PERFORMANCE CHARACTERISTICS OF CAR ALTERNATOR COUPLED DIRECTLY TO MICRO GAS TURBINE (MGT)

By:

LIM CHING HOCK

(Matrix no.: 125020)

Supervisor:

Dr. Khaled Al-Attab

May 2018

This dissertation is submitted to

Universiti Sains Malaysia

As partial fulfillment of the requirement to graduate with honors degree in

BACHELOR OF ENGINEERING (MECHANICAL ENGINEERING)

School of Mechanical Engineering

Engineering Campus

Universiti Sains Malaysia

DECLARATION

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

Signed ..... (LIM CHING HOCK)

Date .....

Statement 1

This thesis is the result of my own investigation, expect where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/reference are appended.

Signed .....(LIM CHING HOCK)

Date .....

Statement 2

I hereby give consent for my thesis, if accepted, to be available for photocopying and for interlibrary loan, and for the title and summary to be made available outside organizations.

Signed ..... (LIM CHING HOCK)

Date .....

ACKNOWLEDGEMENT

A special thanks and from my most sincere gratitude to my final year project supervisor, Dr. Khaled Al-Attab for all his knowledge sharing, suggestion and guidance. The project will not able to be completed in time without Dr. Khaled assistance along my side. It is a great honour to work and complete the project under supervison of Dr. Khaled.

I would like to express my appreciation to Ibrahim I. Enagi, PhD student of Dr. Khaled who is working with me throughout this project. His cooperation, knowledge, advices and assistance play an important role in the success of this project. The time we spent working and thinking together have paid off upon the completion of project.

Finally, I would like to thanks to Mr. Mohd Zafril Khan, Mr. Mohd Zalmi Yop, Mr. Mohd Sani Sulaiman, Mr. Abdul Halim Che Aat, and Mr. Hazwan Mohamad for their generous and willingness assistance in guiding me in the fabrication process. The readiness of them to share their experience in tool handling and work piece creation are part of the key success of this project. I would like to thanks School of Mechanical Engineering for providing this course where I am gain more hand-on technique, knowledge and experience.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CFC - Chlorofluorocarbon

CO_2 - Carbon Dioxide

MGT - Micro Gas Turbine

NO_2 - Nitrogen Dioxide

FFT - Fast Fourier Transform

FYP - Final Year Project

HRU - Heat Recovery Unit

UNB - Unbalance Condition

BDF - Bearing Faulty

BRB - Broken Rotor Bar

ACEP - Automated Cepstrum Editing Procedures

BPFO - Ball Pass Frequency of Outer Race

BPFI - Ball Pass Frequency of Inner Race

FTF - Fundamental Train Frequency

STFT - Short Time Fourier Series

MCSA - Motor Current Signature Analysis

LTSA - Load Torque Signature Analysis

ICE - Internal Combustion Engine

AC - Alternating Current

DC - Direct Current

DFT - Discrete Fourier Transform

IMC - Integrated Measurement and Control

ABSTRAK

Kawasan luar bandar Malaysia menghadapi masalah mendapat bekalan kuasa dan haba. Mereka mempunyai enjin diesel tetapi diesel mempunyai masalah pengangkutan dan hanya memberi bekalan elektik. Walaupun kawasan luar bandar penuh dengan biomas, ia tidak sesuai digunakan dalam enjin diesel. Turbin Gas Mikro (MGT) adalah turbin gas versi yang lebih kecil yang merupakan penyelesaian kepada masalah bekalan tenaga kawasan luar bandar MGT boleh beroperasi dengan pelbagai bahan api sementara memberi tenaga dan haba tetapi mahal. Matlamat utama project ini adalah membina MGT menggunakan turbocharger bersambung dengan penjana di mana kosnya lebih murah. Sambungan mekanik yang kurang baik akan menyebabkan kehilangan kuasa kepada geseran, getaran tinggi dan salah jajaran sehingga rosak. Masalah didapati dalam memastikan kecacatan dalam perseidan MGT dan mengekstrak kuasa dari penjana. Kaedah pengekstrakan yang tidak sesuai akan membawa kepada kebanyakan kuasa yang digunakan untuk mengatasi geseran. Sambungan terus diciptakan untuk menyambung alternator ke MGT untuk penjanaan kuasa elektrik di mana putaran MGT datang daripada blower. Prestasi sambungan terus telah dinilai dengan melakukan analisis getaran. Kaedah yang sesuai untuk pencirian output elektrik telah dibina. Sejumlah tiga sambungan terus yang diciptakan untuk sambungan dan yang sesuai adalah sambungan geseran. Alternator sambungan MGT mampu beroperasi hingga kelajuan maksimum kira-kira 12000rpm. Untuk penjanaan elektrik, pemutar alternator diaktifkan dengan kuasa luaran dan disebabkan oleh putaran rotor oleh MGT fluks magnet berlaku melalui sambungan geseran. Kuasa pengujaan yang sesuai ditentukan secara eksperimen. Hubungan kuasa keluaran maksima dengan kelajuan putaran ditentukan dengan percubaan pencirian beban dengan kuasa pengujaan sesuai. Analisis getaran menunjukkan bahawa sambungan geseran mempunyai amplitud getaran rendah berbanding dengan sambungan logam dari kerja sebelumnya. Salah ajaran selari dan sudut memberi kemajuan apabila kelajuan meningkat untuk sambungan geseran. Kuasa pengujaan yang terbaik untuk pemutar alternator ialah 0.81W dengan 18.33Ω. Output elektrik maksimum menunjukkan hubungan selari dengan kelajuan putaran sehingga tidak dipengaruhi oleh faktor lain. Kuasa keluaran maksimum dengan kuasa pengujaan yang sesuai adalah kira-kira 50W untuk persediaan semasa.

ABSTRACT

Rural area of Malaysia are facing problem getting power and heat supply. They have diesel engine but diesel have transportation problem and only supply energy not heat. Although rural area are full of biomass, it is not suitable used in diesel engine. Micro Gas Turbine (MGT) is smaller version of gas turbine which is the solution to rural area problem where it can run with any fuel type while provide both energy and heat but it is expensive. The current work is about developing a turbocharger MGT coupled to a generator which is more affordable. Selection of poor transmission will cause power loss to friction, high vibration and misalignment thus breakdown. Problem in pinpoint the possible defect in setup and extracting power from generator. The unsuitable extraction method will lead to most power used to overcome friction. A direct coupling was develop to connect an alternator to MGT for electrical power generation where the MGT was powered by a blower. The performance of the setup was evaluated by conducting vibration analysis. A suitable method for electrical output characterization was developed. There a total of three coupling developed for the setup and the one which are suitable is friction coupling. The setup was able to run up to maximum speed of about 12000rpm. For electrical output, alternator's rotor was externally excited and magnetic flux is induced by the rotation of rotor by MGT through friction coupling. The suitable excitation power was determined experimentally. Maximum output power of the setup and its relationship to the rotational speed were determined by load characterization experiment with optimum excitation power. Vibration analysis shows that friction coupling have lower vibration amplitude compare to metal coupling from previous work. Parallel and angular misalignment become less severe as speed increased for friction coupling. The best excitation power for the alternator's rotor is 0.81W with 18.33Ω. The maximum electrical output shows linear relationship with the rotational speed thus it is not affected by other parameter. Maximum output power with optimum power input is about 50W for current setup.

CHAPTER 1 INTRODUCTION

1.1 Background

Earth, our home planet is currently facing an unresolved problem which is continuous raising of atmospheric temperature. This phenomena is known as global warming. It is cause by a natural process called greenhouse effect that warms the Earth surface by trapping heat in the atmosphere [1]. On average, the global temperature have raise by 0.9ºC from 1880 to 2012 [2]. Heat is unable to escape to space as greenhouse gases absorb the heat and direct it back to the Earth surface. Example of greenhouse gases are carbon dioxide, nitrous oxide, chlorofluorocarbons (CFC), carbon monoxide and etc. These gases are mainly came from human activities. Our daily activity have contribute to such issue and cause numerous natural disaster such as mass ice melting at North Pole where it reach it highest temperature of 22 ºC in 2016 and expected that North pole will be gone in two years if condition do not improve [3, 4].

Over the century, there has been countless meeting and conference held across the world to discuss on global warming issue. The best breakthrough is during Kyoto Protocol to the United Framework Convention on Climate Change in 1997 [5, 6]. The main outcome of the conference is to set different binding CO_2 emission level for different countries. However, this emission limitation is unfair to poor country as they are still using fossil fuel to generate energy for their daily operation. After series of debate and toleration, all parties met an agreement and came out with four general objective to overcome global warming as following:

a) Avoid CO_2-emitting processes where possible
b) Improve energy efficiency (combined cycle generation, isolation of buildings, vehicles).
c) Replace CO_2-intensive processes by less CO_2-emitting ones (e.g. replacing coal by gas).
d) Substitute CO_2-emitting processes by CO_2-“free” ones (renewable energy, nuclear energy, fuel cells).

In order to fulfill the four objective fixed, all country around the word started in research and development of renewable energy. Renewable energy such as solar energy, bioenergy (biomass), hydropower, geothermal and wind are currently widely used to

supply daily electricity. It is a more effective and cleaner source of energy compare fossil fuel as it will not emit greenhouse gases [7, 8]. Plus, renewable energy will not depleted like fossil fuel and petroleum which have disruption in supply since early of 1970 [8, 9]. Modern country such as America doubled their renewable energy consumption from 2000 to 2016 thus cut down the dependence on non-renewable energy [7]. Figure 1.1a shows the statistic of renewable energy usage equivalent to oil consumption across the world which concluded by United Kingdom Department of Energy and Climate Change.

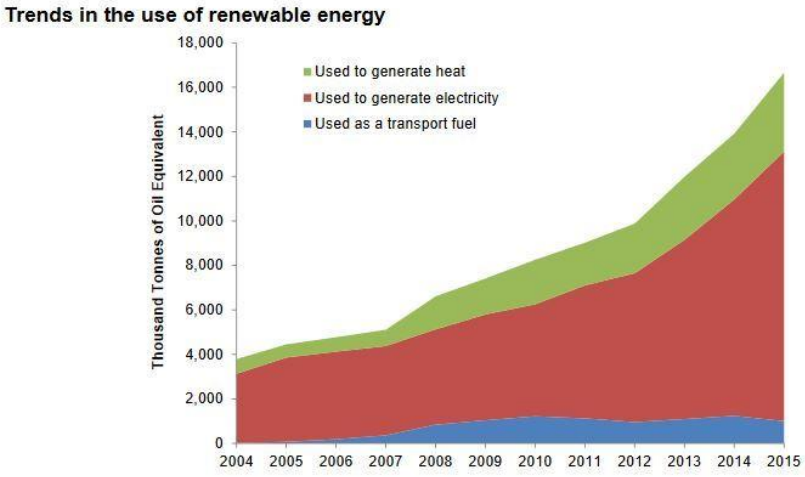

Figure 1.1: Renewable Energy Usage to Thousand Ton of Oil Equivalent [10]

Rural area residents of Malaysia are having difficulty of getting power supply as commercial electrical power line are not available. Although they have a lot fuel supply such as biomass, they do not have a suitable engine to generate enough heat and electricity [11]. Current system installed in Kampung Mantapok, Sabah only consists of 10 kW micro-hydropower system [11]. Total electricity demand of the village is 53.72 kWh/day, with two daily peak load occurring at 11 am and 5 pm [11]. Most of the rural area are now using diesel generator as their main power supply. Diesel generator is a high efficiency power generator but it has a low heat supply [11]. It is insufficient for the residence daily operation such as drying crop. Diesel generator required diesel fuel which required transportation to rural area which is quite a long distance [11]. Rural area are fully of biomass but not suitable for diesel engine as it will damage it. Direct fired gas turbine can be used for biomass power generation but most energy is converted of heat instead of electricity.

Micro Gas Turbine (MGT) is a smaller version of conventional gas turbine. It usually produce between 25kW and 500kW. The basic principle comes from open cycle gas turbine with several feature such as high speed operation low CO_x and NO_y emission [12]. The advantages of using micro gas turbine is the system is simple and compact as it can directly connected to high-speed turbo generator. It has low emissions and required low investment cost. MGT applicable for delivering reliable electrical in both stand-alone and grid connected system. It can also operate on a variety of fuels such as natural gas, biogas, diesel, gasoline and liquid biofuels [13]. Figure 1.1a shows a typical MGT used in industry.

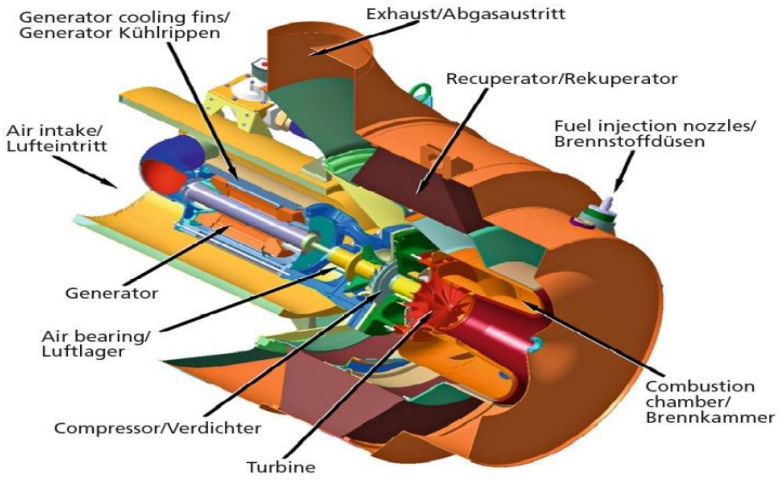

Figure 1.2: Cross-sectional view of Capstone C200 MGT [14]

The invention of electrical vehicle and hybrid electric vehicle gives environmental friendly and better fuel efficiency in automotive industry. In recent development from Bladon, electrical vehicle in search of a power unit that can charge the vehicle's batteries on the move [15]. They used Micro Gas Turbine (MGT) which dramatically lighter and lead to overall 15% weight saving thus resulting in reduction of fuel consumption and carbon emission [15]. MGT might be the solution for continuous electrical supply for rural area. It able to supply high electrical power and the heat need for drying crops. Plus, MGT able to operate with different fuels such as biofuel or biomass which make it more suitable in rural area application. It is also proven to have less pollutant emission which made it more favorable [16, 17].

MGT are a promising technology for distribution power generation in the current society [16]. Internal combustion engine are widely used because of their low price but limited by their high pollutant emission [16]. Plus, the resident in rural area

are lack of technical skill in maintaining internal combustion engine. MGT is a good alternative to replace internal combustion engine but it is expensive. The MGT in Biomass lab (School of Mechanical Engineering, USM) is customized where it used turbocharger instead of turbine fan. Although MGT with turbocharger is less costly, it is not meant for power generation application. Turbocharger cannot withstand high temperature at high operating speed as it will start to fatigue [18]. Electrical power is produce by connecting generator or alternator to MGT through mechanical transmission such as gear, pulley, belting and etc.

1.2 Problem Statement

Automotive alternator operates through mechanical transmission connected to MGT such as gearbox, chain drive and belting [19]. The selection of transmission is depends on its application. For example, aircraft engine required high torque to start-up the engine and high speed during the flight [20]. Thus, the most suitable transmission is gear as it can switch its gear ratio to give required speed and torque [20]. Good transmission ensure continuous power supply and prevent breakdown. Friction in the transmission system caused energy loss as heat. Almost half of the effective power from MGT is gone when it reach the alternator. A big alternator will be needed to supply the high amount of power thus inefficient. Coupling will provide less friction loss but there is alignment problem. The coupling needed to be very accurate and precise as it will cause vibration due to misalignment [21]. Misalignment not only will damage the coupling setup but also the alternator and MGT. Continuous breakdown is a serious problem as rural area resident might not have a require technical skill to fix the problem. Rural area resident. There is a need of finding a better way to connect alternator to MGT.

Problem such as unbalance, damage shaft and looseness are the common problem occur in the MGT with alternator setup [21]. The alternator are unable to produce it full capacity without solving the problems. It might also damage the alternator or MGT if the faulty is not identify on time. It is hard to pinpoint the possible problematic area as it mostly occur during running of the setup. Therefore, there is a need of finding an effective way to discover the problems and locate the sources.

The amount electrical power that can be extract from the current MGT with alternator setup is still unknown. Incorrect excitation power delivery to rotor will lead to most power used to overcome braking due extensive magnetic force. The parameter that affect the electrical output had yet to be establish.

1.3 Project Objective

The objectives of this project are

- To develop a direct coupling to connect alternator to Micro Gas Turbine.
- To evaluate the setup performance through vibration analysis.
- To characterize the electrical power output of the setup.

1.4 Scope and Limitation

A direct coupling is the first be fabricate as the connection of alternator to MGT. Modification will be conducted on the platform and the setup of MGT. The alternator used in this project is Perdua Kancil's alternator. The original alternator is also modified for the application of this project. The turbocharger shaft is also checked if there is any bending and fix it if necessary. Alignment work will be carried out onto the alternator and MGT setup. In the process, there will be continuous modification on platform, stand and direct coupling in order to correctly align the alternator and the turbine. After alignment work is done, vibration level of the setup will be recorded using vibration checker with accelerometer. Vibration level are taken at two places which are the alternator and the platform. The vibration level will be display as Fast Fourier Transform (FFT) spectrum. Faulty in the set-up such as misalignment, unbalance, mechanical looseness and bearing defect will determine from the vibration test. The results is also compare with pervious FYP results [22] for improvement verification. Problem detected that is sever will be troubleshoot and rectify if necessary. Electrical power is generated by alternator by conservation of magnetic induction of rotor which were rotate by MGT. For characterization, an optimize power to excite the rotor will be determined. The electrical output is DC and it is recorded with the optimized power supply for different number of load.

In this project, car alternator is connected to MGT through direct coupling only. Other coupling or connection will not be test and fabricate as it is done by previous FYP student [22]. Faulty in the set-up will only be determine through vibration analysis. Alternative methods such as heat thermal detection and acoustic sound analysis will not be conducted because of lack of such equipment and the unsuitable location of setup. For alignment of setup, this project tends to achieve optimum alignment for continuous operation of setup. The scope of project is not tend to get perfect alignment with zero faulty which is difficult to achieve with the current setup. The rotor is externally excited

instead of self-excited due to the optimum coupling and setup constraint. Lamp and bulb are used for load of electrical power output characterization, other load such as motor, heating coil etc. are not used due to capital constraint.

1.5 Operation of Micro Gas Turbine

Micro Gas Turbine (MGT) operation are based on Brayton Cycle which a constant combustion system [23]. The combustion system can be either directly fired or externally fired follow by heat exchanging process. In MGT, combustion of gas and air takes place in the combustion chamber. Combustion process in MGT consist of mixture of fresh air and fuel and after process complete the fresh air is release as exhaust. Thus, MGT can be consider as an open system [24]. Figure 1.4a shows simple schematic diagram of MGT and thermodynamic cycle based on MGT.

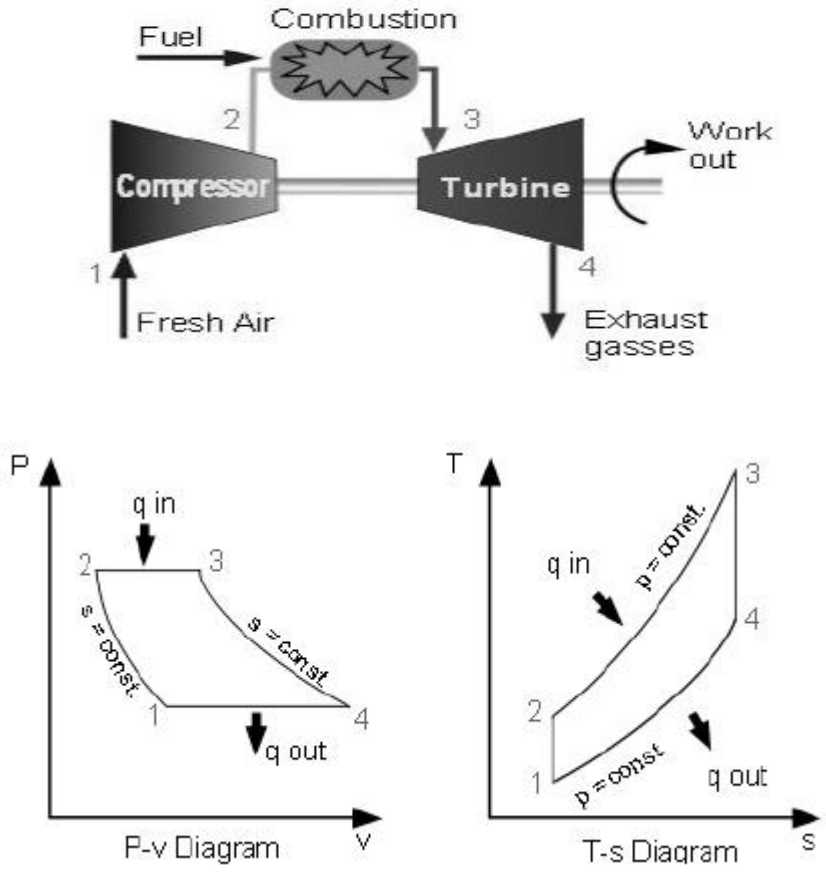

Figure 1.3: Schematic diagram of MGT and Thermodynamic Cycle based on MGT [24].

Based figure 1.3, fresh air at ambient temperature enter the system is first compressed isentropically by compressor to higher temperature and pressure as indicated by point 1 to 2. The compressed air is then mix with fuel before enter the

combustion chamber. The mixture is burnt in combustion chamber (point 2 to 3) where its energy increased and work is done on the turbine. Conservation of energy takes place where heat energy from the air fuel mixture is converted into kinetic energy that turn the turbine. Note that the temperature of air fuel mixture increased at constant temperature. Since turbine and compressor are connected on the same shaft, turbine is drive compressor in compression stage (point 1 to 2). For point 3 to 4, the air fuel mixture is passed through Heat Recovery Unit (HRU) where it is expand and the heat is recovered for some other secondary application. The exhaust is then release to the environment (point 1 to 4). For electricity generation, turbine shaft is sometimes used directly or connected to generator.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The chapter will first discuss the MGT used in this project and other similar MGT as driver to alternator or generator. Vibration analysis on misalignment and components such coupling and bearing defect will be reviewed. The setup for the vibration test and the method for misalignment detection will also be further discussed. Method and setup used to extract electrical power from the MGT will also be examined as well.

2.2 Micro Gas Turbine (MGT)

Micro Gas Turbine (MGT) are simplify and smaller form of gas turbine in which has energy generation around 25kW to 500kW. It based on open cycle turbine which have several typical feature which separate them from normal gas turbine such as variable speed, compact size, high speed operation and low NO_x emission [12]. It is first introduce in automotive market where the design is first based on gas turbine used in generators of missile launching stations, aircraft and bus engines in 1980 [12]. The technology is soon become attractive among those who seeking reliability and independence through self-generating power.

The MGT used in this process is same as the MGT of Enagi et.al. [25]. MGT setup in School of Mechanical Engineering consist of two stages. It is a directly fired MGT. The first stage MGT is used to drive the compressor where it power by direct combustion of fuel while second stage consist of turbine that is connected to alternator to generate electricity. Figure 2.1 shows the schematic drawing of the MGT test rig used in this project. In this project, the focus is on two stage MGT as shown in the red box in figure 2.1.

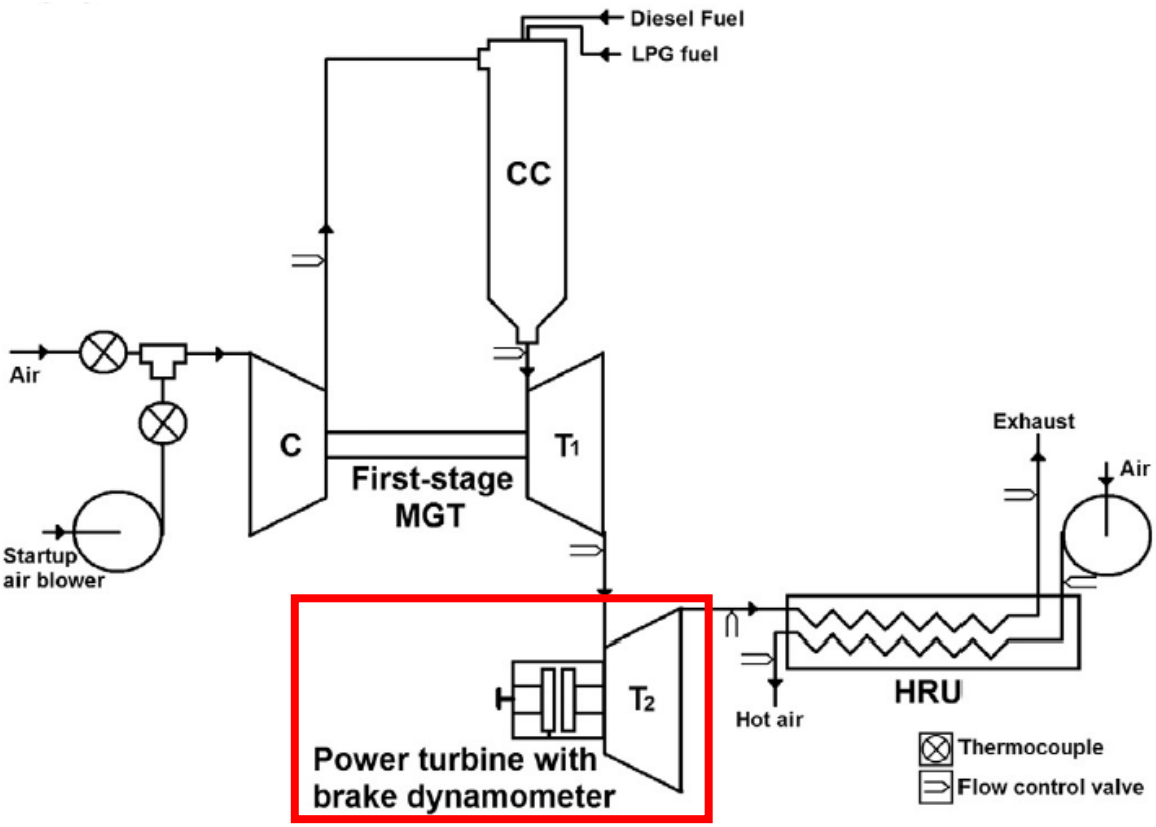

Figure 2.1: Schematic drawing of MGT test rig [25]

In this project, continuation of development of second stage MGT setup were conducted. For the further medication of setup, the second stage MGT was disconnected for the first stage and was power by a blower. A suitable coupling was made to connect the alternator to the turbocharger shaft for generation of electricity. The coupling that was suitable for the application is friction coupling. Vibration analysis was carried out to evaluate the vibration and misalignment of the setup. Characterization of generated electrical power output were done by externally excited the rotor of alternator while it is rotated by turbine.

Another study on the development of micro-power pack using Micro Gas Turbine [19]. The performance of MGT is studied by connecting alternator to MGT with different mechanical coupling. Belt pulley coupling and flexible elbow coupling were the selection. Kyuho Sim coupling method is different from the coupling of this project where direct coupling was used. Belt pulley coupling required good tensioning in its belt which may introduced unbalance force on one side of pulley. This may cause bending on the shaft of either turbine or alternator or even both. Plus, belt pulley coupling need quite large space for optimum alignment and operation which was not

suitable for the application of this project. The space of turbine and alternator were limited. Flexible elbow coupling is one type of direct coupling with allow some degree of misalignment. This type of coupling is not really good because the misalignment allowance will cause bending or offset of shaft of machinery where are fixed in position.

2.3 Vibration Analysis

Smooth operation of machinery is important in maintaining the good condition of components and increase lifespan. In particle, there is no such thing as smooth operation as all machinery are subjected to a degree of vibration and friction contact. Vibration and friction contact of components in machinery can cause components to damage then wear or fatigue thus cause breakdown. It is important for an engineer to minimize the vibration and friction contact for continuous operation of machinery. Vibration analysis is maintenance tool that used to monitor the vibration level of machinery where it can help to check whether there is misalignment, contact between components and damage components.

A vibration was conducted vibration test at the power shaft end in horizontal direction under no-load and load condition [19]. Only horizontal vibration are monitor while vertical vibration were omitted for brevity. Figure 2.2 shows the result of the vibration test for both belt pulley and flexible elbow coupling.

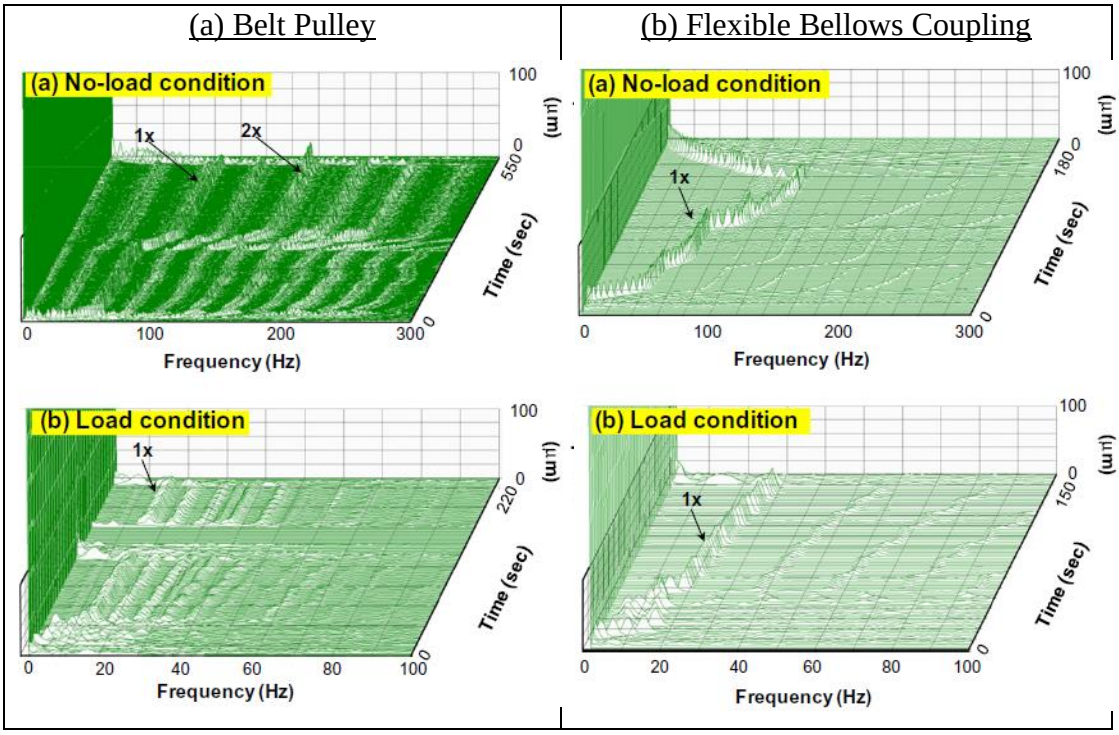

Figure 2.2: Vibration results for (a) belt pulley and (b) flexible bellows coupling [19]

The vibration test in this study shows in 3D Fast Fourier Transform (FFT) and only consist of one rotational speed. The performance measurement in will be carry out in similar way in the project but will present in 2D FFT spectrum. The results in this study indicate the trend of vibration level that can serve as a reference to determine the faulty in this project. Vibration test should be conducted in different rotational speed as it will give different vibration level. Faulty in the setup might occur at different rotational speed thus it is better to test the vibration at an interval of rotational speed until it react maximum.

Paulo Antonia and Delgado-Arredondo [26] also develop methodology for faulty detection in induction motor. The method used were vibration signals and sound acoustic. Vibration analysis is carry out by using accelerometer and the data recorded is in the form of time domain. The time domain is convert to spectrum using Fast Fourier Transform (FFT) for signal processing. The faulty that are treated in this paper are unbalance condition (UNB), bearing faulty (BDF) and broken rotor bars (BRB). The faulty are made artificially by human. The reading of a healthy motor is first recorded and the faulty part is then install to the motor. A new reading will be record and compare it to the previous reading. The vibration signals are acquired with a tri-axial accelerometer while acoustic sound is capture with a microphone. Figure 2.3 shows the experimental setup.

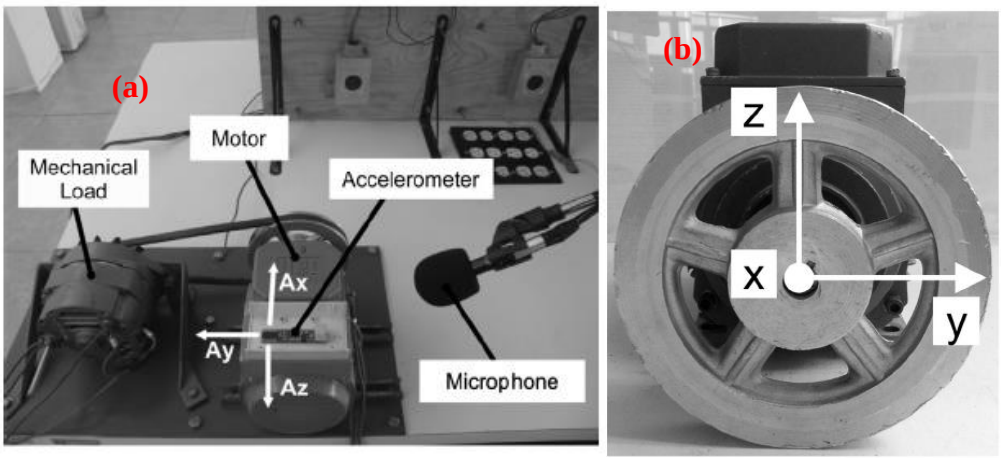

Figure 2.3: Setup of Experiment (a) and Orientation of (b) Accelerometer Axes [26]

The results of the study shows that there is a significant differences in the healthy and damage parts. It clearly stated the cause of faulty and the behaviour in FFT graph. The vibration results trend can be a good reference for the vibration test in this project. In contrast, this is not a good study because the faulty is already known before vibration

analysis carried out. In the project case, the vibration is unknown thus we do not know where the faulty part or area are. The studied found that the best results of vibration signal are obtained in the z-direction axis (Az) thus it only consider z-direction vibration. Vibration test results should include the all the possible direction of motion in the parts as the faulty can occur randomly. The faulty might not be limited in z-direction only, other direction might have faulty which is more significant than z-direction. The faulty detection in the study is only at a specific rotational speed. The behaviour of faulty should be investigate at different rotational speed as it will give different results. Others faulty might appear at difference rotational speed due to the initial faulty.

Patrick Guillaume et.al. [27] had carried out study on bearing faulty detection in wind turbine through vibration analysis. Bearing failure was masked by high energy harmonic signals which come from others machine elements. In this studied accelerometer are mounted on the outside of the gearbox and data is sampled by 40 kHz per channel. By using Automated Cepstrum Editing Procedures (ACEP), the amplitude of vibration due to various faulty are filter leaving only bearing defect in the results. Figure 2.4 shows the FFT spectrum before filter (a) which contain Ball Pass Frequency of Outer Race (BPFO), Ball Pass Frequency of Inner Race (BPFI) and Fundamental Train Frequency (FTF) while after filter consist only FTF.

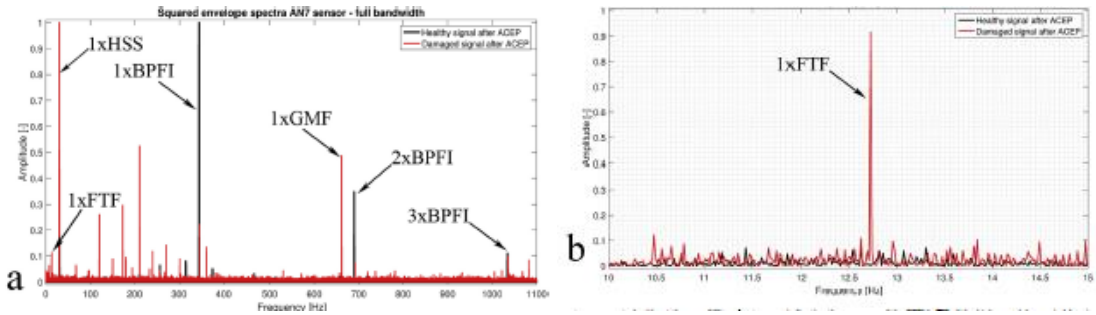

Figure 2.4: Vibration Result (a) before and (b) after filter [27]

The study found that fault frequencies from bearing of low speed shaft are more difficult to detect compare to high speed shaft due to lack of fundalmental frequency. Cepstrum editing prodedure can remove discrete frequncy content thus increase the sensitivity and detection rate of faulty. In contrast, this technique migth filter out the frequency of fault bearing which are close to the faulty of gear thus cause it undetecable. Again the faulty frequencies was already known there the filter can be made. It is better to take the FFT of vibration results and check its harmonic peaks to identify the problem and faulty of machinary.

Vladimir Dekys [28] had come out with a solution to determine vibration source in machinery with Short Time Fourier Series (STFT) using LabView. The machinery under investigation is an internal combustion engine, cooling system with a fan and transmissions transfer power from engine to the next section. Measurements were carried out with only one speed reference which was used for determination of the measured signal and the order of analysis based on rotor speed of the fan. Engine speed is set to the selected level, accelerometers is placed in selected area of the setup. The study give another approach of determining the faulty area which was very useful in this project. Other than FFT graphs, STFT can be used to further validate the faulty in setup. Peaks and excite resonance can be determine more clearly and easily differential which is resonance or faulty peak. However, this method is still limited to experimental solution under the basis of ISO 10816. Since the project was using Institution Measurement Control setup and software, clear and presentable FFT results can be obtained.

A method of detecting mechanical faulty in actuator driven by induction motor was studies by Carlos Verucchi et.al. [29]. In this study, mechanical faulty is discover by using technique based on analysis of Motor Current Signature Analysis (MCSA) and the Load Torque Signature Analysis (LTSA). Angular misalignments and radial misalignment are investigated in this studied using different type of coupling. Data were collected from National Instruments Acquisition Card at a rate of 10k samples per second with current and voltage sensor. The problem with this method it is difficult associate fault indicators with certain degree of misalignment without considering specific features of coupling. Since direct coupling was self-fabricated, the feature is not specify thus this method may not be suitable in this project. However, it may serve as a benchmark by using this method to determine the fault respond for future references.

2.4 Electrical Power Characterization

MGT is famous for its power generation with its compact size and light weight. By using induction motor such as generator or alternator, rotational energy (kinetic energy) of MGT can be converted to electrical energy. Kyuho Sim et.al. [19]coupled MGT to an alternator and run at the highest rotational speed. The characterization of electrical power output should be conducted at different rotational speed of alternator. The study should compare the vibration level and the electrical power output to determine the optimum operation condition.

Jeong Min Seo [30] presented a study on development and experimental investigation of MGT. The MGT used is 500W class ultra MGT with power generator. The specification of the design MGT power generator is tested with GasTurb 11 which is a gas turbine performance software. A test rig is also design to characterise the performance of the design's MGT. The test rig consist of a compressor, turbine, combustor and motor generator as shown in figure 2.5.

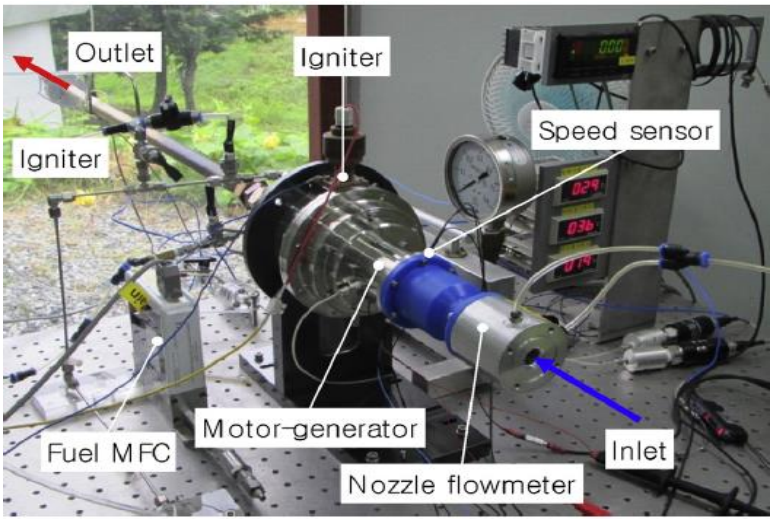

Figure 2.5: Test bench of test rig for MGT [30]

Electrical power generation test is conducted by determine the relationship of various parameter with the power generation which include include mass flow rate of igniter fuel, volume flow rate of main fuel, rotational speed, total-to-static pressure ratio compressor and etc. All the result are recorded and present in graphical method with respect of time. This studied is quite similar to this project in term of setup and data recorded. Instead of using direct turbine firing, blower was used in this project to trigger the turbine rotation. Thus, temperature and fuel flow rate is not available in this project. The electrical output is given by car alternator instead of generator. For current project, the instrument used for rotational speed measurement is tachometer, air speed measurement is hot wire anemometer and electrical power measurement is multimeter. The instruments used in this project is not as good as in the studied but is good enough for experimental characterisation.

F.X. Tan, M.S. Chong [31] presented a study on analytical and experiment study of MGT in electrical vehicle. The purpose of this study is to prove that MGT of 10kW could have driving range comparable to conventional internal combustion engine (ICE). The experimental MGT test rig result is further validate by computational model. The

MGT system is developed using turbocharge unit as compressor and turbine. The turbocharger unit contain oil-lubricated ceramic ball bearing and water cooled housing. The combustor built for the system is fed with liquefied petroleum gas. The MGT system is tested without coupled to electrical generator. Experiment is carried out at MGT self-sustaining operating points where power generated by turbine is balanced by the losses and compressor power consumption. Figure 2.6 shows the setup of the MGT test rig.

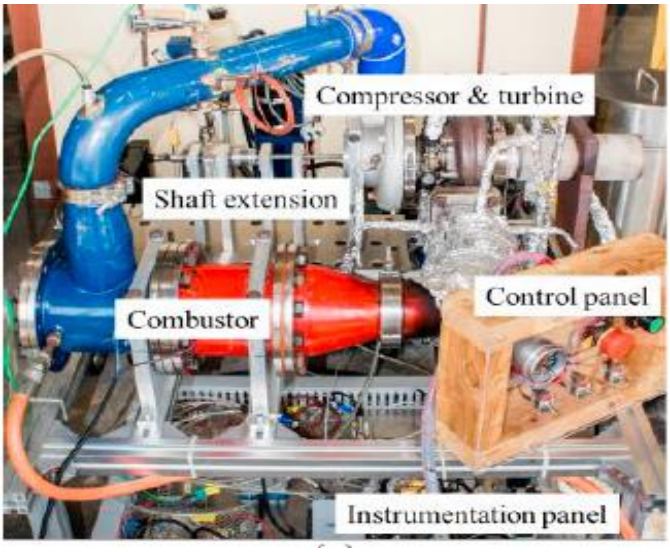

Figure 2.6: Turbocharger converted MGT test rig [31]

The MGT used in the study is quite similar with what we have in this project the only difference were the power output is by alternator and there was no compressor used for second stage MGT. The major difference of this study is the result of experiment. The parameter such as number of load and external excitation power were vary to determine how it affect the electrical power output. MGT is direct coupled with alternator to generated electricity instead of running at operating condition. Verification of experimental results is based on pass FYP results and there is no computational results.

CHAPTER 3 THEORY

3.1 Introduction

In this chapter, various principle operation of equipment such as alternator and turbocharge will be discussed in detail. The theory about vibration analysis and type of problem pattern in vibration analysis will also be reviewed. Electrical circuit connection, electrical load, power calculation and flow rate calculation which include the formula used will be go through and explained.

3.2 Alternator

The modern charging system hasn't changed much in over 40 years where it consist of alternator, regulator and the interconnecting wiring [32]. Charging system is used to maintain the charge in vehicle's battery and it is the main source of electrical energy in a vehicle.

Alternator is the main component in the charging system. It works with vehicle's battery to generate electricity for all the electrical components in vehicle such as dashboard light, front light, radio and etc. Alternator produce alternating current (AC) which is converted to direct current (DC) for the electronic appliances in vehicle as all modern automobiles required 12V DC power source [32]. Electrical power is produce through electromagnetism formed through stator and rotor relationship [33].

The rotor consist of iron core where it is warp by coil of wire. The rotor function as a magnet when DC flow through it. DC is delivered to the coil through slip rings and brushes when the rotor rotate together with the rotating shaft driven by mechanical transmission means. Figure 3.1 shows a simple stricture of rotor inside the alternator.

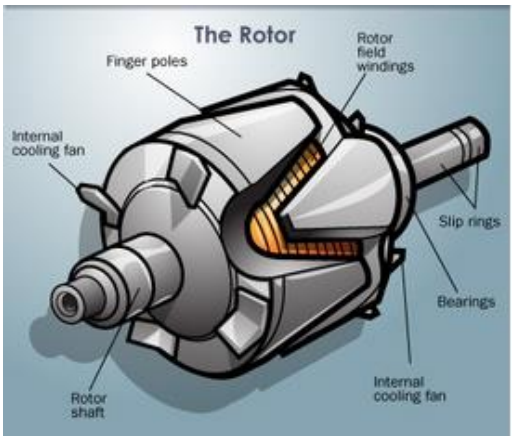

Figure 3.1: Structure of Rotor inside the Alternator [33].

Stator is a set of three coils wounded around the rotor. It is stationary and attached to the housing of the alternator. The rotor and stator assembly fit perfectly with sufficient tolerance where the rotor can rotate at high speed without collide with stator wall. As the rotor rotated inside the stator, power is generated through magnetism. Based on figure 1, the triangular finger poles fixed around the circumference of rotor are staggered [33]. Thus, north and south poles alternate as the rotor is surround by wire field winding. Voltage is induced into the stator due the alternating pattern of rotor which creates magnetic field. The output of is AC which is then fed through diodes where AC is converted into DC. The working principle of alternator is similar to a DC generator which based on Faradays law of electromagnetic induction which says the current is induced in conductor inside magnetic field when there is relative motion between conductor and magnetic field [34]. The rotor of alternator was coupled to turbine which cause rotation and results in magnetic flux cutting the stationary armature conductor which is the rotor.

3.3 Turbocharger

Turbocharger is a device that is commonly used in automobile and aircraft. It can be visualize as an air pump where it take air at atmospheric pressure then compress it to higher pressure and transfer it to the engine's inlet. This can increase the efficiency of the engine as the amount of air entering the engine increase. The aim of turbocharger is to improve engine's volumetric efficiency by increasing density of intake gases [35]. Turbocharge is powered by turbine where it is driven by exhaust gas from the engine outlet. Figure 3.2 shows the internal view of turbocharge and its components.

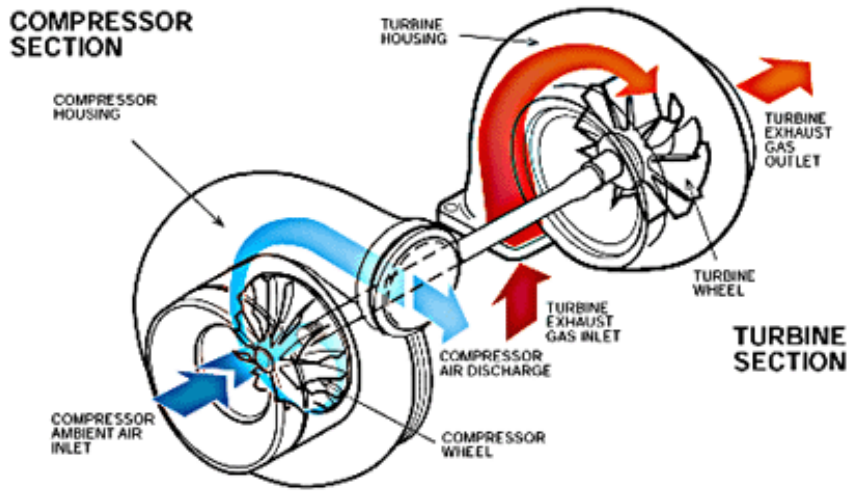

Figure 3. 2: Internal view and components of turbocharger [35]

Turbocharger consist of two main sections which are turbine and compressor. The turbine section is consist of turbine wheel and turbine housing. The exhaust from the combustion process is directed to the turbine wheel by the turbine housing instead of exiting through exhaust pipe. As the hot exhaust gas reach the turbine wheel, thermal energy is converted into mechanical (kinetic) energy where the turbine started to rotate. The rotational speed of the turbine is depends on the exhaust gas and its highest speed can reach up to 150000rpm [36]. There is an exhaust outlet that guide the exhaust gas from the turbine to the tailpipe. As the turbine rotate, the compressor wheel on the other side is also rotate in the same pace. The turbine is connected to the compressor wheel with a steel shaft. The compressor draws the high velocity and low pressure air stream and convert it into high pressure and low velocity air stream [35]. This able to give a denser air and oxygen rich air to flows into the combustion chamber thus increase its efficiency. Figure 3.3 shows the operation of turbocharger in an internal combustion engine.

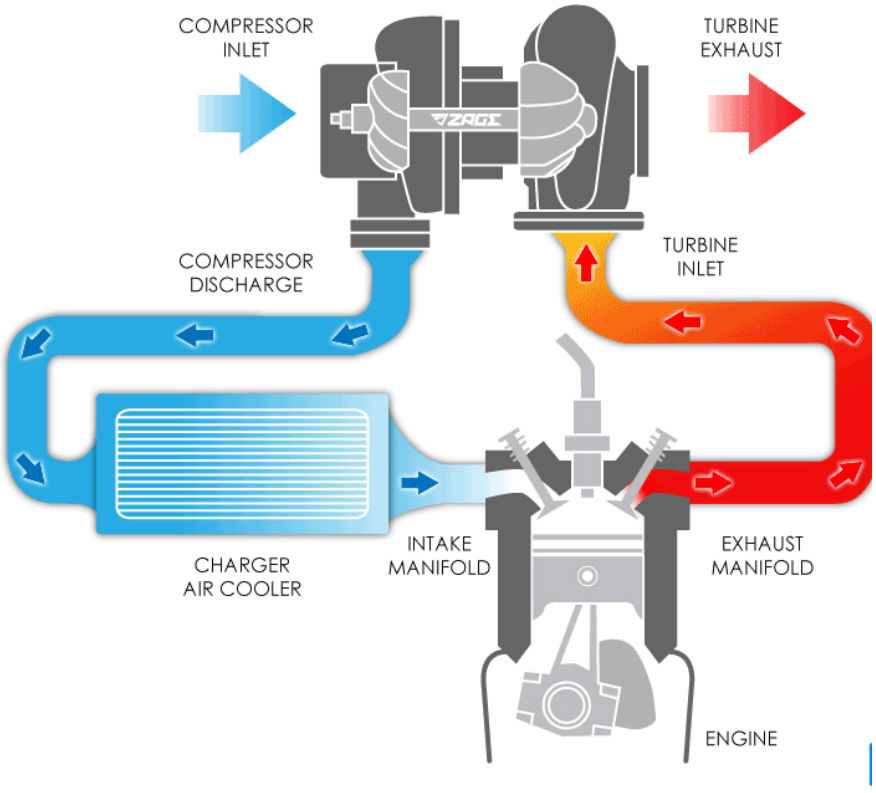

Figure 3.3: Operation flow of turbocharger in internal combustion engine [36]

In using turbocharger, the most common problem occur is turbo lag. Turbo lag is the time between mashing the throttle and feeling the rush of torque from a turbocharged engine [37]. It is actually the time delay came from the engine exhaust

where it need to create enough pressure to spin the turbine. This normally occur when engine is at low rotational speed or low load cruising condition. Turbo lag can be eliminate when it match specific range of rotational speed. It can be reduce by using waste gate or increase the diameter of exhaust system. Note that it is not wise to start the turbocharger at high pressure or speed of gas exhaust gas as it will over speed the turbine and might end up explode the turbocharger.

3.4 Fourier analysis/ Fast Fourier Transform (FFT)

Fourier analysis is a technique that decompose waveform into sinusoids which give another representation of a waveform [38]. The results of the analysis will able to express waveform as sine wave amplitude or function of frequency. A signal which consist of single sine wave will have a peak that match the frequency and amplitude that match wave [39]. In mechanical engineering application, sine waves component signals is not very useful but its frequency component is very helpful. The knowledge in frequency content of rotating machinery is able to help in determine the source of vibration thus prevent breakdown.

In order to evaluate a random signal, the signal must first be digitized by performing a Discrete Fourier Transform (DFT). Fast Fourier Transform (FFT) is the standard numerical algorithm used for DFT which will result in an approximation to the original signal. In other words, FFT is just a fast implementation of DFT which takes the advantage of symmetry in sine wave. It required signal length of power two for transform and splits the process into cascading group of 2 to exploit the symmetries [38]. For example, there are n-point Fourier Transform to digitize the signal as calculated from equation (1) and (2). Take n = 1024.

From direct DFT,

$$Data\ points\ required = n^2 = 1024^2 = 1048576 \quad (1)$$

By using FFT,

$$Data\ points\ required = (\frac{n}{2}) \log_2 n = (\frac{1024}{2}) \log_2 1024 = 5120 \quad (2)$$

The number of data points is greatly reduce thus save time. The number of discrete frequencies are tested as part of Fourier Transform is directly proportional to the number of sample of original waveform [38]. Thus, the sampling rate in a signal is

important for the accuracy of the digitized waveform to the original. The resolution of the frequency in FFT can be calculated or improved by using the formula in (3).

$$Frequncy\ bins(lines), \Delta f = \frac{1}{T} = \frac{F_s}{N} \quad (3)$$

Where T is the total acquisition time, F_s is the sample rate of raw waveform and N is the number of sample. The recording time must be extend to achieve high resolution FFT results. Figure 3.4 shows an example of a FFT of 50 samples to a signal of sample rate of 500 Hz. Thus, the frequency bins (Δf) is 10Hz.

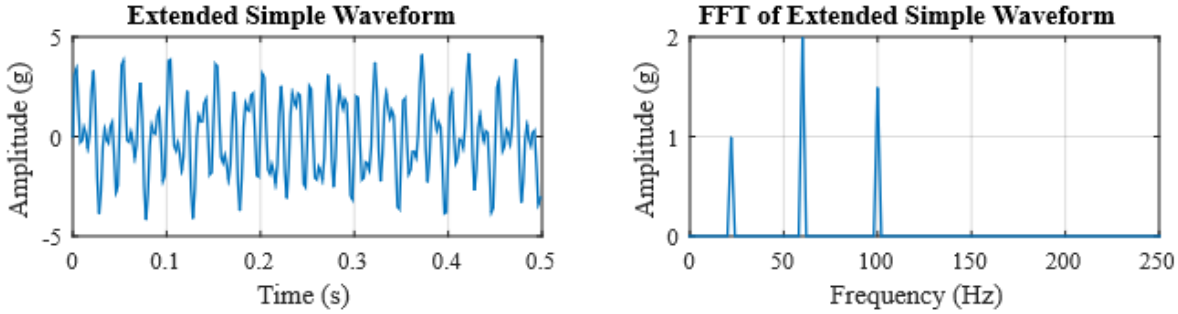

Figure 3.4: Discretization of a waveform using FFT [39].

3.5 Vibration Analysis

Fast Fourier Transform (FFT) is the tool used for vibration analysis in this project. The FFT spectra provide useful information that can help to determine the source and cause of machinery problem. It allow user to analyse vibration amplitude at various frequency thus track the excessive and extensive vibration [40].

Before going into details about FFT spectrum, the fundamental frequency or commonly known as harmonic of the machinery must be determine first. Fundamental frequency is the lowest resonant frequency of the vibrating object [41]. Vibrating object normally have more than one resonant frequency where is frequency is integer multiple of fundamental frequency. This is called as the harmonics. The fundamental frequency can be determine from the rotational speed as in equation (4) and (5).

Since 1 $rpm = \frac{1}{60} Hz$, then [41]

$$Fundamental\ frequency = \frac{N}{60}, where\ N\ is\ the\ rotational\ speed\ (rpm) \quad (4)$$

For its harmonics [41],

$$nth\ harmonic = n\ \times fundamental\ frequncy, where\ n\ is\ an\ intege \quad (5)$$

With the harmonics are determined, its amplitude/peak is check to see if there is any faulty in the machine. If the peak occur at frequency different from the harmonics, it indicate that the vibration is cause by other components other than the one is measuring [40]. The common faulty that are able to detect with vibration analysis are misalignment, imbalance, mechanical looseness, bearing faults and bent shaft.

3.5.1 Misalignment

Misalignment occur when shaft, coupling and bearings are not properly aligned along their centrelines. There are two type of misalignment which are angular and parallel. There are also possibility that the misalignment is due to both angular and parallel. Figure 3.5 shows the angular and parallel misalignment in coupling.

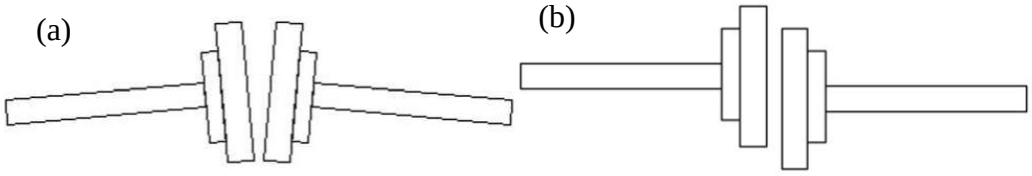

Figure 3.5: (a) Angular misalignment and (b) parallel misalignment [40]

Angular misalignment is due to the joining of two shaft at coupling in such way that induced a bending force on both shaft. It will shows a high amplitude in 1× and/or 2× harmonic frequency in the axial vibration [42]. Parallel misalignment is due to the displacement or offset of shaft centrelines which are parallel to each other. The amplitude in 2× harmonic frequency will be double at the radial vibration [42]. In term of coupling, there are a few rules are apply by determining the ratio of 2× harmonics peak to 1× harmonics peak. The rules are as follow [40]

- If $\frac{A_{2\times}}{A_{1\times}} < 50\%$, coupling condition is still acceptable.
- If $50\% < \frac{A_{2\times}}{A_{1\times}} < 150\%$, high possibility coupling damage will occur.
- If $\frac{A_{2\times}}{A_{1\times}} > 50\%$, several misalignment is available thus repair should carry out.

3.5.2 Unbalance

Whenever mass centrelines does not coincide with geometric centrelines, unbalance occur. There three type of common unbalance which are static, dynamic and couple. Figure 3.6 shows the difference between static unbalance and couple unbalance.

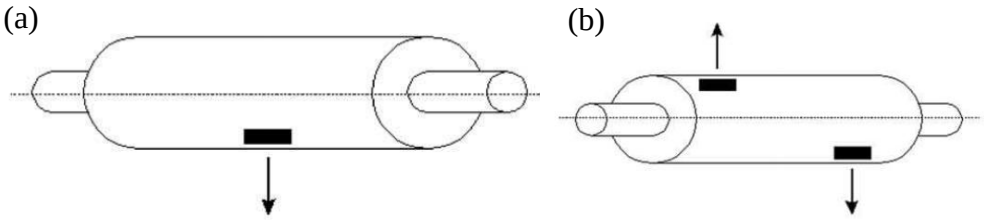

Figure 3.6: (a) Static unbalance and (b) Couple unbalance [40]

Static unbalance involved one force only. There will a specific part of the elements which have high amplitude than the others. The faulty part is always at the same spot no matter how many times the machine run. Couple unbalance are two equal forces which are 180º from each other. When the shaft rotate, the shaft will wobble causing 180º out-of-phase reading from opposite ends of shaft [40]. Most common unbalance is the combination of static and couple unbalance thus it is called as dynamic unbalance. Unbalance faulty in FFT spectrum will give a high 1× harmonics peak and do not produce others harmonic [40]. The vibration in the radial direction is abnormally high compared to the axial direction. In phase analysis, the sensor will shows phase shift of 90º between vertical and horizontal position.

3.5.3 Mechanical Looseness

Looseness occur when there is improper fit between parts components or untighten connection. It is usually characterized by long string of rotating frequency harmonics and half fundamental frequency (1/2 ×) harmonics at abnormally high amplitude [42]. The harmonics can be order of 2×, 3×, 4x… or 2.5×, 3.5×, 4.5×… and the amplitude of the harmonics are about 20% less than the fundamental frequency.

3.5.4 Bearing Defect

Bearing failure is due to other faulty such as misalignment or imbalance. It occur at high frequencies with low amplitude [42]. The frequencies of bearing which align with machine frequencies, there is a high chance of bearing defect.

3.5.5 Bent Shaft

Bent shaft usually gives amplitude and frequencies similar to those in misalignment problem [40]. In order differential both phase analysis is require. Radial phase will shows in-phase while axial phase will shows 180º out of phase with shaft. With dominant peak at 1× peak and 180º out of phase with shaft in axial direction, bent shaft problem is mostly occur.

3.6 Volumetric Flow Rate

Volumetric flow rate is a measure of the volume of liquid that pass through a certain point in a system per unit time. It normally depends on the area of the enclosure (A) where liquid pass through and the velocity of the liquid (v) flow through it. The unit of volumetric flow is metre cube per second (m^3/s) or liters per second (L/s) where 1 m^3/s = 1000 L/s. The formula is given by equation (6).

$$Volumetric\ Flow\ Rate, Q = Av \tag{6}$$

To convert volumetric flow rate into mass flow rate, Q is multiply with density (ρ) as shown in equation (7).

$$Mass\ flow\ rate, \dot{m} = Q\rho \text{ (Kg/s)} \tag{7}$$

Figure 3.7 shows relation of flow rate with area and velocity in a cylindrical tube.

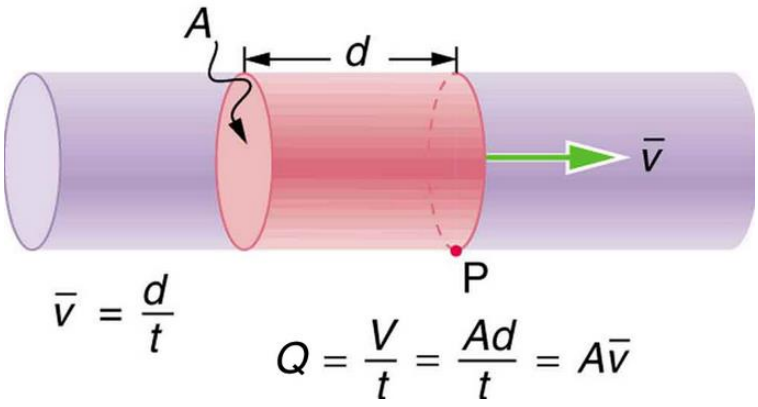

Figure 3.7: Flow rate in a cylindrical tube [43]

3.7 Electrical Measurement and Connection

Electricity had been the main source of power for all household appliances. It is important to know how to measure electrical power because it help to determine how much power the generator produce or how much power a load consume. In this project, a small external power (DC supply) is supply to the rotor of the alternator and produce a high power from alternator through magnetic induction. Thus, there are two part of electric circuit used in this project which are potential divider circuit and electrical output circuit. Voltage across the load can be measured by connecting voltmeter parallel to the load while current can be measured by connecting ammeter in series to the circuit. The measurement can be done with just one multimeter if available where it can measure both voltage and current plus also resistance of load. Direct Current (DC)

circuit are the circuit that will be used throughout this project. Figure 3.8 shows two example on how to connect voltmeter and ammeter in a DC circuit.

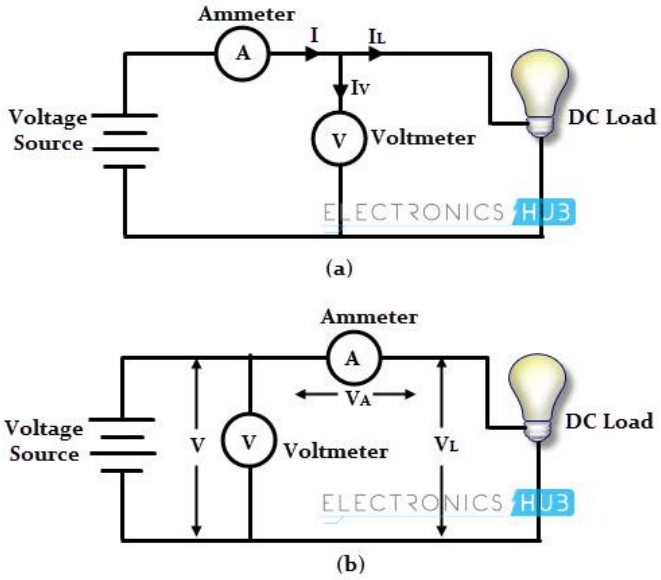

Figure 3.8: Example of voltmeter and ammeter connection [44]

3.8 Potential Divider

Potential divider also known as voltage divider is a simple circuit that used to supply a voltage that is different from the power supply to the load [45]. The circuit take advantage of the way voltage drop across the resistor in series. From ohm law, where$V = IR$, the current in series circuit (I) is always constant thus for a specific ohm of resistor (R) there will be a voltage drop (V) that can be calculated from ohm law. Figure 3.9 shows an example of potential divider circuit.

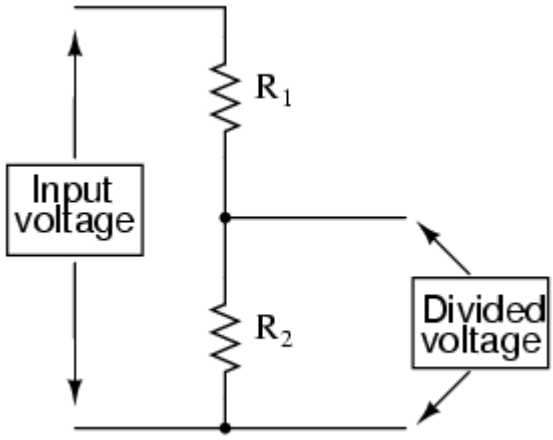

Figure 3.9: Example of Potential Divider Circuit [46]