(d_0 + g_0)^2} + \frac{2K}{(d_0 + g_0)^3} z \tag{5}$$

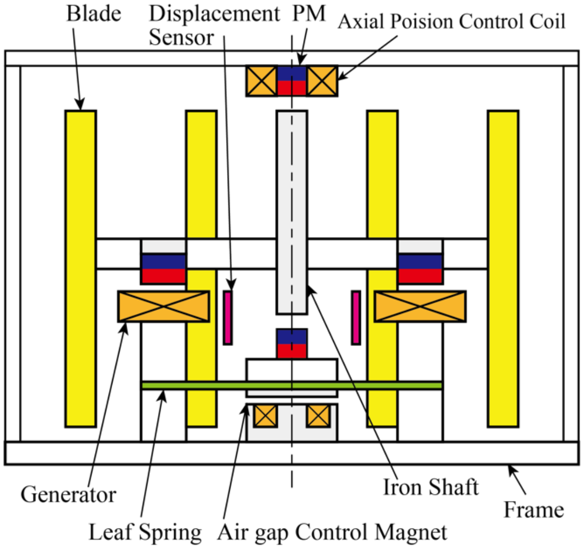


Figure 2. Schematic drawing of the proposed VAWT.

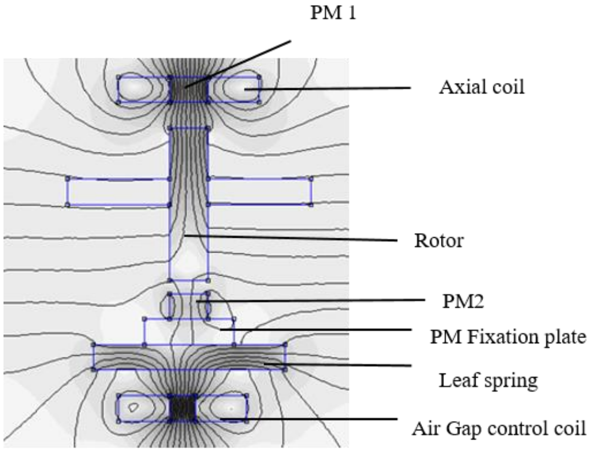


Figure 3. Magnetic simulation for proposed VAWT.

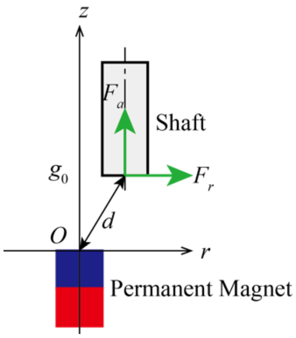
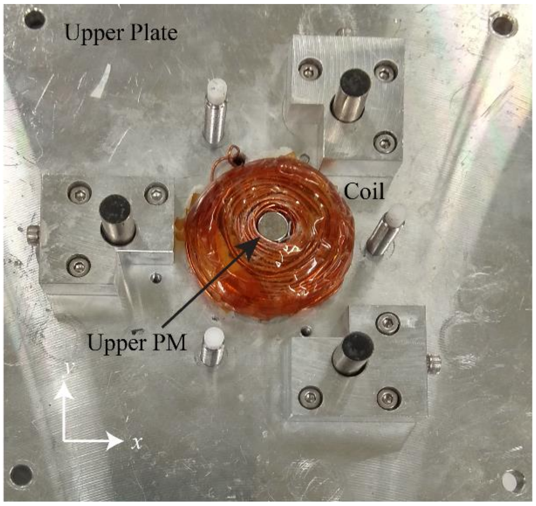


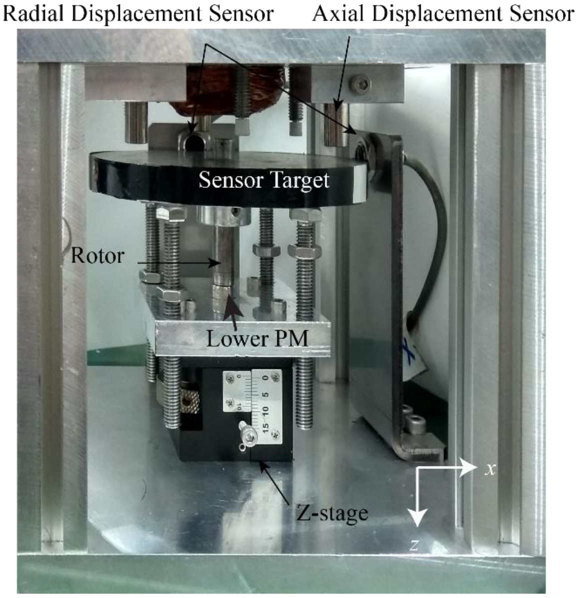
Figure 4. Passive magnetic bearing.

$$F_r \approx -\frac{K}{(d_0 + g_0)^2} r \tag{6}$$

From the above results, the axial direction has negative stiffness, then the feedback control is required for stable levitation, while the radial direction has positive stiffness, then the radial motion is passively stable. The radial stiffness increases by reducing the air gap.



(a) Under view of top plate



(b)Photograph of whole device

Figure 5. Experimental device.

IV. TEST MACHINE

The experimental device is shown in Fig. 5. It consists of the levitated shaft and two neodymium magnets. To examine the stability of the PMBs, an air gap control coil, generator and blades are not installed. The shaft is made of electromagnetic soft iron. The shaft levitates between two PMs. The coil is fixed on the upper side around the PM to control magnetic force, which stabilizes the shaft around the levitation position. The coil is wounded directly around the PM without using iron core. Table I shows the parameters of the PMs and the axial coil used in the experiment.

The rotor has a weight 0.22 kg including the weight of sensor target. Three displacement sensors are used to measure the axial displacement of the shaft, and two displacement sensors are installed on the side of the sensor target to monitor the radial motions. The air gap between the levitated shaft and permanent magnet can be adjusted between 0-5 mm by using z-stage.

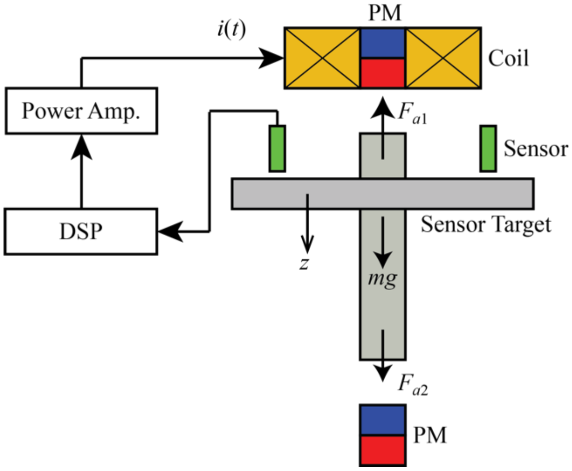


Figure 6. Dynamic control model.

TABLE I. PARAMETERS OF TEST DEVICE

Permanent Magnet Specifications	
Permanent Magnet type	Neodymium
PM thickness	8 mm
PM Diameter	8 mm
Coil Parameters	
Coil Resistance	1 Ω
Coil Inductance (without shaft)	370 μH
Number of turns	300

V. SYSTEM MODELING AND CONTROL

Figure 6 shows the model of the system. The radial and tilt motions are neglected for simplicity. The rotor is subjected to two attractive forces from the upper and lower PMs F_{a1} and F_{a2}. Those forces are linearized around the operating point with respect to the displacement z and the coil current i as

$$F_{a1} = F_1 - K_1 z - K_i i \tag{7}$$

$$F_{a2} = F_2 + K_2 z \tag{8}$$

where F_1 and F_2 are magnetic attractive forces at the levitated position, K_1 and K_2 are axial stiffness of the PMBs and K_i is the force coefficient with respect to coil current.

The equation of motion can be described as

$$\begin{aligned} m\ddot{z} &= F_{a2} - F_{a1} + mg \\ &= mg + F_2 - F_1 + (K_2 + K_1)z + K_i i \end{aligned} \tag{9}$$

At the equilibrium point gravity force and static magnetic forces are balanced, then the equation of motion can be described as

$$m\ddot{z} = (K_2 + K_1)z + K_i i \tag{10}$$

Then the transfer function of plant can be described as follows

$$G(s) = \frac{Z(s)}{I(s)} = \frac{K_i}{ms^2 - (K_2 + K_1)} \tag{11}$$

To stabilize the rotor, the following approximate PD controller is used.

$$G_{PD}(s) = K_P + K_D \frac{s}{T_D s + 1} \tag{12}$$

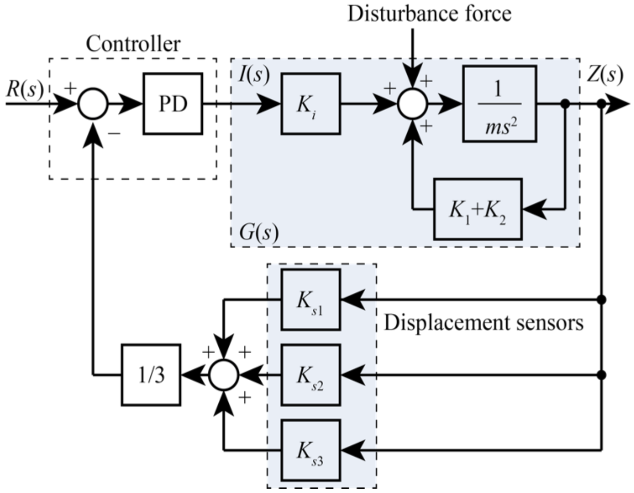


Figure 7. Block diagram of the axial control system.

where K_P is proportional gain, K_D is differential gain and T_D is a time constant of the approximate differentiator. The closed loop transfer function can be approximated to

$$G_C(s) = \frac{Z(s)}{R(s)} = \frac{K_iK_Ds + K_iK_P}{ms^2 + K_iK_Ds + K_iK_P - (K_2 + K_1)} \tag{13}$$

Therefore, when $K_P > (K_2 + K_1)/K_i$ and $K_D > 0$, the rotor is stabilized. The block diagram of control can be describe as shown in Fig. 7.

VI. EXPERIMENTAL RESULTS

Firstly, the characteristics of the PMB are studied. Figure 8 shows the relationship between the air gap and attractive force between the PM and shaft. The axial force is inversely proportional to the square of the air gap. The approximate line was calculated by Eq. (1) with $K = 27, d_0 = 1.2$.

In order to examine the effect of using two PMs on the radial stiffness of the levitated VAWT rotor, two arrangements of PMs as shown in Fig. 9 were tested. Fig. 9 (a) shows one PM arrangement, while (b) shows two PMs arrangement.

Using the set-up shown in Fig. 9 (a) the rotor is levitated successfully as shown in Fig. 10. The rotor is stably levitated at 0.26 mm and a coil current -1.3 A to keep the rotor in the levitation position. The rotor has the stability in the axial direction when subjected to impulse force on axial direction as shown in Fig. 11.

Next, levitation tests were carried out using the setup shown in Fig. 9 (b). Figure 12 shows that the system has the ability to levitate using a coil bonded directly around the permanent magnet from the upper side and passive permanent magnet from the lower side. This coil adjusts the position of the rotor around the levitation point. It is noticed that the system consume power less than the system which uses one permanent magnet during the levitation.

It is important to study the stability of the rotor in both axial and radial direction because the rotor will be subjected to wind forces with different amplitudes and directions during the operation. Figure 13 shows the impulse response of the system which uses two permeant magnets when the rotor is subjected to impulse force on the axial direction. It is clear that the system is stable in the axial direction and the rotor can return to the levitation position.

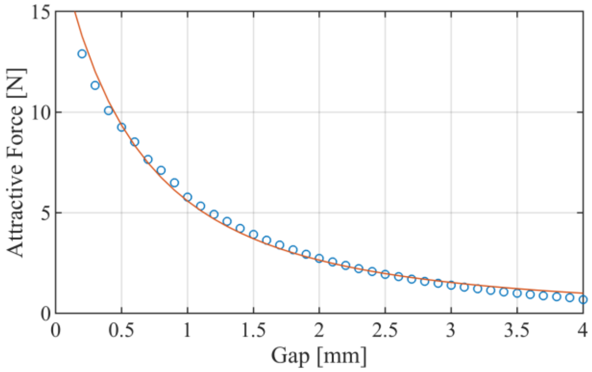


Figure 8. Attractive force between PM and shaft.

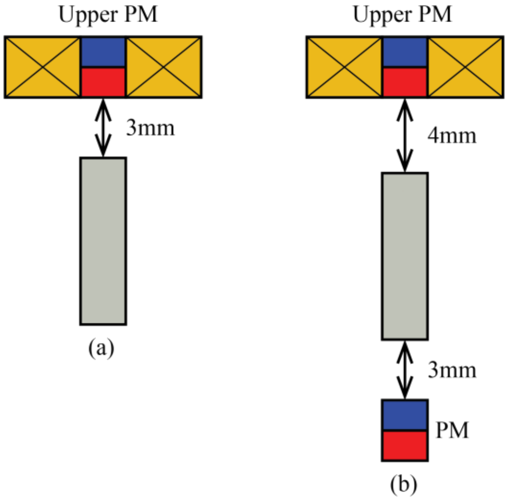


Figure 9. Arrangements of PMs.

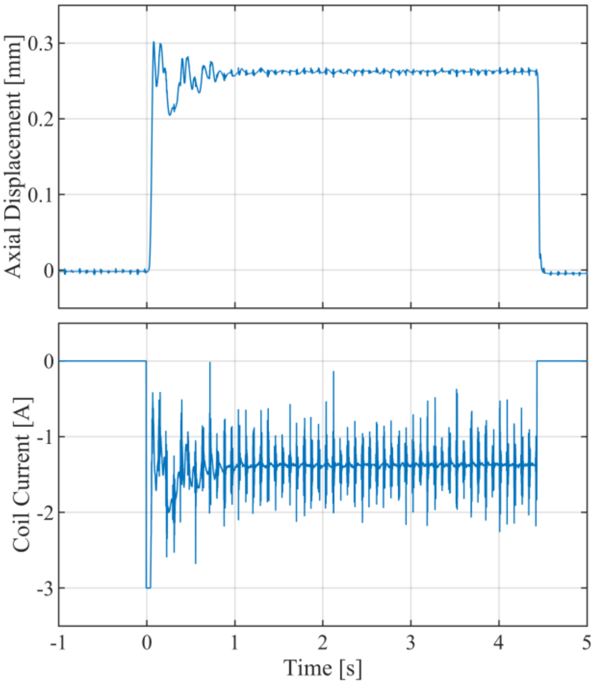


Figure 10. Axial displacement and coil current with one PMB.

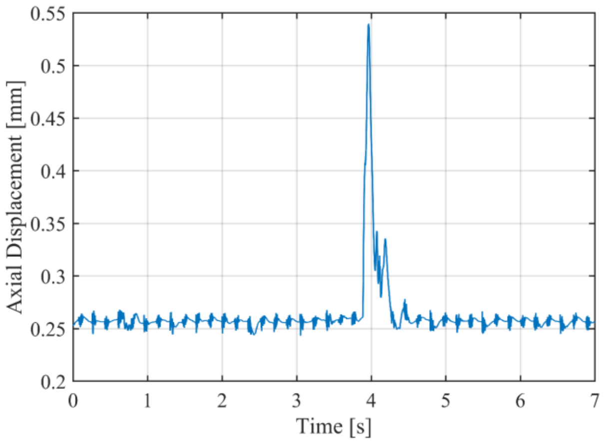


Figure 11. Impulse response of axial direction.

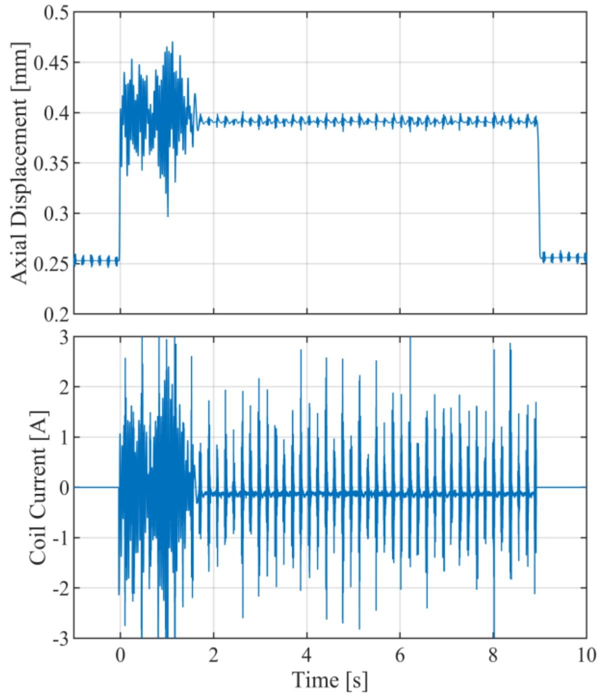


Figure 12. Axial displacement and coil current with two PMBs.

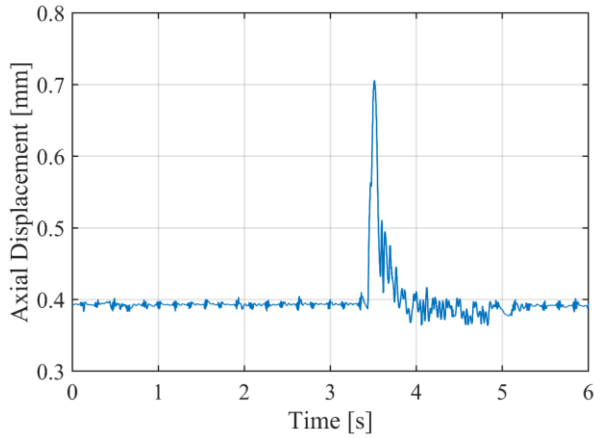
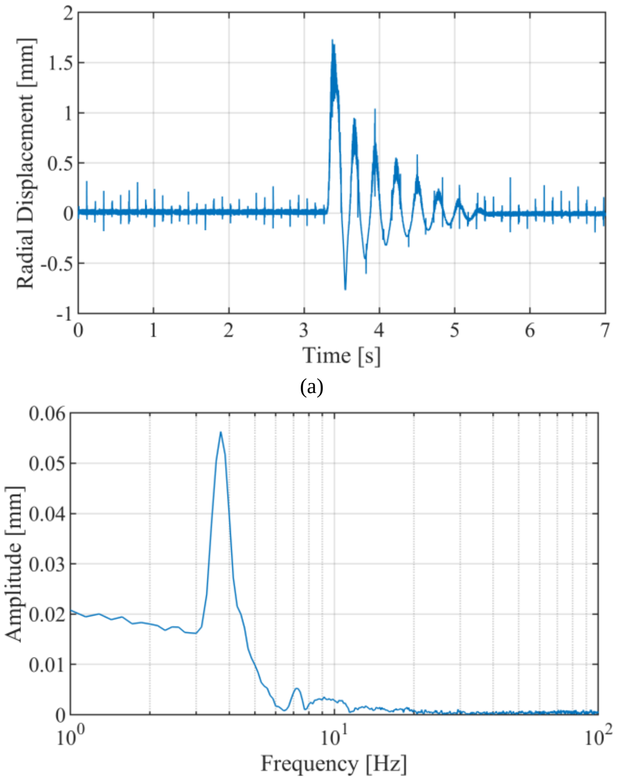


Figure 13. Impulse response of axial direction.



(a)

(b)

Figure 14. Impulse response and FFT analysis in radial direction.

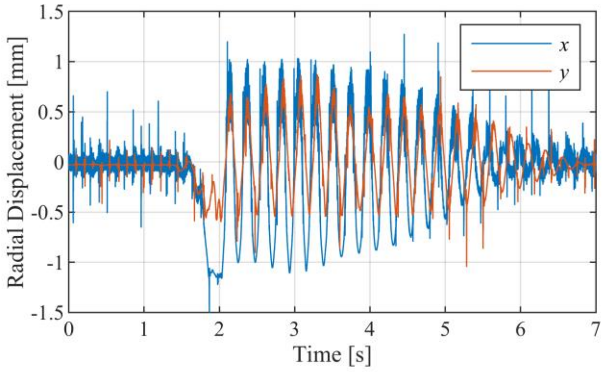


Figure 15. Radial displacements during rotation.

Figure 14 shows the impulse response in the radial direction and FFT analysis. When the rotor was subjected to impulse force in radial direction, it is obvious that the rotor has stability and the rotor can return to the original position. The FFT analysis shows that the natural frequency is about 3.7 Hz and the damping ratio is low.

Figure 15 shows the radial displacement in both x and y-directions during the rotation. When external moment was applied to the rotor at 1.5 sec. In this experiment, the rotor could rotate, however, the rotating speed is too slow because the radial stiffness was not enough. In the future, the radial stiffness should be improved for stable and high speed rotation.

VII. CONCLUSIONS

In this paper, a novel design of Maglev VAWT was proposed with a simple structure and low-cost design compared to other types of Maglev VAWTs. This proposed model was analyzed and verified by a mathematical model and simulation. Non-contact levitation and rotation tests were carried out in the experiment and it was confirmed that the proposed model can be realized to achieve stability during the operation at different wind speeds in both axial and radial direction.

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