INVESTIGATION OF ROADSIDE WIND ENERGY THE HARVESTING MECHANISM

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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Date 06/08/2021……………………

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This dissertation is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/references are appended.

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NAGENTHERAN A/L SATHIASEELAN
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LIST OF ABBREVIATIONS

ABBREVIATION	EXPLANATION
C_D	Drag coefficient
F_D	Drag force
F_L	Lift force
Re	Reynolds number
F_s	Spring force
U_s	Elastic potential energy
T	Oscillation period
L	Length of oscillation rod
g	gravitational constant
N_R	Number of ring gear teeth
N_S	Number of sun gear teeth
S_y	Yield strength of material
SF	Safety factor
S_s	Allowable stress
D	Shaft diameter
T	Torque
L_o	Free length of spring
L_S	Solid length of spring
d	Spring wire diameter
D_o	Spring outer diameter
D_i	Spring inner diameter
D_s	Mean diameter of spring
N_t	Total coils
N_a	Active coils
G	Shear modulus
S_{ut}	Ultimate tensile strength
k	Spring constant
S_{sy}	Maximum allowable stress
C	Spring index
$\tau_{allowable}$	Allowable shear stress
k_B	Wahl's correction factor
F_{max}	Maximum force acting on spring
N	Rotational speed of shaft
I	Moment of inertia
Ω	Angular velocity
α	Angular acceleration
P	Power
RPM	Revolutions per minute
VAWT	Vertical axis wind turbine
HAWT	Horizontal axis wind turbine

ABSTRAK

Angin adalah salah satu tenaga alternatif yang boleh diperbaharui dan telah dituai sejak tahun 1800-an. Kaedah konvensional menuai tenaga angin adalah dengan menggunakan turbin angin paksi mendatar (HAWT) dan turbin angin paksi menegak (VAWT). Untuk penuaian tenaga angin di tepi jalan, VAWT boleh dipertimbangkan untuk menuai tenaga yang tidak digunakan yang dihasilkan dari pusaran kereta. Namun, ketinggian dan reka bentuk bilah VAWT menghadkan prestasi dalam memberikan tenaga pada kecekapan yang lebih tinggi. Oleh itu, projek ini bertujuan untuk mengkaji mekanisme penuaian tenaga angin tepi jalan yang tidak konvensional. Kain pelayar poliester segi empat digunakan sebagai bahan penuai tenaga angin. Mekanisme penuaian tenaga angin yang optima, mekanisme penukaran dua arah ke satu arah dan mekanisme kotak gear direkabentuk dalam SOLIDWORKS untuk menghasilkan tenaga yang berguna. Fabrik layar disimulasikan dalam ANSYS AIM 19.2 Workbench untuk mendapatkan daya angkat yang bertindak di atasnya ketika kenderaan melintas. Pengaruh bilangan kenderaan dan jarak antara setiap kenderaan adalah kajian dalam projek ini. Hasil simulasi ANSYS dari kain layar disahkan dengan teori plat rata nipis dengan aliran udara yang selari. Hasil simulasi digunakan dalam analisis gerakan SOLIDWORKS untuk menganalisis jumlah daya yang dihasilkan. Mekanisme penuaian menghasilkan tenaga maksimum iaitu 37.3278W tanpa gandingan penjana. Titik optimum mekanisme penuaian diperhatikan pada daya angkat 45N untuk menghasilkan daya puncak dan tork. Daya dan tork diperhatikan berkurang setelah daya angkat 45N dan mematuhi hubungan putaran laju-tork. Carta prestasi penjana pemacu langsung digunakan untuk menganggar daya yang dihasilkan. Secara keseluruhan, ketumpatan tenaga mekanisme penuaian adalah 24.9 W/m^2 untuk kawasan permukaan kain layar kira-kira 1.5m^2.

ABSTRACT

Wind is another alternative form of renewable energy that has been harvested since 1800s. Common conventional modes of wind energy harvesting technologies are the horizontal-axis wind turbine (HAWT) and vertical-axis wind turbine (VAWT). For roadside wind energy harvesting, VAWT can be considered to harness the unused energy produced from car wakes and vortex. However, height and optimal blade design of VAWT limits the operational performance to deliver power at higher efficiencies. Therefore, this project aimed to study a new unconventional roadside wind energy harvesting mechanism. A rectangular polyester sail fabric was considered as wind energy harvester material. The optimal wind energy harvesting mechanism, two-way to one-way conversion mechanism and gearbox mechanism were designed in SOLIDWORKS to generate useful output power. The sail fabric was simulated in ANSYS AIM 19.2 Workbench to obtain lift forces acting on it when a vehicle passes by. Effect of number of vehicles and distance between each vehicle were studies in this project. The ANSYS simulation results of the sail fabric were validated with theoretical approach of a thin flat plat with airflow flowing parallel to it. The simulated results were used in SOLIDWORKS motion analysis to analyze amount of power generated. The harvesting mechanism produced maximum output power of 37.3278W without any generator coupling. The optimum point of the harvesting mechanism was observed at lift force of 45N to produce peak power and torque. The power and torque were observed to reduce after lift force of 45N complying the rotational speed-torque relationship. A direct-drive generator performance chart was used to estimate the output power to boost it. Overall, the harvesting mechanism energy density of 24.9 W/m^2 for a sail fabric area approximately $1.5m^2$.

CHAPTER 1
INTRODUCTION

1.1 Project overview

Renewable energy such as wind energy is one of the most resilient and adaptable energy source striving against the recent Coivd-19 lockdown measures. In the first quarter of 2020, global usage of renewable wind energy source rose 1.5% higher than usage in first quarter of 2019. About 3% increase in renewable energy generation was recorded after more than 100GW of solar PV and 60 GW of wind energy projects completed by end of 2019 (Energy & Iea, 2020). Renewable wind energy projects are robust compared to other renewable energies like solar as wind energy is available all day and operate continuously to produce electricity. The installation space requirement factor for the wind energy is low compared to solar (Qiu, Dinçer, & Yüksel, 2020).

Conventional wind energy harvesters such as horizontal-axis wind turbine (HAWT) and vertical-axis wind turbine (VAWT) are still in use to generate electricity. These wind turbines require parts and components from different countries like US, Europe and China. Due to Covid-19 lockdown measures, the manufacturing hubs have slowed down the production of the parts and components (Energy & Iea, 2020). The installation of these turbines is expensive and consumes time. New means of harvesting wind energy mechanisms are also on the verge of development such as piezoelectric flags (Orrego et al., 2017), pyroelectric nanogenerator PNG using the vortex generator mechanism (Raouadi & Touayar, 2018), induction in optimal control of multiple-kite airborne wind energy system (Leuthold, Gros, & Diehl, 2017) and even small scale VAWT wind turbines in roadside (Tian, Mao, An, Zhang, & Wen, 2017).

On that line, roadside wind energy harvesting could be a sustainable solution for energy generation. Wind energy and wakes from moving vehicles are pool of free energy that could be harvested to generate electricity to power road lights, traffic lights, road guide lights and off-grid surveillance camera. Existing HAWT and VAWT wind turbines face some issues in power production when implemented in Malaysia to harvest the wind energy. This is due to limited space and height, low wind speed region and strict regulatory framework requirement in Malaysia (Ho, 2016). New means of harvesting wind energy that mimics the movement of Strandbeest sail (Annie Minoff, 2017) will be focused in this paper that could be a potential design to harvest roadside wind energy.

The focus of the research is to design an optimal wind energy harvesting mechanism that is reliable on factors like power output generation, force acting on sail, cost, installation period, durability, efficiency that is better compared to conventional VAWT wind turbines and ability to work at different vehicles velocities Malaysian roadsides. Thus, study on optimal design of roadside wind energy harvesting mechanism will be carried on in this research paper.

1.2 Project background

The motivation of the research entails the reduction of CO_2 emissions due to wind energy harvester in recent years and Malaysia is on verge of utilizing wind energy. The global emission of carbon dioxide from energy sectors remained little changed in 2019 at 33.2 gigatons (Gt), following two years of increase in year 2017 and 2018. This reduction in CO_2 emissions results from technological enhancements from renewable energy sectors like wind and solar (Energy & Iea, 2020). As technological enhancements growing rapidly, wind energy harvesting will take over the energy sector to replace fossil fuel usage such as coal, petroleum and natural gas which will diminish soon.

The roadside wind energy focussed in this research paper could be a potential solution for a sustainable energy source in electricity generation as it is a pool of free clean energy and available all the time. The conventional wind turbine installation requires high wind speed locations, large installation area, high cost that involves turbine cost, foundation cost, electrical system cost and grid interface cost (Peyre, Hashim, & Yaakob, 2018). These conventional wind turbines also require strict regulations to be installed in Malaysia. Even though, the adequate working conditions and strategic locations for the conventional wind turbines are found, the wind speed conditions are unpredictable in Malaysia due to seasonal changes from Northeast monsoon and Southwest monsoon. The mean wind speed is not more than 2m/s in Malaysia. The minimum wind speed required for the wind turbine to start is 4m/s. This results inconsistent power output and have less efficiency than proposed efficiency due to unfavourable geographic locations and low wind speed in Malaysia.

For Malaysia to venture into wind energy sector, enhancement in wind harvesting mechanism need to be done. The major obstacle to harvest the wind energy in Malaysia is the low wind speed, unfavourable geographic location, high installation and maintenance cost, stricter regulations and requires professional workers. The significance of the present paper is to design an optimal wind energy harvester that that can be placed in median road and harvest wind energy from passing by cars. According to Mohd Yusuf Abdul Aziz, (PLUS chief of operations excellence) around 1.7 million cars passed by in highways in Malaysia every day before MCO was implemented in Malaysia on 18th March 2020 (FMT Reporters, 2020). So, wind energy and wakes from passing by cars in Malaysian highways will contribute to harness that energy instead of wasting it. This will be a new breakthrough in harvesting wind energy and Malaysian highways could be the key to it. This research will overcome obstacles faced by Malaysian government in implementing conventional wind turbines due the reasons stated previously.

1.3 Problem statement

Among the topics discussed above, there are very limited research focusing on wind energy harvesting using sail. Conventional VAWT is ideal for roadside wind energy harvesting but VAWT have low self-starting efficiency, low power coefficient at shorter heights, low self-starting capabilities and faces issues of mechanical vibration that could wear bearings (J. Liu, Lin, & Zhang, 2019). Therefore, the main objective of the present thesis is to design and optimize new roadside wind energy harvester sail that could start from wakes produced from vehicles at lower ground level. The design will highlight the effect of vehicle velocities and lift force acting on the sail to produce maximum power output.

1.4 Objective

The objectives of this research are:

1. To investigate optimal materials for wind energy sail harvester based on multiple factors such as mechanical properties, strength, UV-resistance, flex loss, cost etc.
2. To design a new sail wind energy harvesting model that could generate power from wakes produced by moving vehicles by at various velocities at lower ground level.

3. To determine the performance of the new wind energy harvester such as power output based on number vehicles, distance between vehicles, lift force acting on the sail model and various vehicle velocities.

1.5 Scope of work

The ideal wind energy harvesting mechanism should be lightweight, inexpensive, durable and able to withstand harsh weather conditions. Work scope focussed on the following areas of aerodynamical forces acting on the sail and design criteria of wind energy harvester. Best and optimal material for sail in wind energy harvester based on strength, durability, UV-resistance property, flex loss property and service life need to be chosen. SOLIWORKS will be used to design an optimal wind energy harvester mechanism based on material of harvesting mechanism and maximum angle of oscillation. ANSYS AIM 19.2 Workbench will be used to test the performance of the wind energy harvester model based on lift force on sail during vehicles passing. Only vehicles passing on one side of sail is being simulated as simulation on both sides requires complex dynamic simulation. The power output will be obtained from torque and angular velocity of output shaft that determined in SOLIDWORKS motion analysis.

CHAPTER 2
LITERATURE REVIEW

2.1 Conventional wind turbines

Wind energy harvesting has been done for more than several years in order to generate electricity globally. Some of the industrial wind turbines have been scaled down to be utilized in compact spaces and at low wind speeds. Some researchers study array of VAWT to generate more power output and some researchers tend to invent hybrid wind turbines by implementing modifications. All these studies were carried out to produce more efficient power output from wind turbines from wakes produced from cars. This literature review will focus on energy harvesting from wind energy source only and neglecting other hybrid means like solar, vibration, piezoelectric flags etc. This review also focusing on methods of examining and testing sailcloth with various simulation conditions to obtain crucial parameters like deformation, tensile strength, mechanical properties etc.

In (Tian, Mao, & Li, 2017), VAWT 20-bladed Banki wind turbine was used to obtain the power output from wake generated from cars as shown in Figure 2.1.

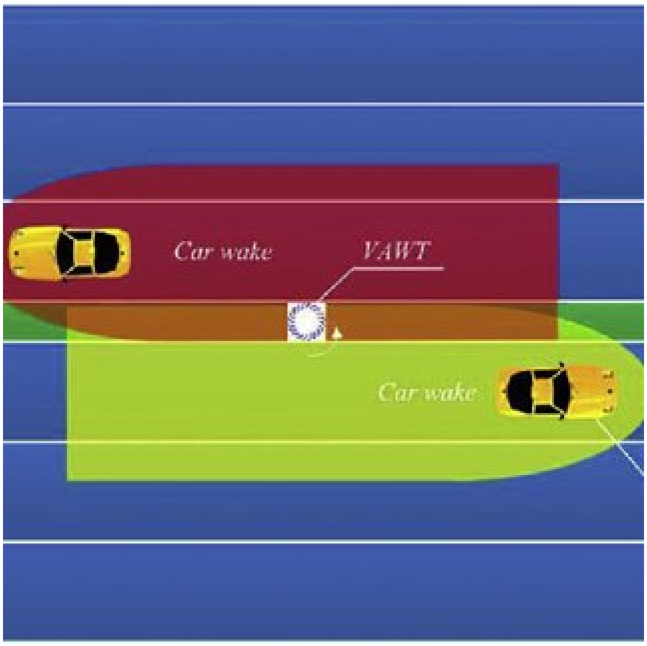

Figure 2.1: Formation of wake for vehicle passing (Tian, Mao, & Li, 2017)

Savonius and Darrieus model wind turbine were not the best choice for the bi-directional movement of cars in highways due to number of blades and aerodynamic properties of the model. Case study of one car passing by is studied and simplified 2D model of the car was used to obtain the wake produced in operation of wind speed. CFD was used in order to solve incompressible Reynolds-Averaged Navier-Stokes (RANS) equations and obtain simulation results from the car model. The vortex produced from the simulation was like Karmen vortex street where repeating swirling vortices patterns were noticed. Crucial parameters like distance of car from the wind turbine, velocity of car and torque of rotor blade were studied for optimal power output generation. The rotor blade able to produce maximum energy of 100.49 J with distance of car from turbine, d = 0.5m, velocity of car, v = 30 m/s and rotor torque of 5 rad/s. The rotor torque fluctuated due to repeated swirling vortices caused by the car wake. A weaker wake was generated by the car when it passes the wind turbine at low velocity. As the distance between car and wind turbine, d increased the rotor performance reduced. The energy output from simulation will vary from the experimental as the simplified car model is not complex as 3D car model and still some of the energy will be consumed by the car to overcome drag force.

In (Tian, Song, & Mao, 2020), wakes produced from high-speed moving vehicle in roads consist some localized amount of wind energy. This paper studied on the turbulent flow that produced from strong wakes of vehicle compared to natural wind flow. Computational fluid dynamic (CFD) was used in order to obtain the effects of wake produced from the different geometry of vehicle on three VAWT like Darrieus rotor, Savonius rotor and Banki rotor. Array of wind turbines were studied for the generation of energy. The 3D Ahmed vehicle model was used to obtain more precise simulation results compared to previous 2D car model. From the CFD simulation, Banki rotor has highest power coefficient against wakes produces from moving vehicles due to greater number of blades compared to Savonius and Darrieus wind turbine models. The performance of rotor array also influenced by the rotor gap. A smaller rotor gap resulted in maximum normalized power coefficient and a larger gap resulted in maximum average power coefficient.

In (Sundaram, Almobasher, Al-Eid, Bazroon, & Abohasson, 2020), research on VAWT to power streetlamps from power generated was carried on. This VAWT turbines utilizes the wind energy caused by the passing by cars from both directions in the road. In this design, permanent magnet synchronous generator (PMSG) was used to produce AC current and an inverter was used to convert it onto DC current to power the streetlamps. The maximum theoretical output calculated was 51.243 W and the maximum experimental power output obtained was 7.032W at wind speed of 8.13m/s.

The huge difference is due to variation in power coefficient, C_p that is highly dependent on blade tip ratio and pitch angle of blade. The power coefficient, C_p for the theoretical is constant throughout the wind speed but on actual experimental condition the power coefficient, C_p changing at every specific wind speed measured at each time.

2.2 Unconventional wind turbines

In (Fazeli, 2016), an unconventional method of harvesting wind energy carried on in a region that is unfavourable for the conventional wind turbine to operate at full capacity and efficiency. Mechanical oscillatory concept was utilized to harness the wind energy by optimizing the sail design, body structure, oscillatory mechanism and power conversion system as shown in Figure 2.2.

Figure 2.2 : Mechanical oscillatory wind energy harvester (Fazeli, 2016)

Two prototypes were fabricated to perform CFD simulations. The 2.5X scaled final prototype able to generate peak power of 1.44mW power and 600 times efficient compared to the first prototype. The sail flipping mechanism switches the direction of sail according to wind directions and the overall structure optimizes the design from two-way rotation to one-way rotation. The conversion from mechanical energy to electrical energy with aid of the power conversion with gears. Only 16.4W from calculated 82 W power could be generated from the sail and the power losses occur at power conversion area and generation area. 4W and 1W of power loss was observed at the bevel gear transmission and current generation at the output shaft. The expected output further reduced by the constant changing of sail orientation from the wind direction.

2.3 Fabric testing

In (Calì et al., 2018), Reynolds Averaged Navier Stokes simulation (RANS) and Shear Stress Transport (SST) turbulence model was used to evaluate and compute the drive force and side force exerted on the sailcloth during operation. Elastic modulus, Poisson's ratio, damping factor and proof stress of Nylon SK75 sailcloth were examined with experimental setups of static and cyclic tensile tests. ZwickRoell Z100 twin column tensile testing machine and TestXpert® v11.02 software was used to carry out static tensile stress. Instron 8501 servo hydraulic dynamic testing machine and FastTrack 2 software were used to carry on cyclic tensile test on the sailcloth sample. Sail deflection was examined by inputting lift and drag forces in Computational Structural Mechanics (CSM) analysis. In this study, inconsistent wind velocity caused problem in retaining the design shape of sailcloth and unfavourable performance delivered. Vortex formed around the sailcloth also caused some performance difference during operation.

In (Ghelardi, Freda, Rizzo, & Villa, 2018), a square shaped Dacron sail sample was tested in wind tunnel with uniform flow regime. Several tests were carried out at different wind velocities in the wind tunnel. As shown in Figure 2.3, the sample Dacron sailcloth was set up with aid of beam and flat bar.

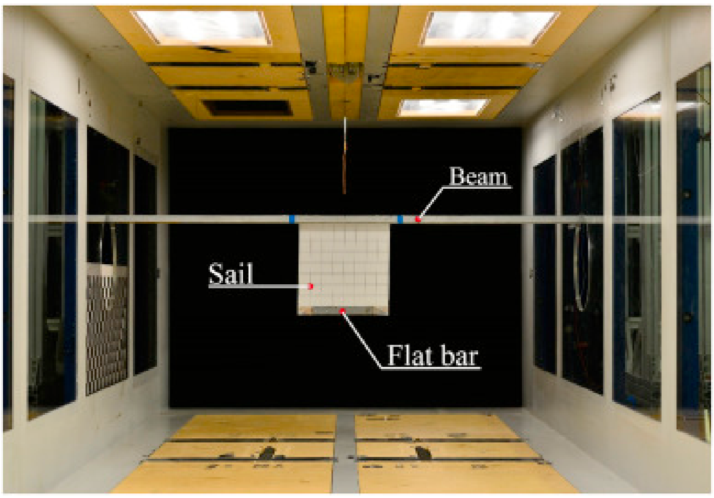

Figure 2.3: Wind tunnel testing on Dacron sail sample (Ghelardi et al., 2018)

Young's modulus, shear modulus and Poisson's ratio of the sailcloth were used as inputs obtained from mono-axial tensile tests for numerical analyses. Finite Volume Method (FVM) based on Reynolds Averaged Navier Stokes (RANS) and Finite Element Method (FEM) were used for structural field analysis. Zwick Roell Z020 testing-machine was used to carry out mono-axial tensile test until breaking point of sample. Stress-strain curves were used to evaluate the deformation of sample sailcloth Dacron during experiment. Warp fibers (vertical along sailcloth) exhibits highest breaking load at lowest strain load. Bias fibers (diagonal along sailcloth) exhibits highest deformation at same load as warp fibers exhibit. Wind tunnel experiments also carried at smooth flow conditions at temperature of 24.5 °C, with 65% of relative humidity and a longitudinal turbulence intensity of 0.25%. ADINA™ 9.2.0 environment was used to create a virtual wind tunnel conditions to test the samples. From the study, oscillations of sample sailcloth were severe when wind velocity in the wind tunnel increased to 10.4m/s. Out-of-plane oscillations were observed due to high wind velocity produced.

2.4 Aerodynamic loadings

The drag force acting on the flat plate will be parallel to the airflow direction. The lift force acting on the flat plate will be perpendicular to the airflow direction. The fabric used in the harvesting mechanism is treated as flat plate with the airflow acting parallel to it. The pressure drags on the flat plate parallel to the airflow is zero that makes the drag coefficient equivalent to friction coefficient. So, the drag force will be equivalent to friction force acting on the flat plate. In accordance to (Cengel & Cimbala, 2010), as the Reynold's number is between the transition region of laminar and turbulent boundary layer, the drag coefficient of fabric is :

$$C_D = \frac{0.074}{{Re_L}^{1/5}} - \frac{1742}{Re_L} \quad [2.1]$$

The drag force acting on the fabric is :

$$F_D = \frac{1}{2} p v^2 A C_D \quad [2.2]$$

The fluid flowing parallel to the fabric is air with density at standard atmospheric pressure of 101.325 KPa at 15°C. The Reynolds number will increase when the airflow velocity increases, and the Reynolds number adversely affects the drag coefficient of fabric.

In (Lichtneger & Ruck, 2018), various types of vehicle models were simulated to obtain the aerodynamical effect acting on a divider wall at different vehicle velocities. A pressure field was generated when a vehicle passes by a wall and this pressure field was influenced by vehicle passing distance, velocity and size of vehicle. Overpressure zone created at the vehicle frontal area and suction zone created at the leading trail of vehicle. The wake and forces generated at the vehicle rear area were weak and unstable compared to aerodynamical loadings at the frontal area. This sudden surge in pressure will cause a pressure jump at the vehicle rear area or space in between two vehicles in vehicle train cases. The slipstream near the wall will cause an unsteady transitional turbulent flow layer. Length of vehicle and streamline of vehicle are crucial in influencing the aerodynamical loadings acting on the wall. More streamlined passenger vehicles induced lower aerodynamical loadings on the wall compared to blunt and box-shaped vehicles like truck. Longer vehicles have two pressure jump points and shorter vehicles have only one suction point.

2.5 Bearing

Bearings are crucial component in wind energy harvester as bearings will reduce the friction between oscillating shaft and housing that supports the oscillating part for a smoother rotation or oscillation. Spherical roller bearings and needle roller bearings become an option for low speed application for this present project. Spherical roller bearings are suitable for large radial loads and low speed applications. Spherical roller bearings are typically used for low friction applications and permits angular misalignment for wind energy applications (Z. Liu & Zhang, 2020). However, these spherical roller bearings are effective in applications involves moderate to high speed full rotation and high load capacities such as gearbox mechanism that is discussed in section 3.2.4.

As shown in Figure 2.4, the needle roller bearings are suitable for low speed applications and back and forth oscillating loads (He, Luo, & Liu, 2014). This is possible where the needle in the bearing operates for very short periods before the oscillating load from the wind energy harvester reverses. Thereby, this permits the needles in the bearing to move back to the original position parallel to the shaft axis

(Carlos Gonzalez, 2015). Cages can be used to improve and guide the needles for better accuracy. Grease with antiwear and extreme pressure additives can be implemented to prevent oscillating damage to the bearing (Mary Beckman, 2020). The size of the needle roller bearings is relatively smaller that makes it suitable for working in limited radial space . Thus, needle roller bearings are considered in this present paper to provide smooth oscillation for the oscillating mechanism that is discussed in section 3.2.2.

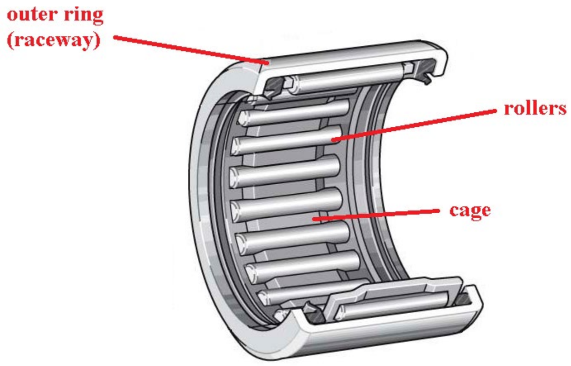

Figure 2.4 : Needle roller bearing

2.6 Spring

Springs will be used in the oscillating mechanism to constraint the angle of oscillation of the wind energy sail. Compression springs will be appropriate for this application but the buckling in springs will affect the performance of the system. Hourglass compression springs and barrel compression springs will be suitable to avoid this buckling problem. Hourglass springs considered as it can handle more weight and prevent lateral movements. The hourglass springs able to reduce resonance and vibration as well due to the conical shape of the springs with uniform pitch and increasing natural period of vibration (Acxess Spring, 2020). The hourglass compression springs shown in Figure 2.5, are tapered so that both ends are larger than the middle that resembles a concave shape. Hourglass compression springs have the some advantages over the barrel springs that the enlarged coils in the hourglass compression springs are better suited in keeping the spring centered on a larger diameter holes (Templeman Co., 2020). The lateral forces acting parallel to the contact point is lower for the hourglass spring compared to the conical spring (Bobade & Yadav, 2017). Thus, hourglass compression springs will be used in the oscillating mechanism to limit the oscillating angle of the sails.

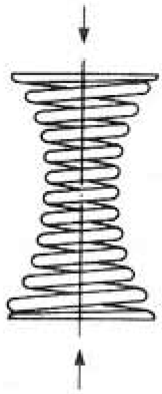

Figure 2.5 : Hourglass compression spring

The spring force will be computed based on the Hooke's law based on the spring constant, k and displacement of spring, x. The negative sign indicates that the spring force is opposite to the displacement of the spring. The spring force is :

$$F_s = -kx \qquad [2.3]$$

The elastic potential energy from the springs is directly proportional to the square of change in displacement and spring constant. The elastic potential energy of the spring is the energy consumed by the spring during the operation of oscillating mechanism. The elastic potential energy of spring is :

$$U_s = \frac{1}{2}kx^2 \qquad [2.4]$$

2.7 Conversion mechanism and gears

The sliding gears (Thang, 2014) one of the concepts of converting the two-way rotation to one-way rotation. The sliding gear design can be opted for the conversion mechanism, but this gear will take some time for direction changeup during back and forth oscillations of sail. This could eventually limit the smooth energy conversion.

The conversion mechanism needs to convert the two-way rotation from the wind energy harvester to one-way rotation. The gear conversion mechanism will consist of bevel gears, ratchets, keyholes, central input rod and pawl as shown in Figure 2.6. Bevel gears will be aligned perpendicular to each other and central shaft will pass through two parallel bevel gears. Pawl will be used to engage the ratchets connected to the bevel gears for one-way rotation only. This mechanism will ensure two-way oscillations to be converted into one-way rotation for electrical energy conversion in the generator part. Noise is one of the unintentional disturbances involved in the conversion process. This problem can be overcome by using appropriate materials and gear ratios for the gears. Plastic have quiet operation in light loads and for low speed applications.

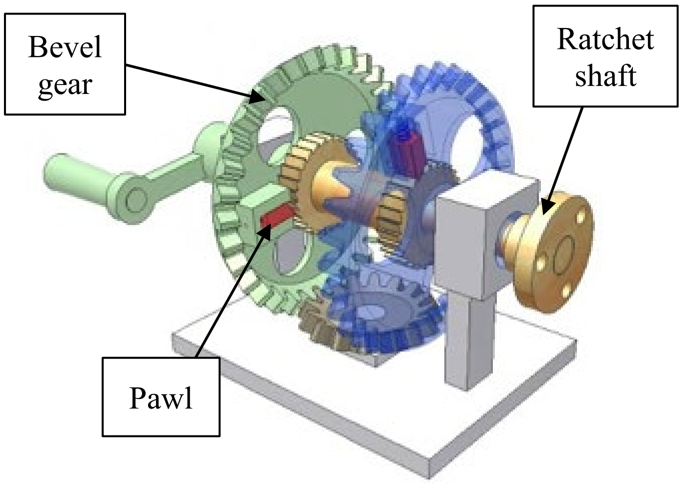

Figure 2.6: Bevel gear conversion mechanism (N.Thang, 2018)

Overall, most researchers able to generate significant power output by adding few modifications to the VAWT. As from the literature review, there are few researchers carry on experiment on wind energy harvesting using sail movement. Various unconventional ways of wind energy harvesting mechanisms could be a competitive solution for the long run against the conventional wind turbines. Wind energy harvesting from sail is a new idea in generating current from wakes produced from passing by vehicles. Although, this research paper focus on new means of harvesting wind energy that mimics the Strandbeest sail movement, some important case studies and simulations can be referred. Study of the wake produced by the passing by cars will aid in finding optimal design to harvest the wind energy. Velocity of cars, geometry size of vehicles and distance of vehicles from the wind energy harvester need to be considered in this present paper to obtain accurate results from sail wind energy harvester. Testing and simulation on sail materials using CFD also need to be done to obtain best material for wind energy harvesting in roads.

Table 2.1 : Summary of review papers on wind energy harvesting and fabric

<table>
<tr><th colspan="2">Type</th><th>Author</th></tr>
<tr><td rowspan="3">Conventional wind turbines</td><td>VAWT</td><td>(Tian, Mao, & Li, 2017)</td></tr>
<tr><td>VAWT</td><td>(Tian et al., 2020)</td></tr>
<tr><td>VAWT</td><td>(Sundaram et al., 2020)</td></tr>
<tr><td>Unconventional wind turbine</td><td>Wind sail with oscillatory mechanism</td><td>(Fazeli, 2016)</td></tr>
<tr><td rowspan="2">Fabric testing</td><td>Nylon SK75</td><td>(Calì et al., 2018)</td></tr>
<tr><td>Dacron</td><td>(Ghelardi et al., 2018)</td></tr>
<tr><td rowspan="5">Software's & Equipment's</td><td>CFD</td><td>(Tian, Mao, & Li, 2017)</td></tr>
<tr><td>CFD</td><td>(Tian et al., 2020)</td></tr>
<tr><td>TestXpert® v11.02 software
-ZwickRoell Z100 twin column tensile testing machine
Instron 8501 servo hydraulic dynamic testing machine
-FastTrack 2 software
-Computational Structural Mechanics (CSM)</td><td>(Calì et al., 2018)</td></tr>
<tr><td>Zwick Roell Z020 testing-machine
ADINA™ 9.2.0 environment</td><td>(Ghelardi et al., 2018)</td></tr>
<tr><td>CFD
CAD software</td><td>(Fazeli, 2016)</td></tr>
<tr><td>Aerodynamical loadings</td><td>Lift force and drag force</td><td>(Lichtneger & Ruck, 2018)</td></tr>
</table>

Bearings	Spherical roller bearings	(Z. Liu & Zhang, 2020)
	Needle roller bearings	(He et al., 2014)
Springs	Hourglass springs	(Acxess Spring, 2020) (Bobade & Yadav, 2017)
	Barrel compression springs	(Templeman Co., 2020)
Conversion mechanism	Bevel gear conversion system	(Thang, 2014) (N.Thang, 2018)

CHAPTER 3
METHODOLOGY

3.1 Case study

Multiple design ideas and experiment setups for the wind energy harvester were generated from the study of research papers and articles. All studies stated in Chapter 2 included in the design of wind energy harvesting mechanism, validation with Ahmed model, simulation setup for the proposed model, lift force acting on sail, bearings and springs. As shown in Figure 3.1, two main softwares were used to simulate the operational condition of the project.

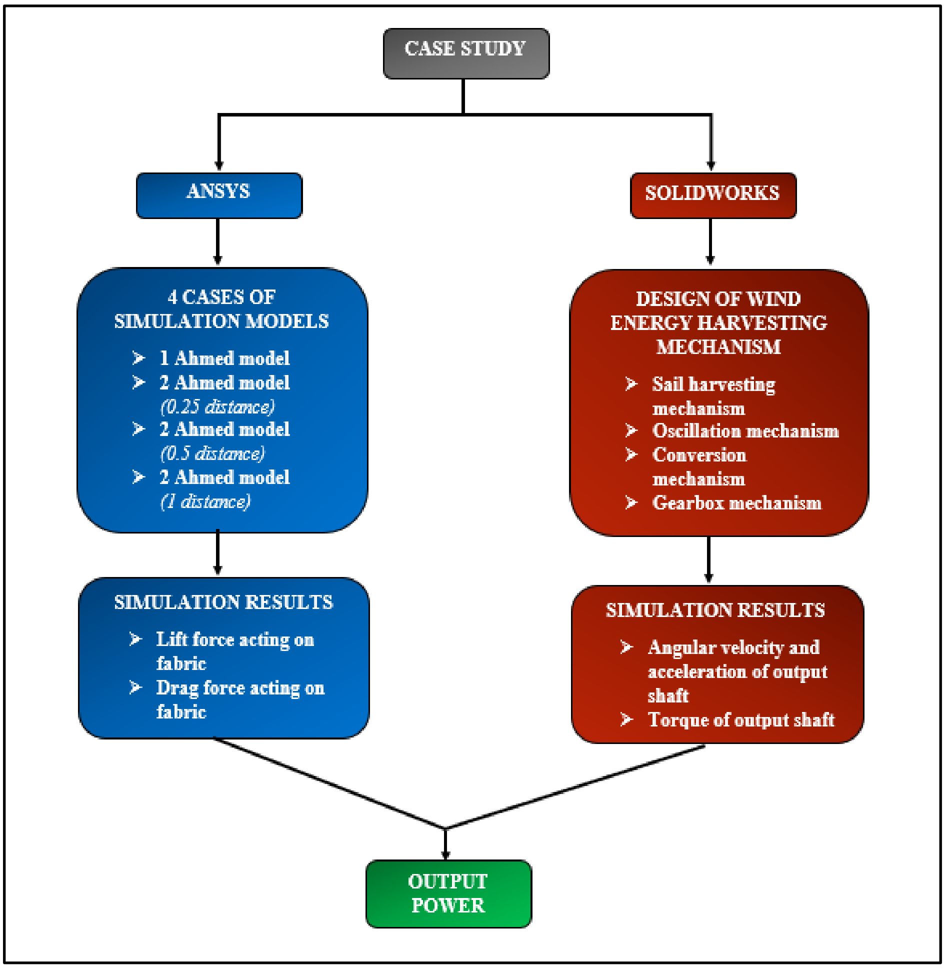

Figure 3.1: Project flow chart

ANSYS AIM 19.2 workbench was used to simulate the effect aerodynamical forces acting on the fabric of harvesting mechanism when a vehicle passes by at different velocities. The simulation model consists of 4 different scenarios such as 1 vehicle passes by and 2 vehicles with 3 different distances between each vehicle as shown in APPENDIX C. The aerodynamical forces such as lift force and drag force acting on the fabric were obtained using the simulation setup discussed in Section 3.4. SOLIDWORKS was used to design the roadside wind energy harvesting mechanism that comprises of sail harvesting mechanism, oscillating mechanism, conversion mechanism and gearbox mechanism discussed in Section 3.2. Simulation results such as angular velocity, acceleration and torque of output shaft were obtained using simulation setup discussed in Section 3.5. Finally, the total power produced by the wind energy harvesting mechanism was computed and tabulated in Chapter 4.

3.2 Design of wind energy harvester

As shown in Figure 3.2, the design idea was inspired from sail used in Strandbeest kinetic sculpture that was powered by wind with few modifications in the harvesting mechanism.

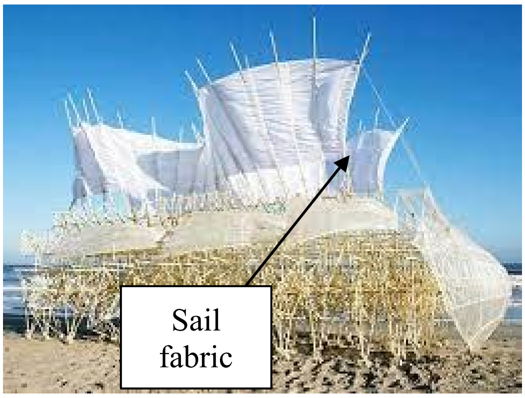

Figure 3.2: Strandbeest sail fabric

3.2.1 Sail harvesting mechanism

Pressure difference produced from passing by vehicles in the roadside will be captured by the sail of the wind energy harvester. The sail will be oscillating in a back and forth direction due to pressure difference created by the vehicles on both sides of the roads. This two-way oscillation of sail will be converted to one way-oscillation through a bevel gear conversion mechanism. The converted rotation will be used to generate electricity with aid of generator and motor.

The wind energy harvester system was designed using SOLIDWORKS. As shown in Figure 3.1, the design consists of wind energy harvesting mechanism and a gearbox setup. The gearbox consists of two-way to one-way conversion system (Figure

3.8), power transmission mechanism (Figure 3.13) and planetary gear mechanism (Figure 3.16). The basic parts required for the harvesting mechanism are Dacron sailcloth, aluminium rods, supporting shaft, central shaft and additional supporting ribs. The basic parts required for the oscillating mechanism are customized journal housing of the oscillating mechanism components, hourglass springs, needle roller bearings, cage and rollers. The basic parts required for the bevel gear conversion system are bevel gears, gear housing and pawls.

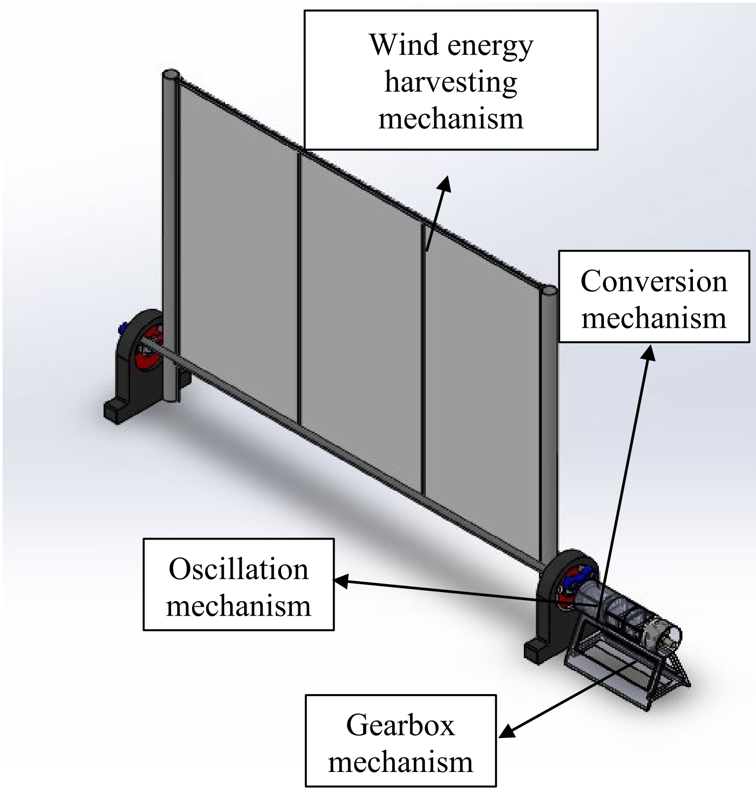

Figure 3.3: Roadside wind energy harvesting system

As shown in Figure 3.3, the wind energy harvesting mechanism consists of Dacron fabric that will capture the wind energy and wakes from the vehicles passing by in form of lift force induced on it. Turbulence created around the vehicle body create a pressure difference that will induce a lift force on the sail fabric. Additional ribs were added to provide structural integrity for the wind harvester model. Steel plates were added in between the sails fabric to hold it stiffer during operations. The Dacron sailcloth will be hold stiffer by the aluminium rods with aid of flat steel mounted on the rods. All the aluminium rods will be connected by a central shaft that will be passing through the needle roller bearing. Two supporting shafts will be positioned at the side to provide structural stability for the harvesting mechanism. These shafts will be passing through the holes in the upper part of the journal housing sail holder as shown in Figure 3.4. Additional ribs were provided to the supporting shafts to avoid wobbling effects from the shafts.

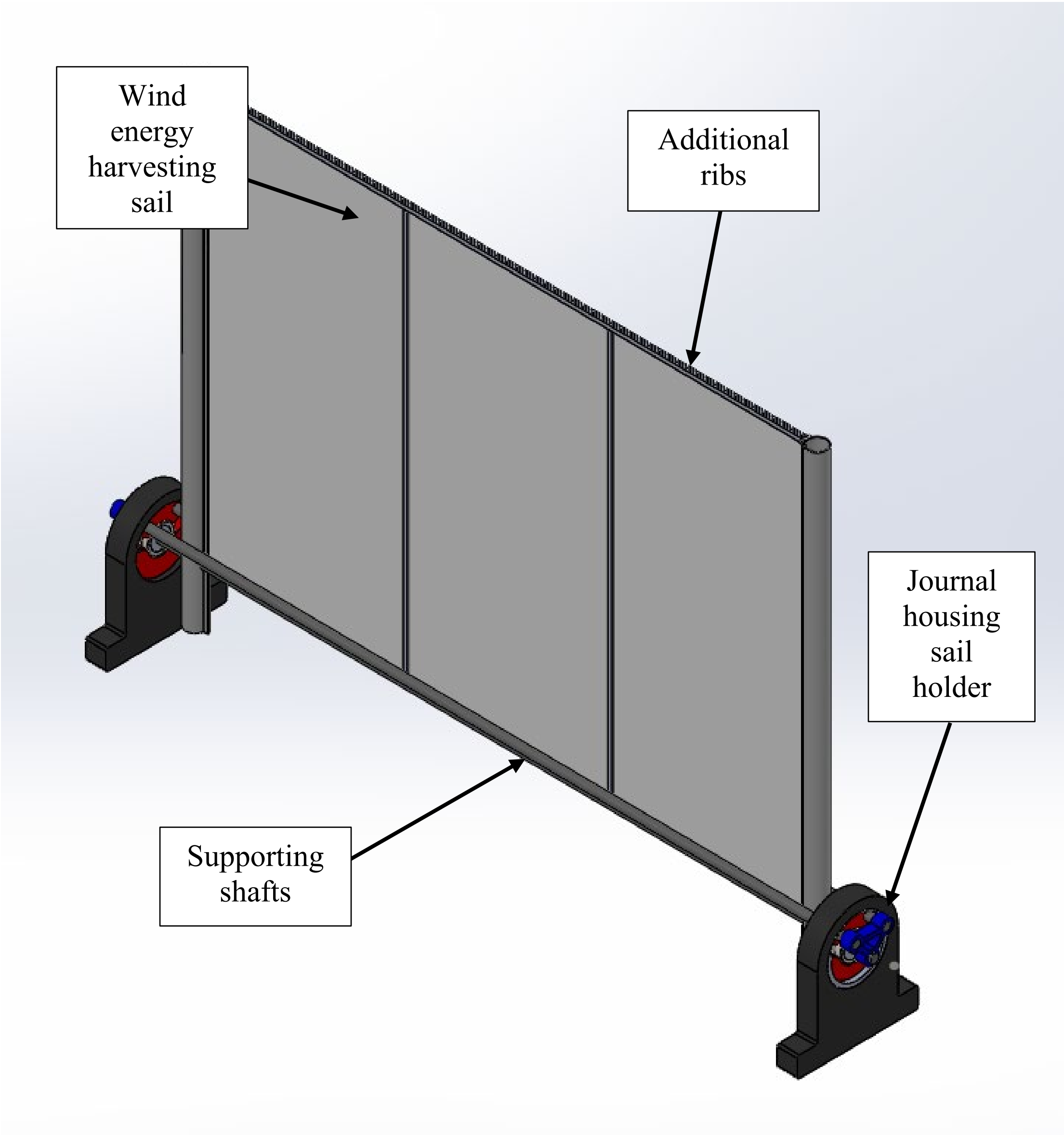

Figure 3.4: Wind energy harvesting mechanism

As shown in figure 3.5, hourglass springs and customized ribs on housing of oscillating mechanism were used to limit the oscillation angle of wind sail harvester within range of 10 degrees only. This boundary was set even before design iteration as this design need to be safe for vehicles travelling near the wind energy harvester. The height of sail from the central shaft is set as 1m to complete approximately 36 cycles of oscillation in 1 minute. The oscillation of the harvesting mechanism is treated as oscillation of simple pendulum.

The complete oscillation period, angular velocity and number of revolutions of the harvesting mechanism is shown in the calculation below,

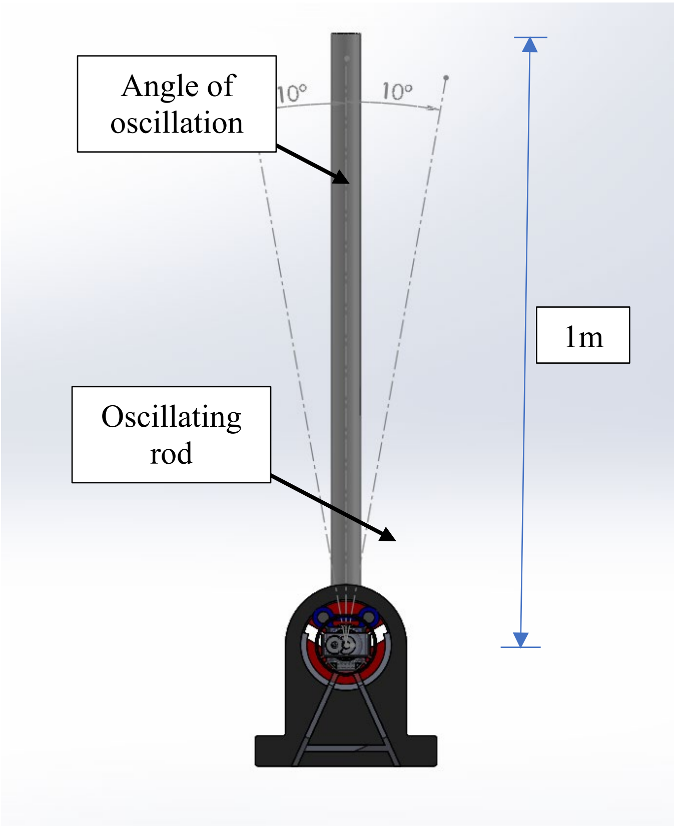

Figure 3.5 : Angle of oscillation of harvesting mechanism

Assumptions

1. The oscillation of the harvesting mechanism is treated as oscillation of inverted pendulum below 15 degrees.
2. No damping occurred during the testing period is assumed as vehicles constantly passing on both sides of roads consistently providing force on the harvesting mechanism.
3. The mass of the oscillating rods also considered for the calculation in accordance to (Law, 2010).

The period of the harvesting mechanism can be calculated using equation below,

$$T = 2\pi\sqrt{\frac{2}{3}\frac{L}{g}} \qquad [3.1]$$

where

L - length of harvesting mechanism connected from centre of oscillating mechanism to the tip

g – gravitational constant

$$T = 2\pi\sqrt{\frac{2}{3}.\frac{1m}{9.81}}$$

$T = 1.6379\ s/\text{cycle}$

Frequency = 0.6105 Hz

The number cycles the harvesting mechanism completed in one minute is:

$$\text{Number of cycles per minute, N} = \frac{\text{1 Minute}}{\text{T}} \qquad [3.2]$$

$$\text{N} = \frac{\text{60s/minute}}{\text{1.6379 s/cycle}}$$

N = 36.63 cycles/min

3.2.2 Oscillating mechanism

As from Figure 3.6, the oscillating mechanism consists of needle roller bearing, hourglass springs, cage and rollers, upper and lower part of oscillating mechanism and housing of oscillating mechanism.

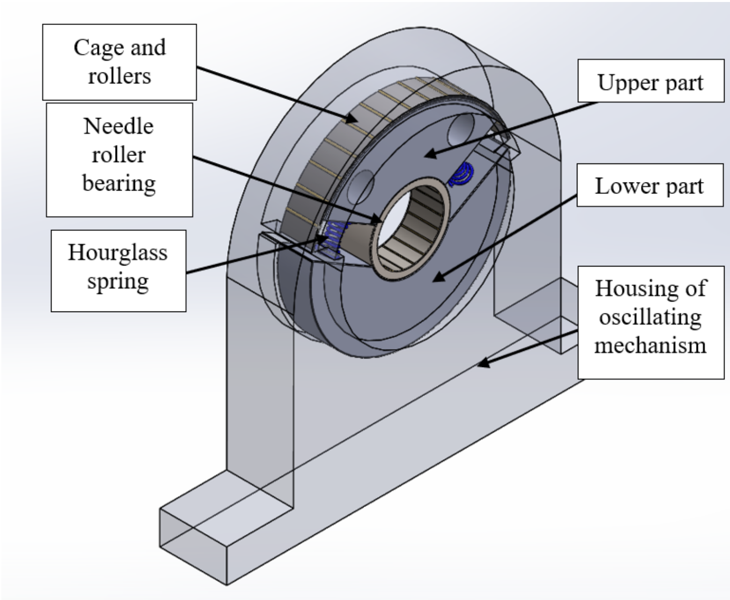

Figure 3.6: Components of oscillating mechanism

The housing will hold all the components in position in the oscillating mechanism. The housing will be fixed on the median road surface and hold the wind energy harvesting sail above the ground level to ease the oscillation movements. The lower part of the oscillating mechanism will be fixed at the bottom of the needle roller bearing and the upper part positioned on top of needle roller bearing. Spring holders are provided at the lower part for the hourglass springs to be positioned correctly. Supporting shafts will be positioned concentric to the holes in the upper part. Cage and rollers were used at the top surface of the upper part to reduce friction during oscillation as shown in Figure 3.7. The needle roller bearing positioned concentric to both lower and upper part and central shaft from the wind energy harvesting sail will pass through the bearing.

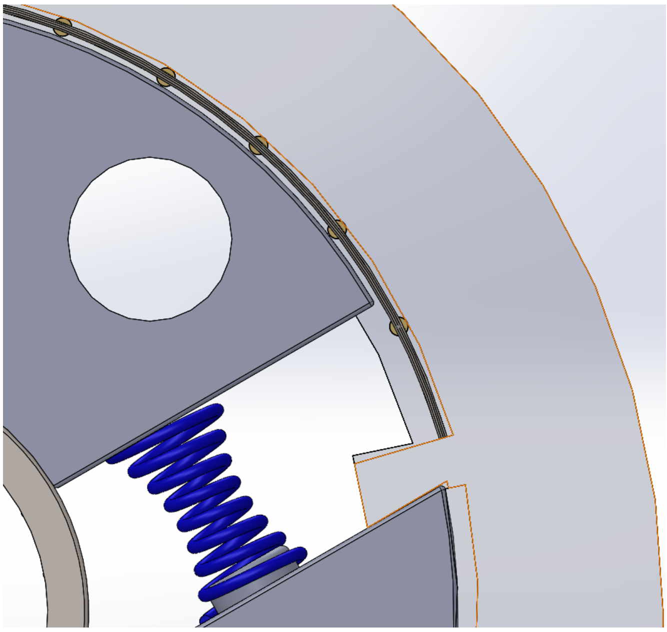

Figure 3.7: Roller mechanism for upper part

The oscillating mechanism will be used to limit angle of oscillation of the sail from the wakes produced from the passing by vehicles. A needle roller bearing was used at the centre of upper and lower part of oscillating mechanism and allow rotation of central shaft from the sail. The lower part will be fixed to the base and the upper part will be the only oscillating component in the design. The hourglass compression springs were used to create an oscillating motion and limiting the angle of oscillations.

3.2.3 Conversion mechanism

The conversion system consists of 3 bevel gears, ratchet shaft, two pawls and needle roller bearings as shown in Figure 3.8. The central shaft from the harvesting mechanism will mounted through the main bevel gear with aid of keyway. The ratchet shaft designed concentrically to the centre of main shaft and held with aid of two needle roller bearings mounted in the centre of main bevel gear. The bottom bevel gear positioned with 50mm mounting distance from other two bevel gears positioned perpendicularly as shown in Figure 3.9. The bevel gears are made of 1045 Carbon steel and the gear tooth are hardened to avoid teeth breakage during operation. The conversion mechanism holder is designed in a way to be fitted inside 10cm tube. The holder will aid in positioning the bevel gears concentric to the main shaft from the harvesting mechanism. Circular geometry of holder will ease in assembly and disassembly for maintenance operations.

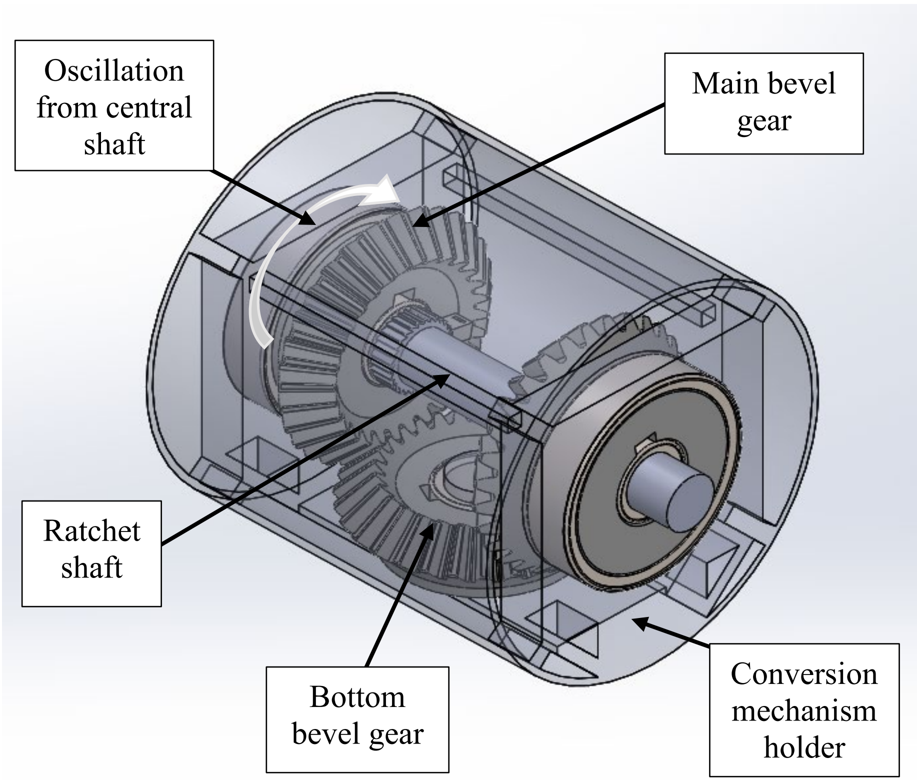

Figure 3.8: Two-way to one-way bevel gear conversion system

As shown in figure 3.9, a keyway is also designed for the 20mm central shaft to be mounted in it to allow oscillations. An outer diameter of 62.8mm will be appropriate when fitted horizontally inside the conversion mechanism holder. A slight lift for the