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A PROJECT REPORT

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ABSTRACT

Dynamometers are devices used to measure the torque or force. In the automotive industry, dynamometers refer to devices used to measure the torque output of an engine. Dynamometers are used throughout the world to test and tune engines for various applications by manufacturers as well as end users. Most industries in the country are forced to import dynamometers resulting in very high costs. This project focuses on the study of dynamometer design and instrumentation to develop a low-cost dynamometer for the local market. Water brake was found to be the best choice due to its low cost of manufacturing and operations. The water brake design was studied and tested using CFD to find the most effective design. Rudimentary test bed was made to allow mounting of the brake, the engine and to connect the two. A cooling tower was constructed based on past project to control water temperatures. A control system was developed to take data from the dyno and produce useful information from it. Finally the dyno was tested was successfully using a 125cc Engine and was successfully able to produce the required brake force.

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Symbols

Latin Letters

n – Engine Speed
D – Brake Nominal Diameter
N-m – Newton meter
lb-ft – pound foot/pound feet
hp – Horsepower
kW – kilo Watt
F – Force
Pa - Pascal
P - Pressure
p - Power
k – Dynamometer capacity constant
Q – Heat transfer
$\dot{m}$ – Mass flow rate
C_p – specific heat at constant pressure.
T – Temperature
^{o}C – Degree centigrade
K - Kelvin
g – Grams
l – Liters
s – Seconds

Greek Letters

τ - Torque

Abbreviations

EFI – Electronic fuel injection.

RPM – Revolutions per minute.

Nomenclature

Dyno – Short for Dynamometers.

CHAPTER 1

Introduction

1.1 Dynamometers

A dynamometer is a device that measures the mechanical power and torque output of a rotating device such as an engine shaft. It accurately measures a vehicle's performance by simulating the load that the engine would receive when travelling on a road. A braking system applies a load to the engine, and the power production is determined by the speed of the rotation element at the applied load.

Dynos can be divided into various categories and subcategories depending on the type of brake used and location of brake mounting. Discussed below are some of the more commonly used types of dynos for automotive applications.

1.1.1 Types of dynos based on brake used:

A brake refers to a device that can oppose the motion of a mechanical system. A dyno measures torque/power comparing the intensity of the applied brake to the rotational speed of the coupling it is connected to.

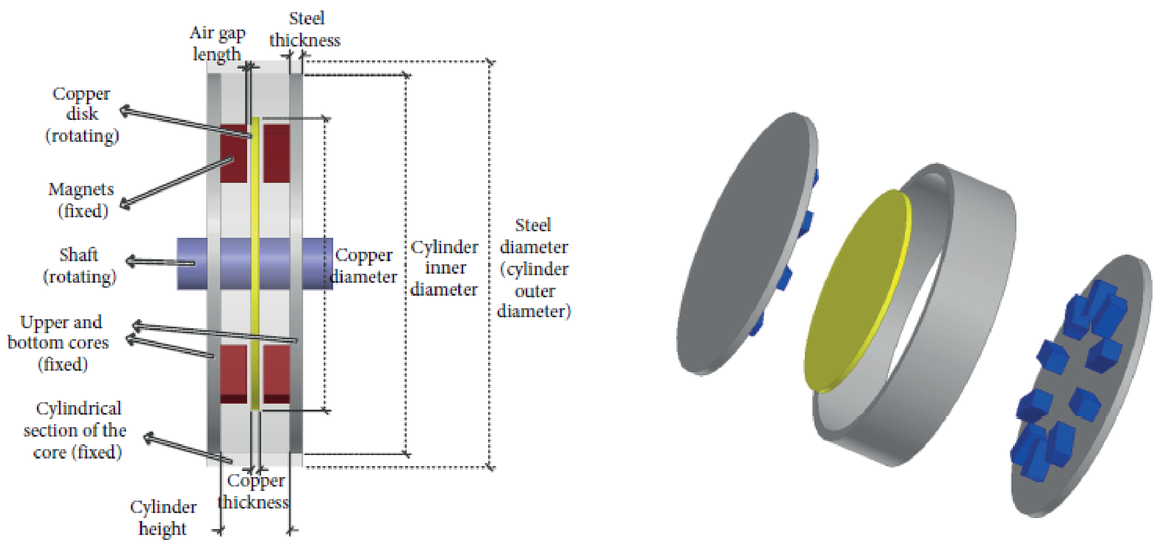

Figure 1-1: Exploded view of an eddy current brake [12]

Discussed below are some types of dynos based on the type of brakes they use:

- Eddy current dynos – Eddy current dynos works on the principle of faradays law of electromagnetic induction. In this type of dynamometer, a rotor rotates in an electromagnetic field which generates eddy currents on the rotor. The eddy currents produce a magnetic field in the opposite polarity to the one in which the rotor rotates. This produces braking force. The intensity of the braking force can be controlled by varying the strength of the magnetic field in which the rotor is rotating. The torque from the engine is calculated using a load cell attached to the dyno body.
- Hydraulic Dynos: Hydraulic dynos work by using the energy coming from the input shaft to pump a high viscosity fluid, usually oil. In hydraulic dynos the load is adjusted by providing resistance to the flow of the fluid usually using a valve installed on the output end of the pump.

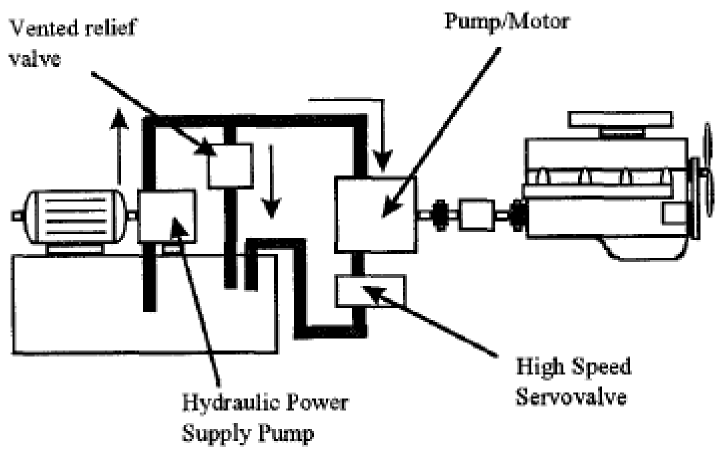

Figure 1-2: Schematics of a hydraulic dyno [13]

The torque from the engine is calculated by using the pressure at the outlet of the pump and input RPM.

- Water Brake dynos: Water brake dynos are different from hydraulic dynos such that they act as a very low efficiency pump, dissipating the energy from the engine to heat which is absorbed by the water in the dyno casing. They consist of a rotor to drive the fluid and a stator that produces resistance against fluid flow. Water brake dynos can be either constant fill or variable fill types, where the applied brake force is varied by changing the area of rotor exposed to the water in the dyno casing or changing the level of water in the dyno casing respectively. The torque from the engine is calculated using a load cell attached to the dyno body.

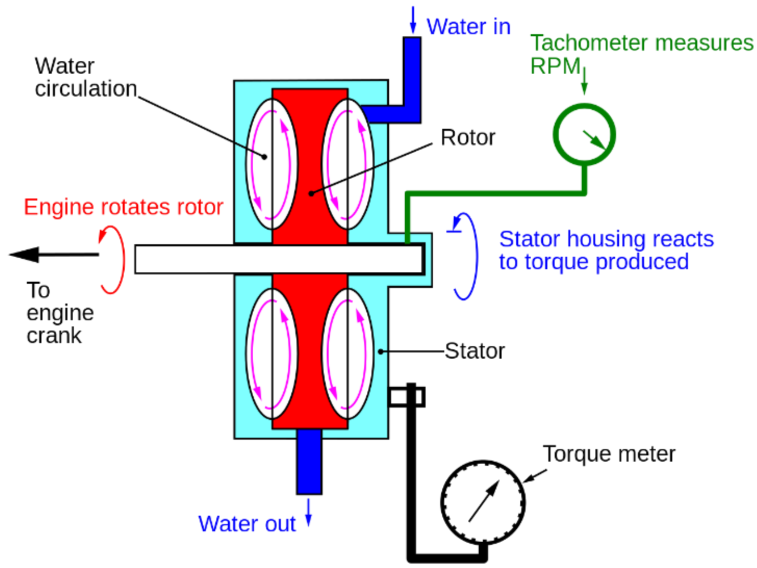

Figure 1-3: Cut view of a variable fill water brake

- Electric dynos: Electric Dynos are usually electric motors that can act as generators. They can be powered by either AC or DC current. Such types of dynos convert the energy coming from the engine into electrical energy. Electric dynos are unique in the sense that they can be used to drive the engine itself to test transient responses and mechanical losses. The power from the engine is calculated using the electrical energy produced by the dyno.

- Inertial dyno: Such dynos work by transferring the rotational energy from the engine into a flywheel. The rate of change of the rotational speed of the flywheel is used to measure the torque coming from the engine. The instantaneous torque and rotational speed are used to measure the power of the engine. Inertia dynos can only measure the torque/power output of the engine during acceleration and deceleration, and so are mostly used for tuning of engines that only work at wide open throttle.

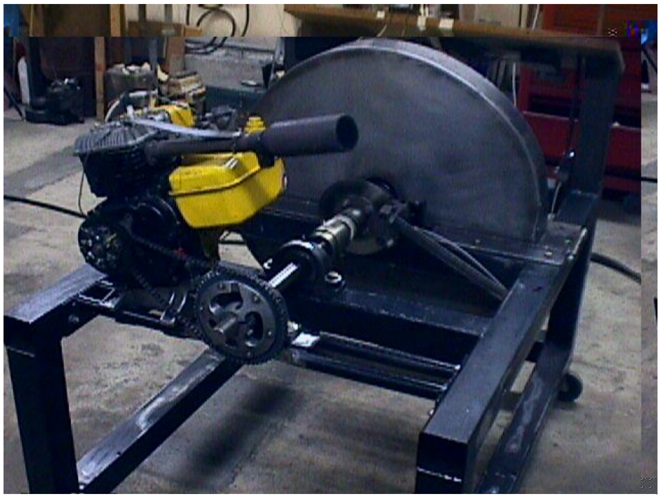

Figure1-4: Inertial dyno with engine mounted

1.1.2 Types based on location of brake mounting:

In automobiles, the rotation produced in the engine travels through numerous components before reaching the driving wheels. Any of these components, including the driving wheels, can serve as a location for mounting the brake units. Some common types of dyno types based on the location of brake units are:

- Chassis dynos – Such dynos work by loading the entire vehicle onto the dyno and measuring the output of the engine at the end of the drivetrain i.e., they measure the power of the engine that is reaching the road. Wheel dynos and Hub dynos, which measure the engine outputs at the tire and wheel hubs respectively are types of chassis dynos. Such dynos have the advantage that they can be used to measure the torque that reaches the road, after all mechanical losses.

Figure 1-5: Chassis dyno, with eddy current brake visible.

- Engines dynos – Such dynos mount the engine only onto the dyno and measure the engine output directly from the engine. Such dynos can be mounted to either the flywheel, output shaft, crankshaft, or the gear box depending on the engine type. Such dynos are usually much smaller than the chassis dynos and require less material, as they must only bear the load of the brake and the engine instead of the entire automobile.

1.1.3 Comparison of dyno properties:

It is very important to select the correct type of dynamometer for the testing of a unit, as it can affect the accuracy of results. For example, dynos made for testing of prime mover engines are designed to calculate very high torque values over a small range of rotation speeds and therefore are designed for low rotational speed operations with brakes that apply huge amount of resistance even at the lowest settings. Such dynos cannot be used to test engines that are installed in consumer automobiles as they will likely stall the engine.

Another consideration is the cost of the testing unit. For example, an eddy current retarder that has an advertised power and torque limit of 540 kW and 3800 Nm respectively can cost upwards of $2000 [1], such a brake unit may be too much if the engines to be tested have a lower max torque rating, say, around 500 Nm.

The type of testing required also determines the brake that should be used. For example, if emissions testing of an engine is necessary, motoring ability becomes a requirement to simulate the engine operation while the automobile is heading down hill, which can only be achieved by use of electric dynos.

There are many other factors that affect the type of dyno brake that must be used for the particular test being performed. The table below highlights some properties of various brake types:

Table 1-1: Comparison of Brake Properties

Brake Type	Moment of inertia	RPM Range	Cost	Maintenance Required	Motoring ability
Eddy current	High	Moderate	High	High	No
Hydraulic brake	Low	Moderate	Moderate	Moderate	No
Water brake	Low	High	Low	Moderate	No
Electric	Low	Moderate	Very High	High	Yes
Inertial	Very High	High	Very Low	Low	No

The type of engine being tested, and the industry affect the location of brake mounting. For example, for testing aircraft engines, or turbine engines, only an engine dyno or a shaft dyno can be used, as the propellor or the shaft attaches directly to the engine.

Note that engine dynos are much cheaper than chassis dynos, as they can be made with less material due to the lower weight on the bed. This ties in with the cost aspect discussed previously in this section.

1.2 Motivation and SDGs

The purpose of this project is to design a dyno that can be used to test and tune motorcycle engines so that they may produce more power, consume less fuel, and provide better emissions.

According to a study from 2018, over 50% of the households in Pakistan have a motorcycle, with Pakistan having the 5th largest motorcycle market in the world [2], with over 10 million motorcycles on the road as of 2014 and rising [3]. As such, most of the vehicles found on the roads of Pakistan are motorcycles. A large percentage of the motorcycles in Pakistan still have the same design and technology they did 40 years ago. Although beloved for their low cost, maintenance, and good fuel economy, they still run on carburetors and have no emissions control system. This makes them one of the major polluters on the roads today.

One of the major factors contributing to lack of emissions control and little to low increase in fuel economy over the history of motorcycle production is the lack of easily available facilities to test engines and new engine technologies. A low-cost dynamometer will provide this facility not only to manufacturers but also to end users.

This project aims to target the following sustainable development goal, defined by the United Nations, either directly or indirectly:

SDG 9 – Industry Innovation and Infrastructure: The availability of tools and instruments to design and test engine and engine technologies will not only allow manufacturers to make better products, but also open job opportunities in the industry for operators of as well as manufacturing of such tools.

SDG12 - Responsible Consumption and Production: Trade deficit for developing countries is one of major concern and fuel is one of the major imports of third world countries. The world is testing new engines to increase fuel efficiency. More efficient and overhauled engines will automatically reduce fuel consumption to combat increasing energy crises.

SDG 13 – Urgent climate actions: The old engines cause emissions of toxic chemicals through exhaust gases. These chemicals mainly consist of hydrocarbons, oxides of nitrogen, aldehydes, Sulphur etc. They are one of the major causes of air pollution and environmental changes, for example depletion of ozone layer, formation of smog in big industrial cities respiratory disorders etc. If the engines being used on a large and small scale or tested and made efficient these concerns can be reduced to a significant level. The availability of readily available dynos in the market will allow manufacturers to design their engine to have lower emissions.

1.3 Literature review:

The defining quality of this project will be its low cost and ease of production in the local market. Therefore, past literature was studied for information on similar projects. Most attempts at a low-cost dyno used either a variable fill type water brake [4] [5] [6] or a hydraulic brake [7] [8] as both these brake types have great energy dissipation even at smaller size resulting in lowered price. Furthermore, they can operate at a very high range of RPMs and have a low polar moment of inertia, which makes them the ideal dyno for small engines. Considering most low-cost dynos used water brakes, the authors of this paper decided to use a water brake in their project as well.

An article by N.N.N. Rao [9] suggests that diameter of water brakes is related to the torque absorbed by an exponent of 1/5. That is, very high values of torque can be absorbed by a water brake. It derives an expression for the dynamometer absorption constant “K” based on the effect various design factors of the water brake have on its torque absorption.

A journal article by Banis [10] identified that water brakes have low torque absorption at low rotational speeds and tests various design parameters of the rotors using computational fluid dynamics to study the effect of rotor design parameters on torque absorption capabilities of the water brake over various rotational speeds. It presents the results of over 21 different rotor geometries with the same nominal diameter and their torque absorption capabilities.

An article by Bronder and Jewett [11] shows that most water brakes are very light weight with a weight to absorbed power ratio of 0.025 lb/hp or about 0.015 kg/kW. The report suggests that an adequately designed water brake can operate over a wide range of torque values and rotational speed, that water brakes can be used with various types of engines, and that the total footprint of the water brake can be kept small by using multiple sets of rotors and stators.

Only a few low-cost dyno projects were made specifically targeting small engines, i.e., engines with a displacement of 300cc or less. The authors will use the results, formulations and design criteria defined by previous studies to make a complete dyno unit.

CHAPTER 2

Design and Calculations

2.1 Brake Design

The water brake can be considered a low efficiency pump, which instead of converting most of the input power (from the engine) into pressure head, transforms most of it into heat which is absorbed by the water. The energy dissipated by the water brake is influenced mainly by the diameter of the brake and the impellor geometry [9] [10].

2.1.1 Brake Diameter:

The torque applied by the water brake depends upon its rotational speed and the diameter of its rotor and impellor. The between the torque and rotation speed is super-linear [10] and is given by:

$$\tau = k\, n^2 \qquad (1)$$

Where "k" is an empirical constant called the dynamometer absorption constant and its value depends on various empirical features of the water brake. The standard formula for the calculating the torque application of the water brake is:

$$\tau = k\, n^2 D^5 \qquad (2)$$

The value of "k" can vary a lot even in a dyno [11] and as such should only be used to estimate the required size of the brake depending on the torque and power output of the engines that are to be tested.

Equation (1) defines the torque absorption ability of a rotor with impellor blades on one side only, this can easily be doubled by using an impellor that has blades on both sides and increased further by using more than one impellor. It also implies that a smaller impellor with blades on both sides can have the same torque absorption as a larger impellor with blades only on one side.

Rao [9] suggests that the value for "k" in commercial dynos ranges from 0.1×10^{-3} lb-min^{2}ft^4 to 20×10^{-3} lb-min^{2}ft^4. Assuming engines producing up to 50 N-m or around 37lb-ft that can have rotation speeds of up to 15000RPM and thus a maximum power output of 78.5kW, using the recommended values of "k" in equation (1) as suggested by Rao, we find that the water brake would have a nominal diameter within the range of 0.096ft – 0.277ft or 0.029m – 0.084m. Reviewing past literature [4] [6] [7] shows that past attempts at manufacturing of water brake dynamometers used rotors of 30cm, which falls within the range of nominal diameters calculated. As such the rotor diameter was selected to be 30cm for the dyno.

2.1.2 Rotor Geometry:

In water brakes, the relations between the torque absorbed and rotational speed, and thus power dissipated vs RPM is super linear, ie. the torque absorbed or power dissipated is low at lower rotational speeds. It is therefore necessary to design the impellor such that it would provide relatively good energy dissipation at low rotational speed without limiting the maximum energy that the brake can dissipate. The energy dissipated by an impeller depends on the radial velocity of the fluid exiting the impellor, therefore the blades of the rotor must be designed such that they can accelerate the water to relatively higher speeds at low rotational speed. The study by Banis [10] shows that the best torque absorption/ power dissipation with a safe design is achieved by using the following parameters: Blade width – 16mm, Rotor to stator gap – 4mm, Blade fillet - 10º. These parameters were used to create models for the rotor and stator in SolidWorks.

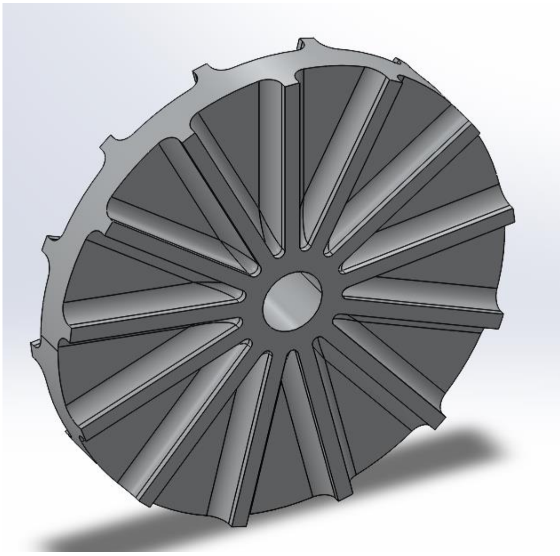

Figure 2-1: Rotor Geometry

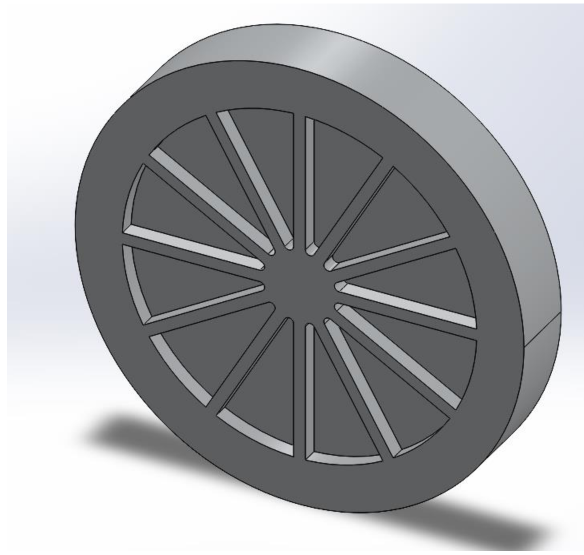

Figure 2-2: Stator Geometry

2.2 Shaft:

A shaft would be used to connect the water brake components to the engine under testing and assemble the brake components together. Due to some part of the shaft being exposed to the water inside the water brake, it becomes necessary to construct the shaft out of nonferrous material. The shaft was designed so that the rotor may be press fitted onto it, with the stators floating on both sides of the rotor on the shaft held in place with brackets.

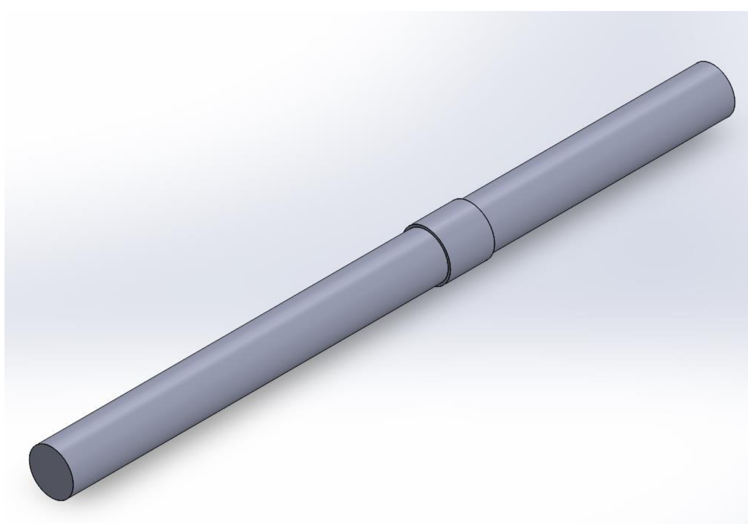

Figure 2-3: Shaft Design

2.3 Hydraulic System:

Since the load provided by the water brake depends on the level of water inside the brake unit, a good hydraulic system which can quickly vary the water level is necessary. To have linear control of applied load, specialized valves must be used either at the inlet, outlet, or both to linearly control the fill level inside the brake unit.

Furthermore, since the heat is dissipated into the water, it is important to maintain a high flow rate of the water through the brake unit while maintaining the fill level of the brake, because high temperatures may cause boiling of water inside the brake unit which would affect the stability of the applied load and cause deposition inside the brake unit and piping system which may affect range of operation. An acceptable temperature is less than 50ºC. A rule of thumb is that a flow rate of 1 g/min is required for every 16.67 hp [11], or about 1 l/min for every 3.28 kW, and thus about 24 l/min for 78.5 kW. Using the heat transfer equation:

$$Q = \dot{m} c_p \Delta T \qquad (2)$$

Using:

$\dot{m}$ = 24 l/min => 0.4kg/s

Q = 78.5kW => 78.5 kJ/s

c_p = 4.18 kJ/kg*K

Giving us a temperature rise of about 44.5 ºC. Thus, to maintain the temperatures below 50 ºC, an inlet temperature of 5.5 ºC would be required. Note that this is an extreme case, realistically engines being tested on the dyno would be producing about 20 kW of power and would produce a temperature rise of about 12 ºC at 24 l/min.

Adding a cooling solution would help keep the water in the reservoir cool but will add to the cost of the project. Furthermore, a large (~200 l) tank would be required in order act as a reservoir of to keep the overall temperatures of the system in control. As such two designs of the hydraulic system can be consideration:

a) A small water reservoir is under the test bed with a high flow, high pressure pump attached to it, moving the water from the reservoir to the brake unit, and the water in the brake unit being dumped back into the reservoir.

b) The water reservoir is present above the test bed, using gravity to cause water to flow through the brake unit into a secondary tank at the bottom with a conventional pump returning the water from the secondary tank to the overhead tank.

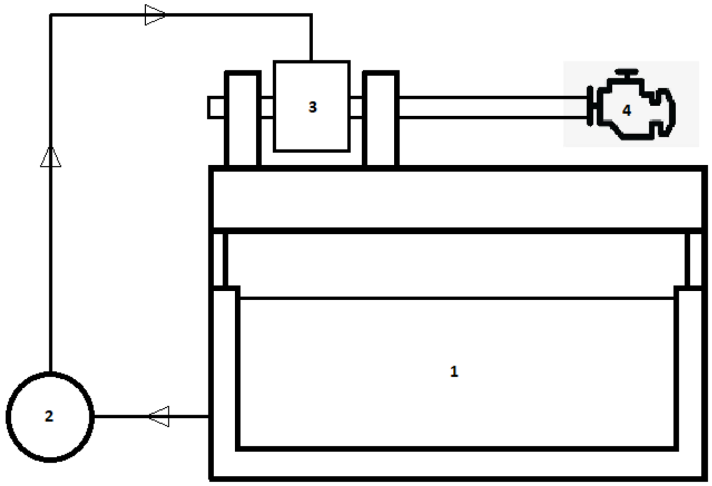

Figure 2-4: Schematics of Design (a) highlighting; 1. Water reservoir, 2. High pressure pump, 3. Water brake, 4. Engine

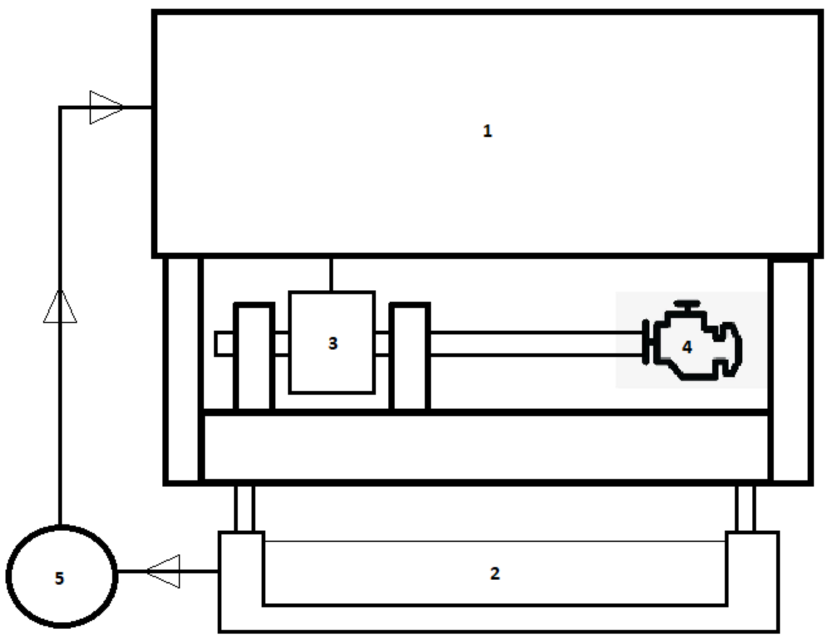

Figure 2-5: Schematics of design (b) highlighting; 1. Main reservoir, 2. Secondary reservoir, 3. Water brake, 4. Engine, 5. Pump

Note that the pressure requirement is about 400 kPa therefore in case of design (b), the water tank must be placed at a high enough point so that the hydrostatic pressure at the entrance of the water brake is equal to or more than 400 kPa. Using the formula for hydrostatic pressure:

$$P = \rho g h \qquad (3)$$

Using;

P = 400kPa

$\rho = 1000 \ kg/m^3$

$g = 9.81 \ m/s^2$

It is found that the outlet of the tank must be at least 41m higher than the inlet of the water brake. This results in difficulty in the design and installation of the dyno. Therefore, using design (a) becomes a more feasible option.

The smallest motors available in the market provide a flow rate of about 60 l/min at 5 bars of pressure. Using equation (2) we find the temperature rise to be about 19 ºC, which means in order to maintain a maximum outlet temperature of 50 ºC, the water inlet temperature must be 31 ºC.

2.4 Cooling system:

As discussed in the previous section, long use of the dyno adds heat into the water, until eventually the entire water in the reservoir is heated up and no longer suitable for use in the dyno. As such a cooling solution becomes necessary for long use. A conventional radiator requires high temperature differences between the working fluid and external environment to operate efficiently, which would be difficult in our case. Thus, a cooling tower is used for the purpose of cooling the water.

The tower consists of a tall, open structure with a large fan at the top. Hot water enters the tower and is distributed over a "fill" that increases the surface area for heat transfer. As the water flows down through the fill, it is exposed to a flow of air generated by the fan. This air absorbs the heat from the water, causing a portion of it to evaporate, which further enhances the cooling process. The evaporated water, along with the excess heat, is expelled into the atmosphere through the tower's top, while the cooled water is collected at the bottom and pumped back into the system.

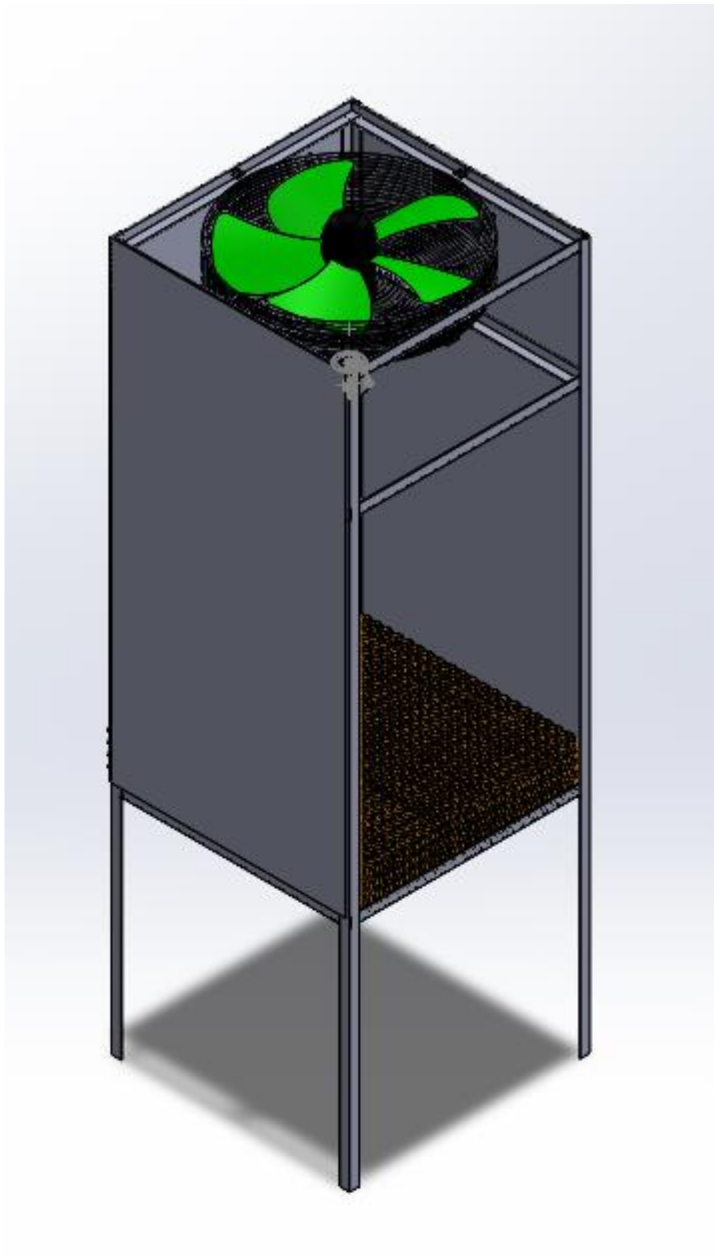

Figure 2-6: cooling tower assembly

The design of the cooling tower was selected according to a past project, with a smaller size, 6x2x2 ft in dimensions, and a splash-film type fill. The fill material selected was the locally available cellulose fill. This type of fill material is mainly used in air coolers and promotes the evaporation of water. The fan selected was a 18 inch unit from PakFans with an advertised air flow of 1200 CFM. For the water inlet, a spray was made using PRC pipes, with holes drilled into them. Such a nozzle may not produce a fine mist of the water, but would enable water to be distributed over the fill at a low cost.

2.5 Control System:

A robust control system is required for accurate load control and data acquisition. The control system would have to measure the rotational speed of the rotor/engine and the torque produced by the engine, allow manual control of the braking load, be able to vary braking load for sweep testing and calculate torque and power using the data from the sensors.

The sensors required for basic functioning of the dyno would be a hall effect sensor, to measure the rotational speed, mounted on the input shaft of the rotor and a load cell, to measure engine torque, mounted to the brake casing using an armature (moment arm) of known length.

The center of the control system would be an Arduino connected to a pc running a MATLAB script to view real time data from the dyno, run the dyno in the required operation mode and plot torque/power graphs.

The length of the moment arm has a profound effect on the force applied on the load cell, according to the equation:

$$\tau = F.r \qquad (4)$$

Equation (4) suggests that at a constant torque, the force applied on the load cell would be inversely proportional to the length of the moment arm, that is the longer the moment arm is, the smaller the force experienced. It is therefore necessary to ensure both that the moment arm is not too short so that the force becomes very high and that the load cell being used has a high enough load measuring capability.

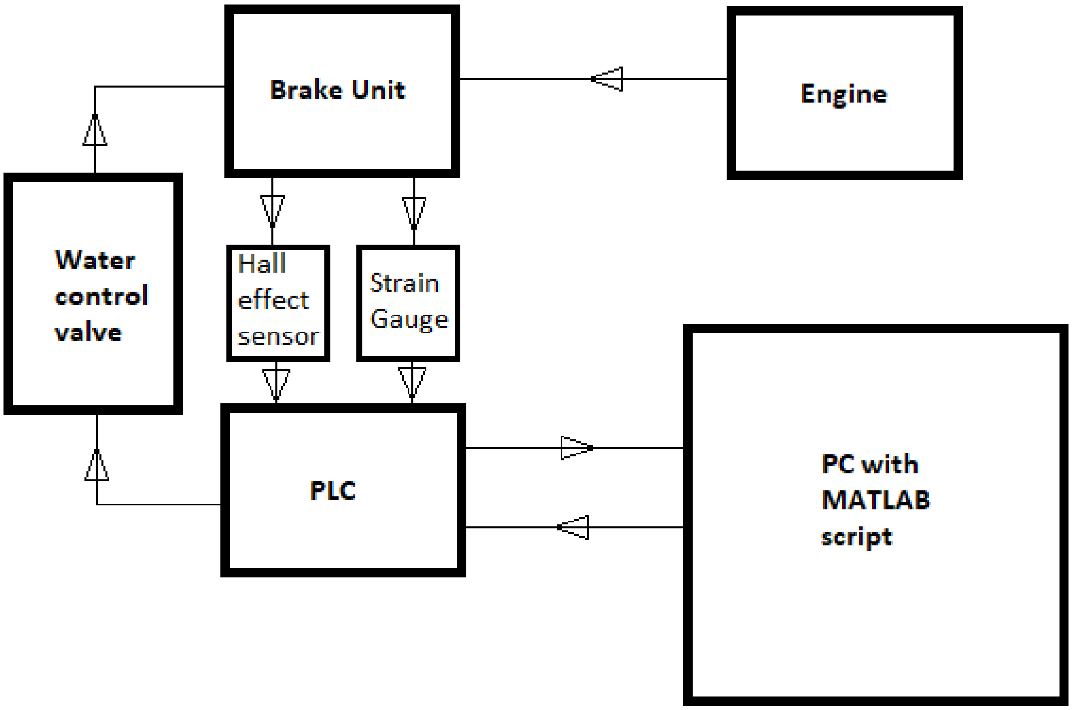

Figure 2-7: Block diagram of basic dyno control loop

2.6 Coupling

To connect the engine to the dyno, some form of coupling is required. The coupling must connect the output shaft of the engine to the input shaft of the dyno and must be able to withstand not only the load from power transmission, but also those from shock and increased stresses due to misalignment. Common chain and sprocket style connection proves to the most viable as it easily covers all the design requirements that were discussed previously.

Most small engines, especially small motorcycle engines have a primary reduction gear place before the transmission. These serve to increase the output torque. But they also reduce the rotational speed at the output. This reduction ratio is generally of the order of 3.5 – 4. This proves to be a great problem for the water brake, as the brake force produced by it depends on its rotational speed. Thus, if the rotational speed falls too low, the brake may not be able to operate properly. As such a gear box must also be designed to allow for increasing the rotational speed of the dyno shaft. For this purpose, spur gears from the reverse gear of the Suzuki Ravi were used as they provide a gear ratio of 1.9. Combining two of such gears to form a gear train nets us a total gear ratio of 3.61. Off the shelf gears were chosen as they allow for greater efficiency. Spur gears have a general efficiency of 98%, and chain-sprocket connections have a total efficiency of around 95%. Thus, our proposed gear train would have a theoretical efficiency of 91.24 efficiency.

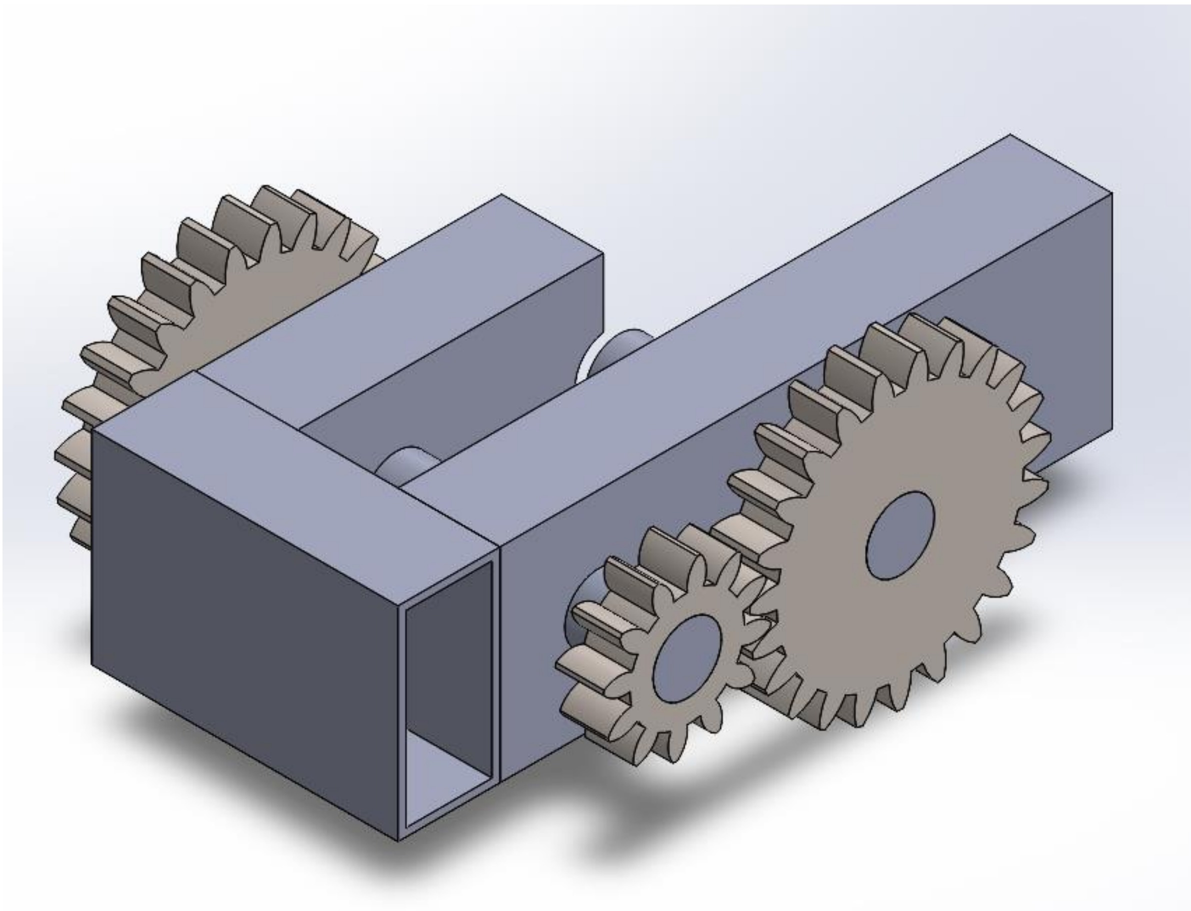

Figure 2-8: Gear box assembly

2.7 Test bed:

The test bed serves as the mounting point for all the dyno components. As it must not only bear load in the form of weight, but also absorb vibrations from the engine, it is generally mounted onto a thick plate (> 2 cm in thickness) or bolted into the floor. Since the dyno is intended to be used in the automotive lab in the university, it would likely be mounted into the floor within the lab, however for the sake of the project a portable test bed must be assembled.

The test bed assembly consists of two separate beds, one for the brake and one for the engine. The beds were made separate to allow for easier transport and coupling.

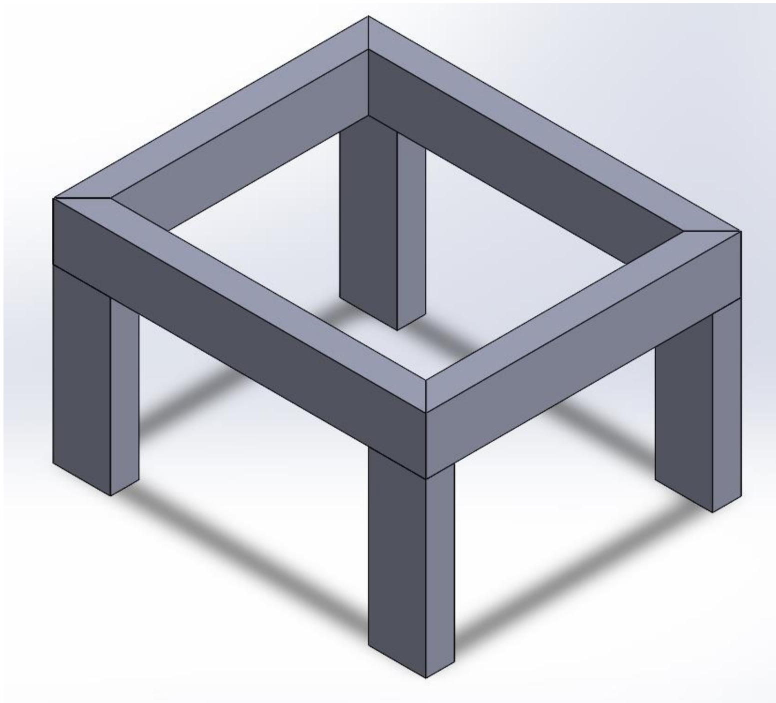

Figure 2-9: Dyno Bed

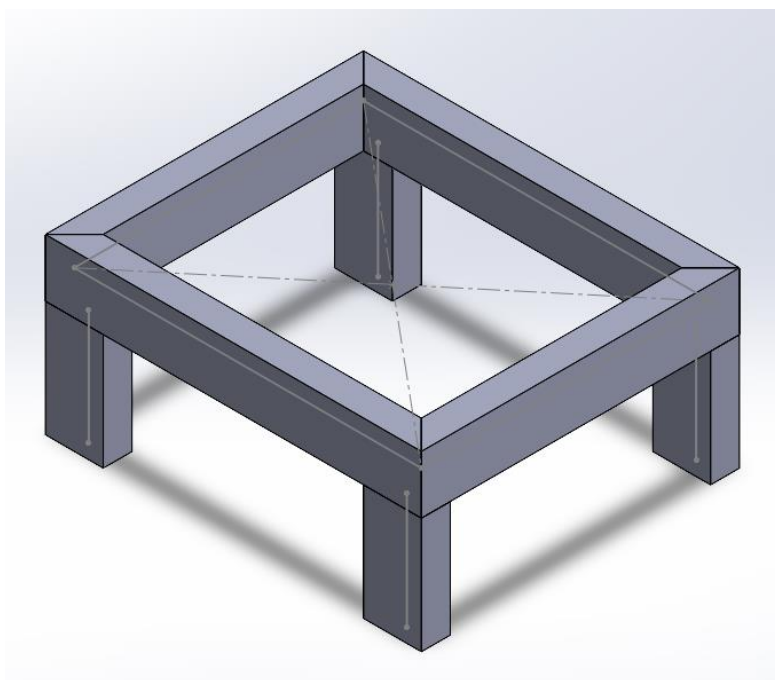

Figure 2-10: Engine Bed

Both the engine and dyno beds were made to have the same shape, with the engine bed having a lower height, this was done to ensure that the engine sprocket and input sprocket of the gearbox are aligned so that they may be coupled using a chain, without the chain colliding with any of the supporting beams.

It must be added here that a dynamometer assembly should be mounted on a heavy slab or mounted directly into the ground at the location it is intended to be used. The purpose of using separate dyno and engine beds was only to allow for easy transportation of the project and that it must be mounted properly before use.

2.8 Material Selection:

The most important consideration to be made when selecting the material for the brake unit (Rotor, Stator, Casing etc.) is that the material should resist corrosion due to water. This requirement eliminates iron and most steel alloys for use in the brake unit. The second important aspect in our design is the cost of the material, that is if FEA analysis of the unit proves that a cheaper metal can withstand the fatigue and stresses produced during operation with an acceptable, it would be preferred over the more expensive metal. The material selected for the brake component is 6061-T6 grade aluminum. The shaft of the brake unit must bear torque and must be resistant to corrosion by water, so stainless steel was selected for the shaft.

The material for the cooling tower structure is aluminum angles with fiber-glass walls. Aluminum angles are relatively cheap, and their geometry allows them to bear considerable weight without deforming, allowing them to be used for the structure. Fiber-glass sheets for making shades are coated with weather resistant films and can withstand constant exposure to moisture without fouling, and thus they are a good choice for acting as the wall of the tower.

The sprocket, gears and chain were selected off the shelf and are made of hardened steel. Selecting these components off the shelf makes it cheaper as they are manufactured in bulk and so the unit cost of each part drops, and since they are made of hardened steel, for use in similar or situations with much greater loads, they can be safely used in the dyno.

Since the beds are not expected to be used for long and they are not intended to encounter water, they were constructed using 1x2 inch 18-gauge rectangular AISI 1020 steel tubes. The steel tubes have performed well when used as a structural member, withstanding forces from all directions easily.

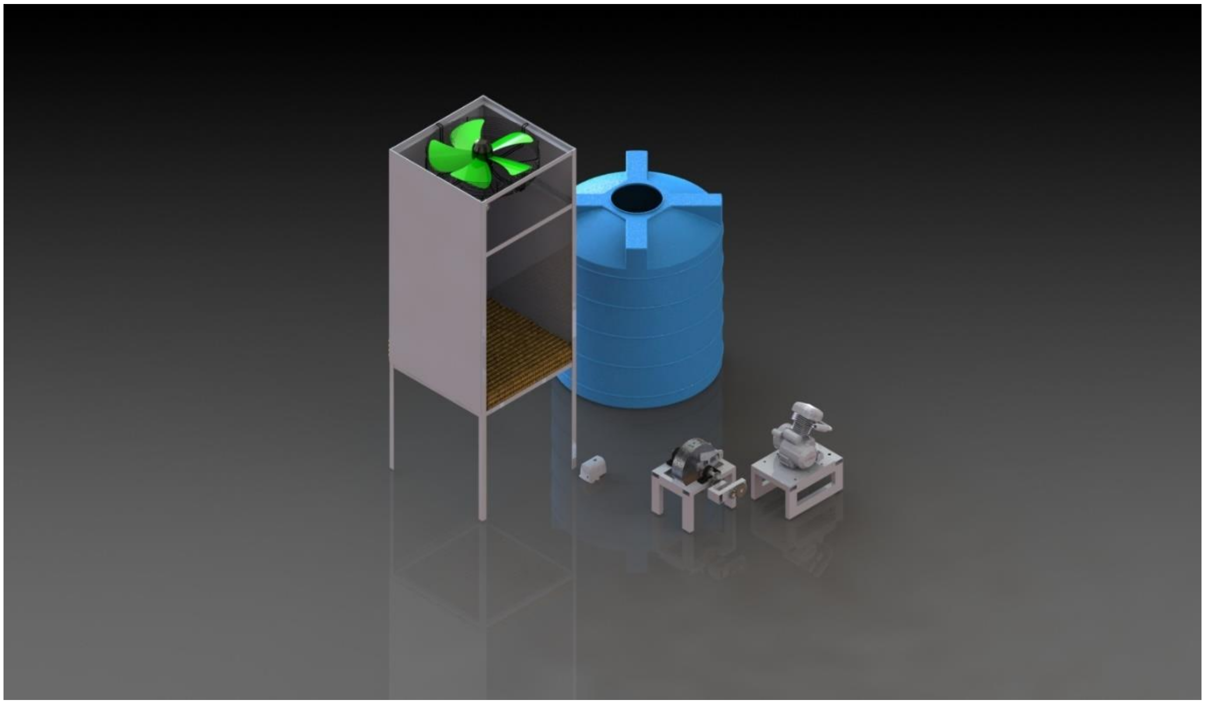

Figure 2-11: Render of complete dyno assembly

CHAPTER 3

Simulations, Manufacturing and Controls

3.1 Water Brake

Since the formulas developed for water brakes are all empirical, we cannot use them to completely define the geometry of the water brake. As such, we chose to simulate fluid flow in the water brake as it would allow us to estimate the brake torque.

The CFD for the water brake was done in SolidWorks, as it allows us to easily study various rotor sizes and blade geometries. The boundary conditions for the simulations were set according to the suggestions by Banis [10]. The simulations were mainly focused on the braking torque produced at 2000RPM. The rotational speed of 2000 RPM is significant as engine testing generally begins at this speed, and with the water brake's tendency to produce low braking torques at lower speeds, the braking torque produced at this speed would represent the minimum it can produce.

Various designs were simulated with the most appropriate blade geometry as defined in literature (discussed in section 2.1) and rotor sizes ranging from 10 cm to 30 cm. it was found that a rotor with a diameter of 15 cm proved to be the most effective in terms of both brake force and cost, producing 10 Nm of braking torque and weighing in a 1.8 Kg, it can be cheap to manufacture.

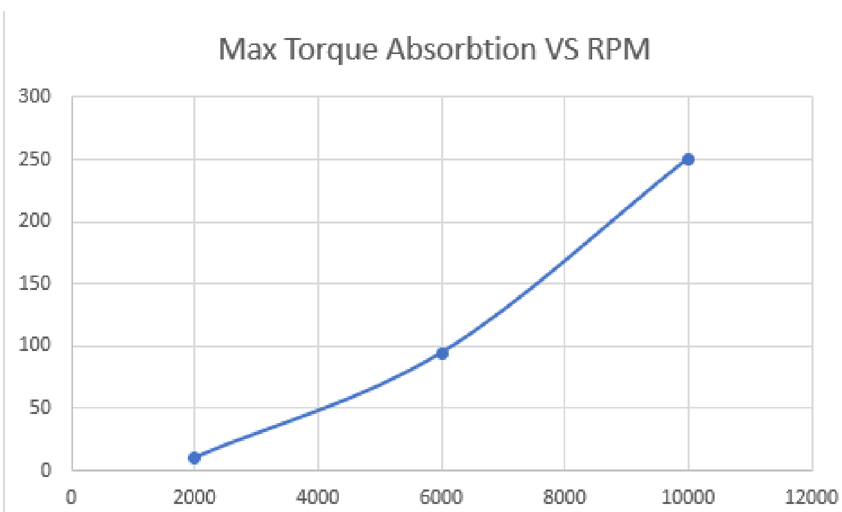

Figure 3-1: Maximum torque (Nm) vs rotational speed (RPM) of water brake

The initial consideration for the manufacturing process of the water brake components was to have them milled from aluminum blocks using CNC machines. This would ensure that the proper blade geometry is made, and the rotor is dynamically balanced due to equal density distribution. However, CNC milling is an expensive operation, and so using it for manufacturing it would defeat the purpose of the project. Thus, the rotor was cast. To ensure that the proper blade geometry is achieved, the pattern for the mold was 3D printing in PLA with a tolerance of 2mm on both side to allow for facing. The facing process also led to balancing the small imbalance that was produced because of the casting process. The inside faces of the rotor and stator were not cleaned. This was done on purpose, as the rough surface of the pockets would produce better shearing on the rotor surface and thus better braking performance. Do note that the braking force due to shearing on the pockets is very small, as most of the braking is produced by the blades of the rotor and stator.

3.2 Test bed

Regardless of the duration of use, the test bed must be strong enough to tolerate the load and vibrations it may encounter during use, as such it was analyzed for its strength and modes. Modal analysis becomes important as smaller engines generally have a single cylinder and thus have a large force imbalance during operation, producing vibrations. If the engine speed and thus the vibrations of the engine and the natural frequencies of the beds match, it would lead to increased vibrations that may end up destroying the test bed.

ANSYS was used for both the stress and modal analysis and the bottom of the legs of the beds were fixed to simulate operation while the test bed is fixed in the lab using one of the solutions discussed prior.

For the stress analysis, a load of 5,000 N, corresponding to a weight of over 500 kg, was applied to the top, front and side of both the dyno and engine bed. Both the engine and dyno beds were able to withstand these forces, with a minimum factor of safety of 1.726 for tensile, 1.6176 for shear, 1.2938 for fatigue and 2.733 for tensile, 2.4735 for shear, 2.0488 for fatigue occurring in the longitudinal force simulation of both the engine and dyno beds respectively. It should be noted here that the maximum weight that would be placed on the bed would not exceed 50 kg, or the maximum mass would not exceed 490.5N. In other words, the beds have more than enough strength to tolerate dyno operation.

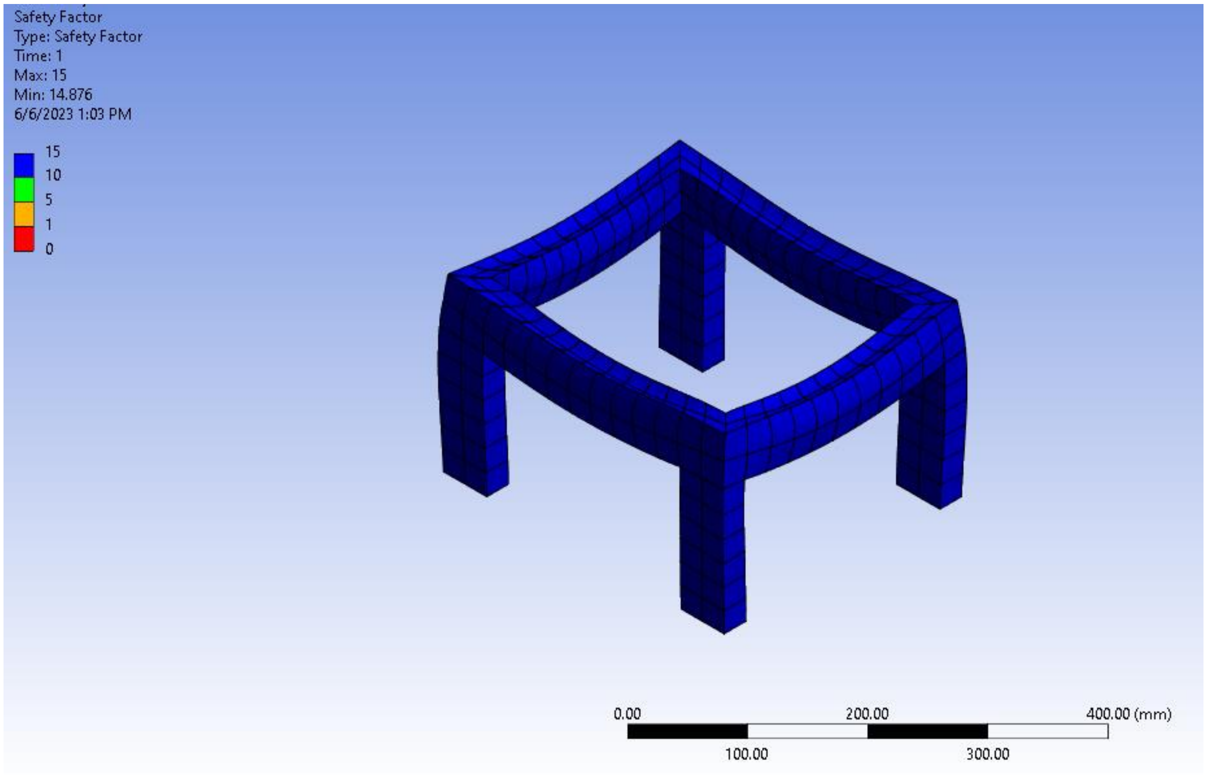

Figure 3-2: Dyno Bed, Top load safety factor

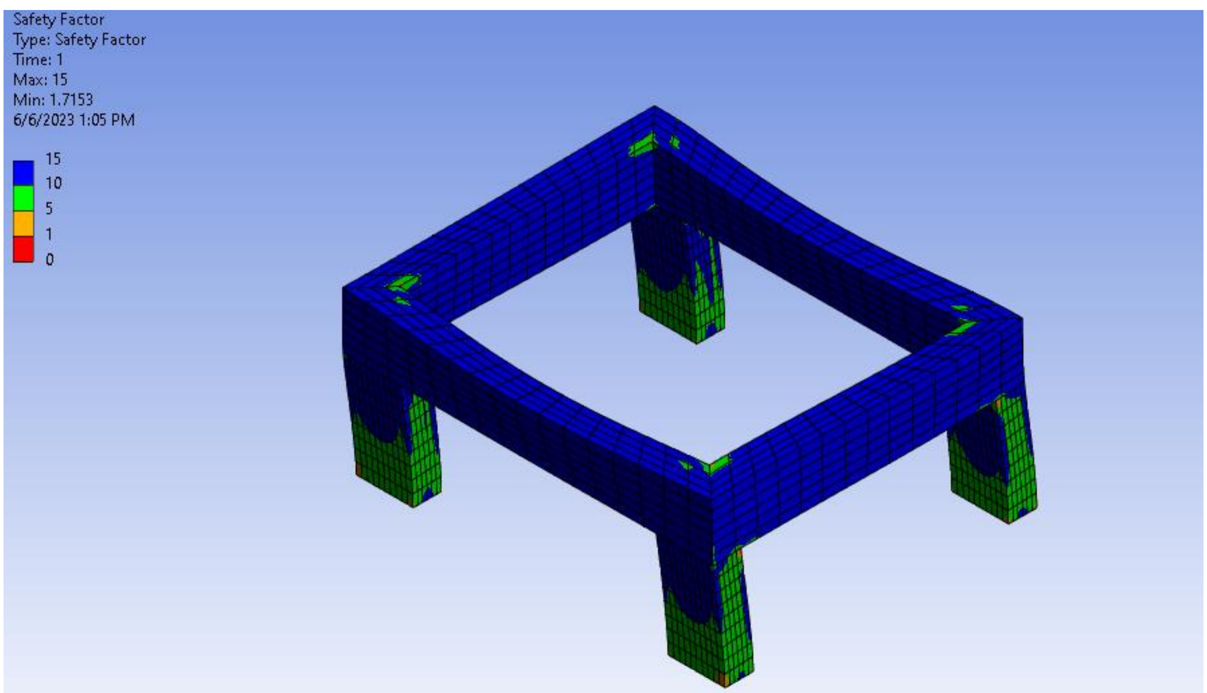

Figure 3-3: Engine Bed, Top load safety factor

The modal analysis shows that the first modes of the dyno bed and engine bed are formed at 539.48 Hz and, corresponding to a rotational speed of 32368 RPM and 46186.2 RPM respectively. The engines intended for use with the dyno do not exceed a speed of 12000 RPM, and thus damage due to vibration is minimal.

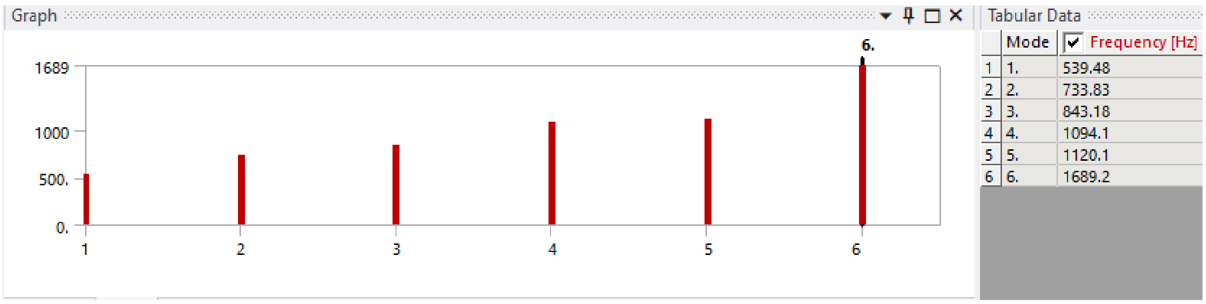

Figure 3-4: Modal Analysis, Engine bed

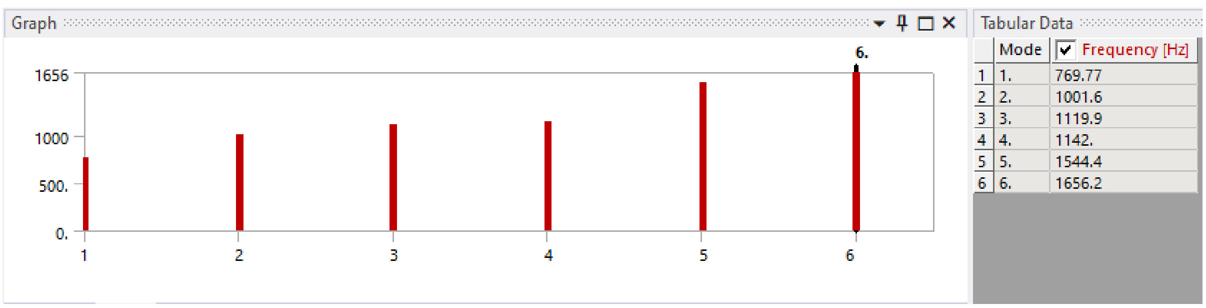

Figure 3-5: Modal Analysis, Dyno Bed

The Steel tube used for the construction of the test bed were cut with a miter joint and welded. The miter joint has the advantage that it allows for a seamless connection between the two tubes, with the weld adding to the strength of the joint.

The gearbox was also made of steel tubes and welded onto the dyno bed.

3.3 Cooling tower

The maximum possible cooling capacity of the tower was already estimated to be sufficient in the worst operating conditions, therefore the simulations of the cooling tower consisted only of the strength of the tower structure. Same as with the test bed, the load and modal analysis of the tower was done in ANSYS, with the bottom of its legs fixed.

For the stress analysis, a load of 1000N, corresponding to a weight of 100kg was placed on the top part of the cooler, where the fan would be mounted. This resulted in a factor of safety of 7.11, 6.62 and 2.1 in the case of tensile, shear and fatigue respectively.

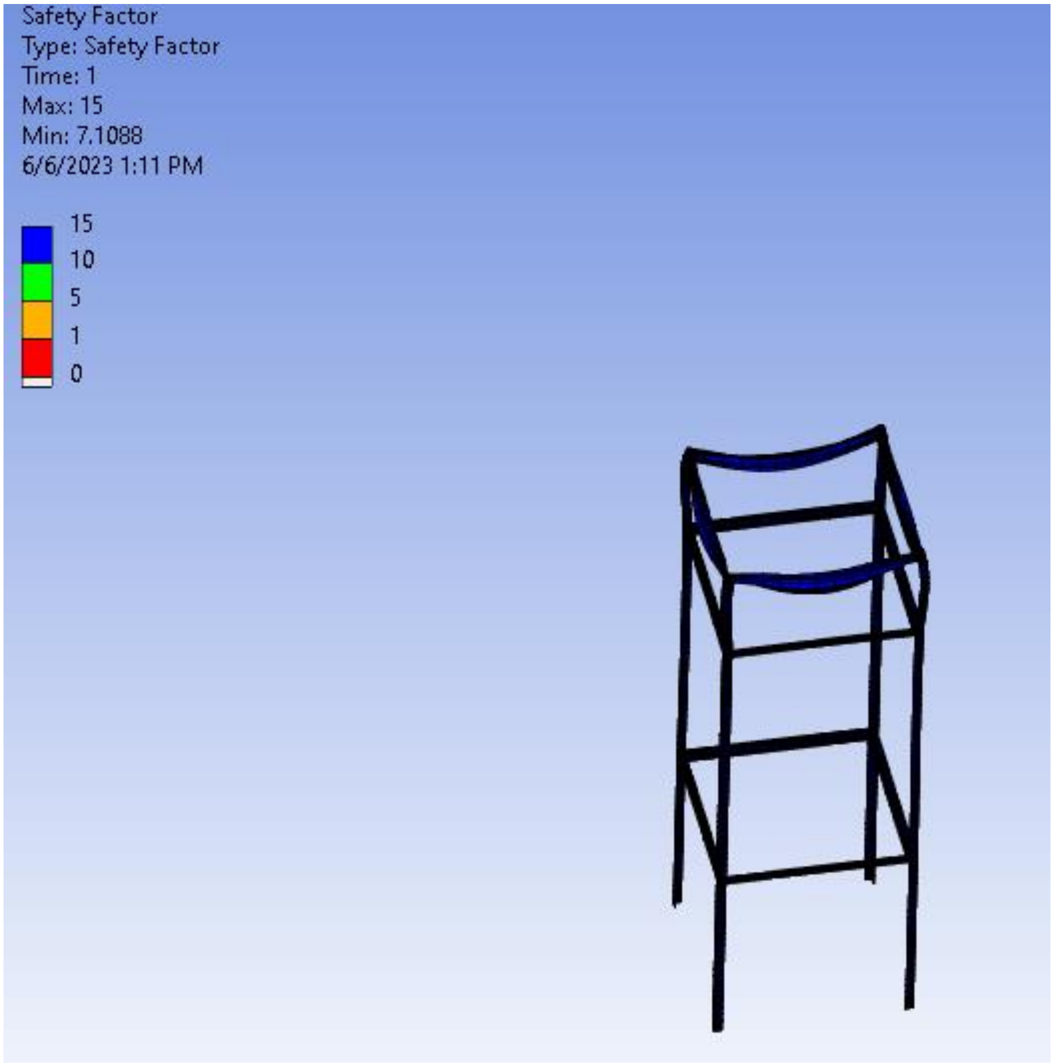

Figure 3-6: Cooling tower, Top load safety factor

The modal analysis shows that the first mode of the tower forms at 11.37 Hz. It must be noted that the rotation of the fan does not induce any vibration into the structure, considering the fan blades do not have anything stuck onto them, as the fan operation is generally well balanced and does not produce any vibrations. And even if one assumes that it does, none of the modes occur at the rotational speed of the fan (1500 RPM).

The structure of the tower was erected using rivets and screws, allowing for easy assembly and disassembly. The aluminum angles used for holding the structure together also serve as the mounting points for the fill, the inlet, and the fan. The fill was cut to size and pressed into its place in the tower. This allows for quick and easy removal of the fill for cleaning or replacement. PPR pipes were used to create a water spray system, with 8 rows of 3 holes, 5 mm in diameter across 4 pipes. For a single hole of 5mm with 4 bar, the maximum flow rate of water through a single hole is:

$$Q = C_d * A * \sqrt{(2*\Delta P*\rho)}$$

Where;

$$A = \pi * (d/2)^2 = \pi * (5mm/2)^2 = \pi * (0.005m/2)^2 \approx 0.00001963\ m^2$$

Assuming a C_d of 0.61:

$Q = 0.61 * 0.00001963\ m^2 * \sqrt{(2*400000*1000)}$

$Q = 0.00003474\ m^3/s$.

Or;

$Q = 2.0844$ l/min.

Thus, for (3*8*4) 96 holes, the maximum possible flow rate would be 200.1024 l/min, which is sufficient.

The fiber-glass sheets were riveted to the structure and silicon sealant was used to ensure no air or water leaks out from the sides.

3.4 Control system

The control system was based around the Arduino due to its low cost and availability. The Arduino uno has sufficient processing power to be able to calculate the rotational speed and torque and power figures. But to ensure that the accuracy of the data is not affected by the processing power of the Arduino, a MATLAB script was also written to be able to integrate with the Arduino during operation and take the processing load off the Arduino.

The Arduino code calculates the rpm of the rotating dyno shaft, and the force on the load cell and sends it to the MATLAB script via serial communication.

```
#include <Wire.h>
#include <HX711.h>

#define DOUT_PIN  2
#define CLK_PIN   3

HX711 scale;

void setup() {
  Serial.begin(9600);
  scale.begin(DOUT_PIN, CLK_PIN);
}

void loop() {

  float force = scale.read();

  float momentArm = 0.15;  // Moment arm in meters
  float torque = force * momentArm;

  int hallPin = 4;
  int pulsePerRevolution = 2;
  int rpm = calculateRPM(hallPin, pulsePerRevolution);

  Serial.print("T:");
  Serial.print(torque);
  Serial.print("Nm,");
  Serial.print("P:");
  Serial.print((torque * rpm * 2 * PI / 60)/1000);
  Serial.print("kW,");
  Serial.print("R:");
```

```
  Serial.println(rpm);

  delay(100);
}

int calculateRPM(int hallPin, int pulsePerRevolution) {
  static unsigned long lastTime = 0;
  static unsigned long pulseCount = 0;

  if (digitalRead(hallPin) == HIGH) {
    unsigned long currentTime = micros();
    if (currentTime - lastTime > 1000) {
      pulseCount++;
      lastTime = currentTime;
    }
  }

  unsigned long elapsedMillis = millis() - lastTime;
  if (elapsedMillis > 1000) {
    int rpm = (pulseCount * 60 * 1000) / (elapsedMillis * pulsePerRevolution);
    pulseCount = 0;
    lastTime = millis();
    return rpm;
  }

  return 0;
}
```

The MATLAB script takes the data from the Arduino, performs the unit conversions and calculations to get the appropriate data from the readings. It then displays the data on a graph and the live values. When the code is terminated, the MATLAB script saves all the data points in an excel spreadsheet and the graph as an image.

```
s = serialport("COM3", 9600);

rpm = [];
torque = [];
power = [];

figure;
ax = subplot(2, 1, 1);
hold(ax, 'on');
hTorque = animatedline(ax, 'Color', 'red');
hPower = animatedline(ax, 'Color', 'blue');
xlabel('RPM');
ylabel('Torque / Power');
legend('Torque', 'Power');
title('Torque and Power vs RPM');
grid on;

ax2 = subplot(2, 1, 2);
hRPM = animatedline(ax2);
xlabel('Time (s)');
ylabel('RPM');
title('RPM vs Time');
grid on;

while ishandle(ax)

    data = readline(s);

    values = split(data, ",");
    t = str2double(extractAfter(values(1), "T:"));
    p = str2double(extractAfter(values(2), "P:"));
    r = str2double(extractAfter(values(3), "R:"));

    rpm = [rpm, r];
    torque = [torque, t];
    power = [power, p];

    addpoints(hTorque, rpm(end), torque(end));
    addpoints(hPower, rpm(end), power(end));
    drawnow limitrate;

    addpoints(hRPM, numel(rpm), rpm(end));

    if ~ishandle(ax)
        break;
    end
```

```
end

data = [rpm; torque; power];
headers = {'RPM', 'Torque', 'Power'};
xlswrite('data.xlsx', [headers; num2cell(data)]);

saveas(gcf, 'plot.png');

fclose(s);
delete(s);
clear s;
```

Using this method of separating the data acquisition and control system onto two platforms, that is, the computer and Arduino respectively, helps keep the overall code clean and keeps the operating speed of the Arduino fast to allow for better resolution in the results and provides enough head room for more features to be added to the dyno later down the line.

CHAPTER 4

Limitations, Recommendations and Conclusions

4.1 Brake unit

The major drawback of a water brake is its tendency to have low torque absorption at lower rotational speeds. While the water brake in the project was designed to be able to produce the required torque even at low RPM, it still leaves much to be desired, especially considering the very high torque absorption at higher engine speed (figure 3-1). Also, the inclusion of the gearbox, to increase the rotational speed of the water brake, also introduces mechanical losses into the coupling, which has an impact on the accuracy of the measurement.

One possible solution to this problem would be to attach a motor/generator unit to the brake, effectively converting it into an electrical – water hybrid brake unit. The motor/generator unit would act as the primary source of brake at lower RPMs, combatting the low braking of the water brake, while the water brake, with its excellent braking at higher speeds would take care of the braking at higher speeds. It would also enable transient testing of engines, enable the dyno to be used with a smaller gearbox and enable the dyno to be able to test even larger engines.

Such an addition would require the shaft of the unit to be extended to allow for coupling the water brake and motor. It would also require the redesigning of the gearbox to a single reduction since the need for such high gear ratios would be mitigated with the inclusion of the motor/generator unit.

4.2 Cooling tower

The current cooling tower design was selected purely on a budget basis, since the dyno would not be operated at it's maximum potential at all times, and therefore the temperature rise of the water exiting the brake would not be as significant as was found in the calculations. But that does not mean that there would be no change in water temperature and so, to ensure stable long-term operations, the inclusion of the tower is necessary.

Currently, the fill used for the tower is 7090 cellulose fill, where 7090 refer to the size of the air passages in the fill (7mm by 9mm). Cellulose has great water absorption properties and cellulose fill is commonly used in air coolers, where its primarily purpose is to cool the air, not the water. It also promotes water evaporation, to help increase the humidity of the air.

While the current tower design does produce cooling in the water, the properties of the fill are not the most desirable for use in a cooling tower and so the fill may be replaced in the future. The new fill can be film fill, splash fill or a combination of bother depending on the budget and future requirements. A simpler solution may be to place a drift eliminator at the top of the tower just before the fan, which would reduce the water losses in the tower.

4.3 Control system

The current control system does everything it needs to with enough head room for additions of more features in the futures. Such features may include an inclusion of a stepper motor to control automate the value operation, fuel metering capabilities for BSFC calculations, inlet and exhaust temperature and air content analysis for emission testing and so on. The current platform allows for easy implementation of these features. Furthermore, a standalone program can also be created with MATLAB to enable use of the dyno control system on computers which may not have MATLAB installed.

4.4 Conclusion

The initial deliverables set for the project were the design and manufacturing of a water brake and it control system. The team has successfully completed the project, meeting the deliverables, and then some.

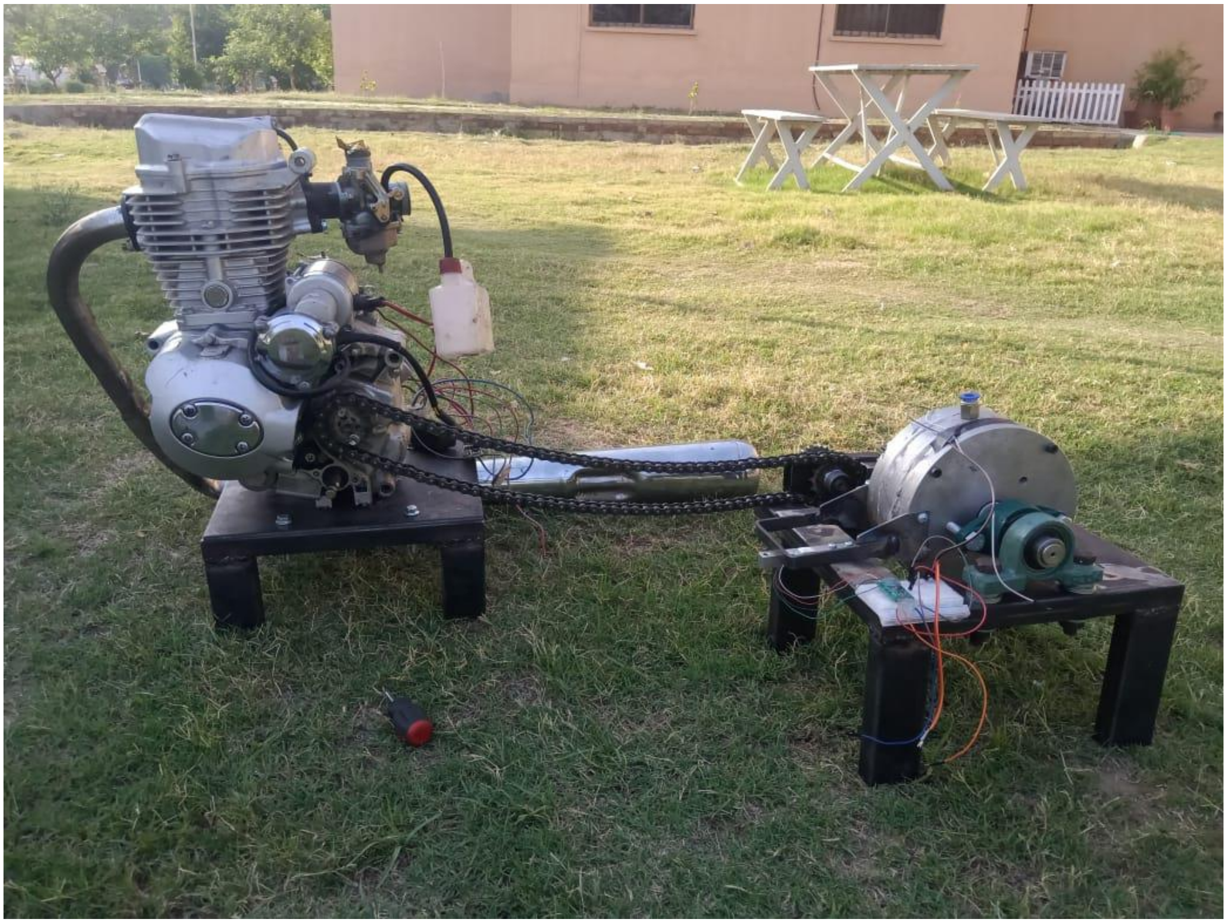

Figure 4-1: Dyno and Engine mounted on the beds.

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