DEVELOPMENT OF HYDRAULIC REGENERATIVE BRAKING TESTBENCH

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LIST OF ABBREVIATIONS

APP	=	Accelerator Pedal Position
BPP	=	Brake Pedal Position
CAD	=	Computer-Aided Design
CATIA	=	Computer-Aided Three-Dimensional Interactive Application
FBD	=	Free-Body Diagram
F1	=	Formula One
HEV	=	Hybrid Electric Vehicle
HHV	=	Hydraulic Hybrid Vehicle
HPA	=	High Pressure Accumulator
HRB	=	Hydraulic Regenerative Braking
HRBS	=	Hydraulic Regenerative Braking System
KERS	=	Kinetic Energy Recovery System
MG	=	Electric Motor/Generator
PTTR	=	Parallel-Through-The-Road
PWM	=	Pulse Width Modulation
SOC	=	State Of Charge
WLTC	=	Worldwide Harmonized Light Vehicles Test Cycles

ABSTRAK

Kenderaan hibrid adalah kenderaan yang beroperasi dengan menggunakan gabungan dua sumber kuasa. Teknologi hibrid membantu mengurangkan penggunaan bahan api dan pelepasan gas daripada kenderaan melalui sistem brek regeneratif dan pecutan bantuan. Disebabkan kebanyakan kenderaan ringan dipasang dengan sistem hibrid elektrik, projek ini memberi tumpuan kepada pemasangan sistem hibrid hidraulik ke dalam kenderaan ringan penumpang untuk mengkaji prestasi kenderaan hibrid hidraulik. Meja uji untuk sistem hibrid hidraulik dalam keadaan rangka badan kenderaan yang selari melalui jalan telah dibina yang melibatkan proses pemilihan konfigurasi-konfigurasi hidraulik, mereka bentuk sistem kawalan, susun atur litar hidraulik dan model meja uji menggunakan komputer, dan menganalisis prestasi yang dijangka untuk sistem brek regeneratif. Analisis prestasi terdiri daripada pemilihan panduan tali pinggang berbentuk V untuk brek regeneratif dan pengesahan kadar nyahpecutan kenderaan hibrid hidraulik menggunakan data kitaran memandu. Analisis pemilihan tali pinggang V menunjukkan satu tali pinggang V jenis D boleh mengharungi brek regeneratif tanpa haus. Untuk analisis kadar nyahpecutan, kadar nyahpecutan purata untuk kenderaan hibrid hidraulik lebih tinggi daripada nilai dalam kitaran memandu dengan perbezaan sebanyak 85% manakala kadar nyahpecutan maksimum untuk kenderaan hibrid hidraulik mempunyai perbezaan sebanyak 22% sahaja dengan nilai dalam kitaran memandu. Oleh itu, pengubahsuaian terhadap sistem kawalan sangat diperlukan untuk mengawal nyahpecutan oleh kenderaan hibrid hidraulik. Dengan adanya keputusan daripada analisis-analisis ini, pengubahsuaian dan pembinaan meja uji kenderaan hibrid hidraulik yang lengkap dapat dilaksanakan pada masa akan datang, begitu juga dengan pelaksanaan ujian terhadap operasi hibrid hidraulik.

ABSTRACT

Hybrid vehicle is a vehicle that operates with the combination of two power sources. The hybrid technology helps reduces the vehicle fuel consumption and gas emissions through the regenerative braking and acceleration assist system. As most of the light duty vehicles are equipped with electric hybrid system, this project focuses on the implementation of hydraulic hybrid system into the light passenger vehicle to study the performance of hydraulic hybrid vehicle (HHV). The test bench for hydraulic hybrid system in parallel-through-the-road architecture is developed which involved the processes of hydraulic configurations selection, designing the control system, the hydraulic circuit layout and test bench CAD model, and analyzing the expected performance of regenerative braking system. The performance analysis comprises of V-belt drive selections for regenerative braking and validation of HHV deceleration rate using drive cycle data. The V-belt selections analysis shows that one V-belt type D can undergo regenerative braking without slip. For deceleration rate analysis, the average deceleration rate of HHV is much higher than that from drive cycle with the difference by 85% while the maximum deceleration rate of HHV have the difference by only 22% from the drive cycle value. Therefore, the modification on the control system is necessary to control the HHV deceleration. With the result of these analyses, the modification and complete fabrication of HHV test bench can be accomplished in future as well as the testing of hydraulic hybrid operation.

CHAPTER 1

INTRODUCTION

1.1 Background of Hybrid Technologies

The development of fuel saving technologies for vehicle has become one of the popular topics nowadays due to the concern on the impact of carbon emissions from the vehicle to the environment (Vjekoslav Tvrdić, 2018). Excessive usage of non-renewable energy sources (fossil fuels) by the conventional vehicle propulsion system has contributed to the increasing environmental air pollution through the extensive carbon emissions. Therefore, further research and development on hybrid vehicle system is crucial in order to further minimize the carbon emissions by the vehicle. The light and heavy commercial hybrid vehicles currently can be categorized into two major technologies which are Hybrid Electric Vehicle (HEV) and Hydraulic Hybrid Vehicle (HHV).

The hybrid vehicle uses regenerative braking system to recover the kinetic energy losses during braking and stores it inside the energy storage equipment to be used during acceleration. For HEV, it uses battery to store the recovered kinetic energy. However, due to the nature of batteries that store low amount of power per unit volume, another alternative which is HHV system is considered the best choice which uses accumulator as the energy storage equipment with the capability to store large amount of power per unit volume (Muhammad Iftishah Ramdan, 2019). By using HHV system, more kinetic energy losses during braking can be recovered and stored inside the accumulator and that large amount of stored energy can greatly boost the vehicle acceleration with significant reduction of power output from the engine compared to HEV system. During regenerative braking process, the input from the brake pedal initiates the system where the hydraulic pump uses the kinetic energy that otherwise be wasted from braking to pressurize the hydraulic oil from hydraulic tank and transfer it into the accumulator. The process of charging the accumulator converts the kinetic energy into potential energy. For the acceleration assist process, the input from the throttle pedal will initiate the system where the hydraulic motor will reuse the previously stored potential energy by converting it back to kinetic energy in which producing extra power to the driving wheels to assist the vehicle acceleration. Both processes of the system is repeated during vehicle's stop and go motions.

1.2 Problem Statement

Globally, the development of HHV system has been mainly focused on the heavy duty vehicles which operate with high power propulsion system. This means that this vehicle category is able to recover great amount of kinetic energy during braking. However, the HEV system is the most popular being implemented into the light duty passenger vehicles rather than HHV system. Therefore, further research study on the implementation of hydraulic hybrid system into the light duty vehicle is crucial to be conducted to obtain more knowledge and information regarding its performance.

1.3 Objectives of the project

- To design and fabricate a Hydraulic Regenerative Braking (HRB) test bench.
- To perform analysis on the HRB system performance.

1.4 Scope and Limitation of the project

This project focuses on the Hydraulic Regenerative Braking (HRB) test bench development, analysis on the regenerative braking performance and analysis on suitable number of belts required for V-belt drive system of regenerative braking. The HRB test bench setup is based on passenger vehicle of Perodua Myvi with 1.3L K3-VE engine. The selection of suitable size and specification of hydraulic components is involved in designing the test bench. The design of HRB test bench is modeled first using Computer-Aided Design (CAD) software to demonstrate the layout of HRB system components on the test bench before the fabrication takes place. The purpose of analysis on HRB performance is to obtain average and maximum vehicle deceleration rates, and validates these data with that data from drive cycle. The different types of V-belt is analyzed to select the best V-belt type that could resist belt slippage during regenerative braking.

The limitation of this project is the testing of HRB operation on the test bench will not be conducted due to the constraint of the project duration. As the fabrication of HRB test bench is a very time consuming process, therefore the project scope has been narrowed down from the original scope. This means that there will be no experimental result of average and maximum deceleration rates to validate the analysis result. So, the testing of HRB performance on the test bench will only be performed in future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter explains various types of hybrid vehicle and the description of Hydraulic Regenerative Braking (HRB) system. The previous related work on the development of HRB test bench are presented as well as the description of main hydraulic components.

2.2 Types of Hybrid Vehicle

There are various types of hybrid vehicle that have been used commercially and in racing applications nowadays which are hybrid electric vehicle (HEV), kinetic energy recovery system (KERS) and hydraulic hybrid vehicle (HHV). An HEV is a vehicle that propels using an engine and an electric motor/generator (MG), where the MG operates as a generator to recover the kinetic energy from the braking and stores it inside the battery (Li Houyu, 2011). The MG operates as motor to use the stored energy for assisting the acceleration. Next, KERS is a system that also recovers the dissipated kinetic energy during the braking and stores it inside an energy storage device which is flywheel for mechanical KERS (Pottabattini Naveen, 2014). KERS was popular for its usage in the racing cars especially when it was first being implemented into few F1 cars in 2009 season (Pottabattini Naveen, 2014). However, this implementation lasted only for one season as the system was too expensive (Pottabattini Naveen, 2014). The introduction of KERS was intended to boost the performance of the racing cars. Lastly, the HHV is a vehicle fitted with hydraulic components where the wasted kinetic energy from the braking is recovered using the hydraulic pump and is stored inside the high pressure accumulator (HPA) (Sérgio Valente, 2009). This HPA has compartments to store pressurized hydraulic fluid and the nitrogen gas. The obvious advantage of hydraulic hybrid against electric hybrid and KERS is the high power density of hydraulic components.

2.2.1 Hydraulic Hybrid Vehicle

The hydraulic hybrid system is chosen to be implemented into the passenger vehicle instead of electric hybrid system due to the high power density of hydraulic components compared to the electrical components that have low power density (Muhammad Iftishah Ramdan, 2019). The high power density of hybrid components is very necessary especially to help propelling the heavy vehicle. In order for the electric hybrid system to operate with large amount of power, more batteries need to be used in the system which will add more weight to the vehicle. For the electric hybrid system, the climate control system need to be placed in the HEV to regulate the suitable temperature for the battery to work as the battery is very sensitive to intense temperature especially hot (Muhammad Iftishah Ramdan, 2019). Consequently, the system will becomes more complex, more costly and again adding more weight to the vehicle. Therefore, the hydraulic hybrid system is the better choice for the development of hybrid passenger vehicle in this project.

HHV consists of three system architectures which are parallel, series and power-split. The parallel design retains the conventional drive train and uses it together with the hydraulic hybrid system where both are connected in a parallel configuration as shown in Figure 2.1 (Vjekoslav Tvrdić, 2018). The hydraulic hybrid system is used to recover the wasted energy from braking and then uses it to supply power to the drive train to assist the acceleration. A clutch is attached between the engine and the drive train where disengaging the connection between two allows the engine to be turned off and let the hydraulic system operates the vehicle by using the stored energy inside the accumulator (Vjekoslav Tvrdić, 2018). There is a parallel hybrid type called parallel-through-the-road (PTTR) where the engine system fitted at drive axle and the secondary propulsion system (hydraulic) fitted at driven axle are not mechanically connected, but instead connected by the road on which the vehicle moves (S A Zulkifli, 2015). The example schematic diagram of hybrid PTTR architecture is shown in Figure 2.2 (Haley M. Moore, 2012). The advantage of the parallel architecture is that it has high transmission efficiency as both engine and hydraulic system are connected mechanically. On the other hand, the disadvantage of this architecture is that the engine speed must operate based on the wheel speed (Vjekoslav Tvrdić, 2018).

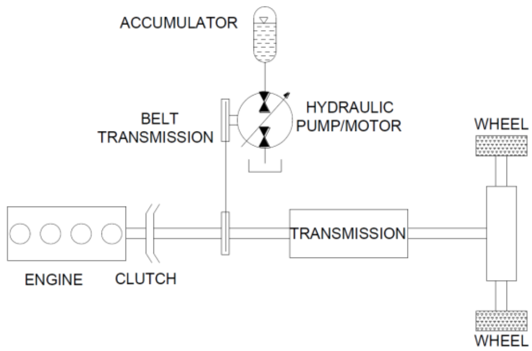

Figure 2.1: Schematic Diagram of Parallel HHV Architecture for Rear-Wheel Drive (Vjekoslav Tvrdić, 2018).

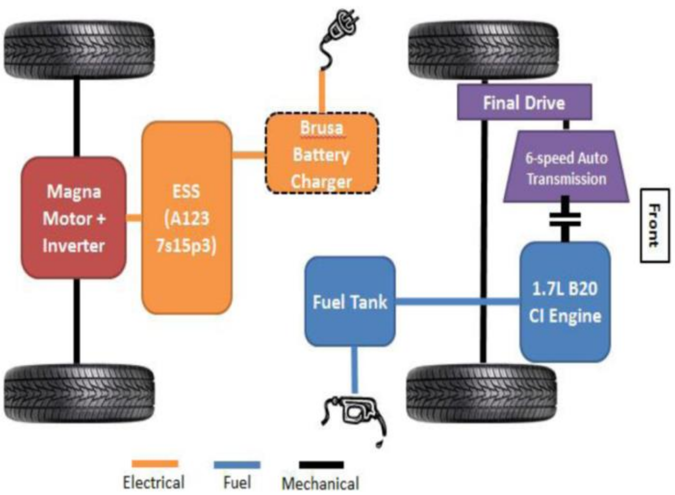

Figure 2.2: Schematic Diagram of Plug-in HEV Parallel-Through-The-Road Architecture for Front-Wheel Drive (Haley M. Moore, 2012).

For the series design, the transmission is completely replaced by the hydraulic system while retaining the engine as shown in Figure 2.3 (Vjekoslav Tvrdić, 2018). Meaning that the engine is not directly connected to the rear wheel as the hydraulic system is positioned between engine and rear wheel. A clutch is attached between the engine and the hydraulic system where disengaging the connection between two allows the engine to be turned off and let the hydraulic system operates solely the vehicle. From this configuration, the engine does not need to operate according to the speed of rear wheels as hydraulic pump/motor is directly connected to the wheels (Vjekoslav Tvrdić, 2018). However, this configuration have poor transmission efficiency as high power losses occurred when converting the power from the engine to the hydraulic system (mechanical power to hydraulic power) and then from the hydraulic system to the rear wheels (hydraulic power to mechanical power).

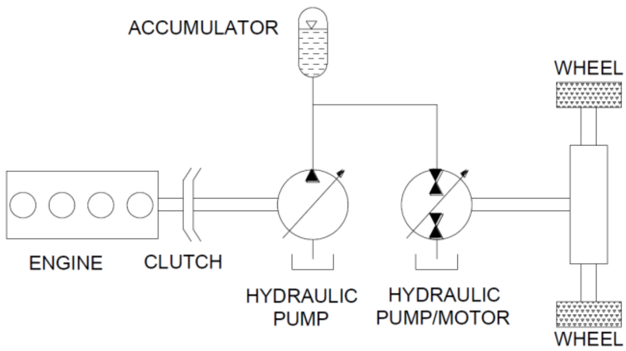

Figure 2.3: Schematic Diagram of Series HHV Architecture for Rear-Wheel Drive (Vjekoslav Tvrdić, 2018).

Next, the power-split architecture is an architecture that combines the advantages of parallel and series architectures as shown in Figure 2.4 (Vjekoslav Tvrdić, 2018). This architecture retains the connections of the engine to the mechanical drive train and the hydraulic pump/motors to the rear wheels (Vjekoslav Tvrdić, 2018). A clutch is attached between the engine and the drive train where disengaging the connection between two allows the engine to be turned off similar as in parallel and series architectures. This architecture has the advantages of having high transmission efficiency while enabling the engine management system to be fully optimized (Vjekoslav Tvrdić, 2018). However, the drawback from this architecture is the complexity to control the system where the improper design of system architecture can results in inefficient operation of hydraulic hybrid system.

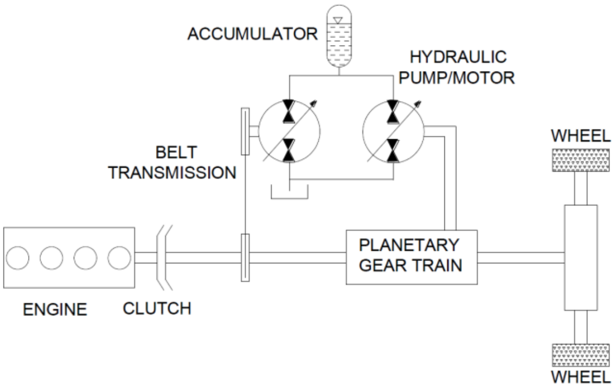

Figure 2.4: Schematic Diagram of Power-Split HHV Architecture for Rear-Wheel Drive (Vjekoslav Tvrdić, 2018).

After reviewing all the hybrid architectures, the parallel-through-the-road architecture is selected for this project as it is similar to the architecture of test vehicle (Perodua Myvi) with less complex modification to be made on the vehicle drive train compare to the other architectures.

2.3 Hydraulic Regenerative Braking System

The components required in the conventional vehicle for Parallel Hydraulic Regenerative Braking System consist of hydraulic pump, hydraulic motor, hydraulic accumulator and hydraulic fluid tank with maintaining the conventional drivetrain. For regenerative braking system, it is crucial to have Pressure Relief Valve as it regulates the hydraulic system pressure at the safe condition (Kumar, 2012), especially when the pump pressurizing the oil flow from hydraulic tank to the accumulator. Check valve is used

(Kumar, 2012) to prevent any backflow of oil when the oil flows from tank to the accumulator. While for both regenerative braking and acceleration assist system, Flow Control Valve can be used to control the oil flow throughout the hydraulic system (Kumar, 2012).

During deceleration, the kinetic energy wasted from the braking is recovered by using hydraulic pump that supplies the oil from hydraulic fluid tank into the high pressure accumulator until the accumulator reaches its maximum allowable pressure. The nitrogen gas inside the accumulator will be compressed to the highest allowable pressure as a result from the storage of pressurized oil (Kumar, 2012).

During acceleration, the stored pressurized oil inside the accumulator is used by the hydraulic motor to produce extra power to the wheels in order to assist the engine power to propel the vehicle (Kumar, 2012). The pressurized oil flows from the accumulator to the motor to assist the vehicle acceleration and the used low pressure hydraulic oil flows back to the hydraulic fluid tank. This will significantly reduce the usage of fuel during the acceleration which will contributes to the better fuel economy of the HHV comparing to that of the conventional vehicle.

2.3.1 Previous Related Works on the HRB Test bench Development

Referring to the project report on ‘Aftermarket Hydraulic Regenerative Braking System’ written by Nicholas Jansky et al. (Nicholas Jansky, 2010), they have designed a tabletop test fixture to fit the actual size of aftermarket hydraulic regenerative braking system (HRBS) in parallel architecture. The usage of this system design is targeted for commercialization on taxicabs. The objective of this HRBS is to be able to propel the vehicle weighted about 2268 kg from 0 to 14.5 km/h at the acceleration rate of 0.939 m/s^2 using the hydraulic system alone. The sizing of HRBS major components are made based on the calculation of energy required for hydraulic motor to perform that objective. The calculation analysis also has been done on the performance of hydraulic components for regenerative braking and launching assist to meet the objective. The design of this tabletop test fixture fitted with aftermarket HRBS has been successfully created using CAD software with the suitable size of hydraulic components.

From the journal article on 'Design and Analysis of Hydraulic in a Heavy Commercial Vehicle by Recovering Energy during Braking' written by Setyamartana Parman and Eijaz Zainuddin (Setyamartana Parman, 2016), the work focuses on analyzing the performance of Hydraulic Regenerative Braking System (HRBS) implemented in heavy vehicle to obtain its energy efficiency. The analysis consists of designing the configuration of hydraulic & mechanical components in the system using CATIA software and calculations on HRBS performance that took account of important parameters for vehicle's braking and acceleration. Tata LPK-2523 garbage truck was used as the vehicle model. The configuration of HRBS in the vehicle was designed in parallel architecture where the vehicle engine and the mechanical transmission were maintained. For the energy efficiency calculations, the focuses are on the amount of kinetic energy recovered during braking that can be transformed into hydraulic (potential) energy and the engine power output required to decelerate the vehicle where both focuses are at the deceleration speed from 70 km/h to 10 km/h. Based on the calculations performed, the recovered power of hydraulic energy obtained were ranging between 38% to 43% of the engine power output during deceleration.

2.4 Main Hydraulic Components

The main hydraulic components that will be used in our HRB system consists of hydraulic gear pump, orbital motor, high pressure bladder accumulator and hydraulic tank/reservoir.

2.4.1 Hydraulic Gear Pump

Gear pump is a type of hydraulic pump with two gears coupled together inside it and the rotation of these gears against each other results in pumping action of hydraulic oil flow from low pressure location to the high pressure location (Yuken Kogyo Co., 2006). In this project, the gear pump will be used for pumping the oil flow from hydraulic reservoir into the high pressure accumulator. The gear pump is basically a fixed displacement hydraulic pump type. The gear pump consists of two categories which are external gear pump and internal gear pump. Inside internal gear pump, there is an external gear that is used to drive the internal gear (John Petersen, 1993). Internal gear pump has low operating speed which makes it only suitable for the applications of transporting high viscosity substances with low operating pressure (John Petersen, 1993). For external gear pump, it consists of two similar size gears inside it where one of it acts as a drive gear and another one as a driven gear. External gear pump has the capability to operate at high speed and is suitable for applications that require pumping of high pressure fluid (John Petersen, 1993). Therefore, the external gear pump of model Standco SGP-3A-F25RCC with displacement of 25 cc/rev is the best choice for this project that requires transferring pressurized oil. The normal and cross-sectional views of external gear pump are shown in Figure 2.5 (Yuken Kogyo Co., 2006). For precaution, the both sides of gear pump which are the suction and discharge ports must be sealed properly with side plates (Yuken Kogyo Co., 2006) to avoid any coarse particles from entering the gear pump which could disrupt the pump performance and ended up with damage to the pump. Gear pump is relatively reasonable in price with smooth performance in pumping and is most popular used for automotive applications.

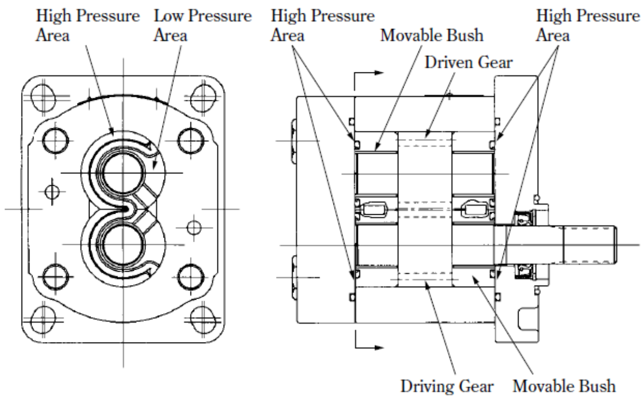

Figure 2.5: Normal and Cross-Sectional Views of External Gear Pump (Yuken Kogyo Co., 2006).

2.4.2 Orbital Motor

In this project, the purpose of orbital motor is to convert the hydraulic (potential) energy stored inside the accumulator into mechanical (kinetic) energy to supply it to the left driven (rear) wheel. The orbital motor is a fixed displacement motor type which displaces the constant volume of oil for every gearwheel revolution. This hydraulic motor operates at low speed but with high torque which suitable for this project that requires application of high torque to drive the wheel. The output torque of this motor relies on the pressure difference between motor inlet and outlet (Danfoss, 2015) where the large pressure difference will result in great amount of torque output. The motor operating speed relies on the oil flow rate (Danfoss, 2015) where the high rate of oil flow into the motor will result in high motor speed. According to the Sauer Danfoss Orbital Motors catalogue, the OMR type motor is a similar model to the Standco HYD Motor 50 CC with displacement 50 cc/rev used in this project. The gear-wheel set of this motor consists of an external gear and an internal gear at which the flow of oil will rotate the external gear thus transmitting the output torque and speed to the internal gear (Danfoss, 2015). The cardan shaft connected to internal gear will rotate the spool valve which then distributes the output torque and speed from the gear-wheel set to the output shaft (Danfoss, 2015). The internal view of OMR orbital motor is shown in Figure 2.6. This orbital motor uses Roller-Star technology of gear-wheel set as shown in Figure 2.7 which has low friction, high mechanical efficiency and high starting torque (Metaris, 2016).

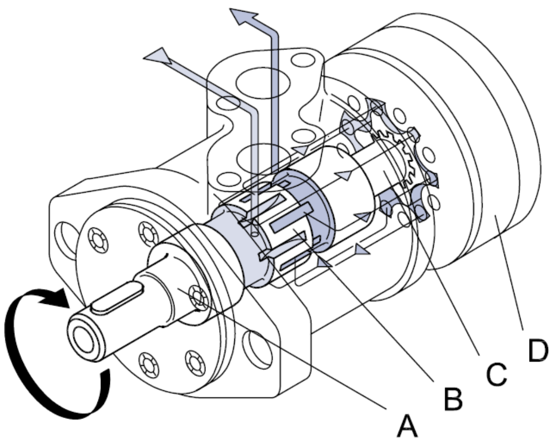

Figure 2.6: Internal View of OMR Orbital Motor where: A=Output Shaft, B=Spool (Distributor) Valve, C=Cardan Shaft, D=Gear-Wheel Set (Danfoss, 2015).

Figure 2.7: Roller-Star Technology of Gear-Wheel Set (Metaris, 2016).

2.4.3 Bladder Accumulator

The bladder accumulator is a type of accumulator that consists of fluid and gas regions where both regions are separated by the rubber bladder. The gas inside accumulator is compressed by filling up the fluid region to store high pressure fluid inside the accumulator. During fluid discharge, the gas expands and pushes the pressurized fluid out of the accumulator (HYDAC). The cross-sectional view of bladder accumulator is shown in Figure 2.8 (HYDAC).

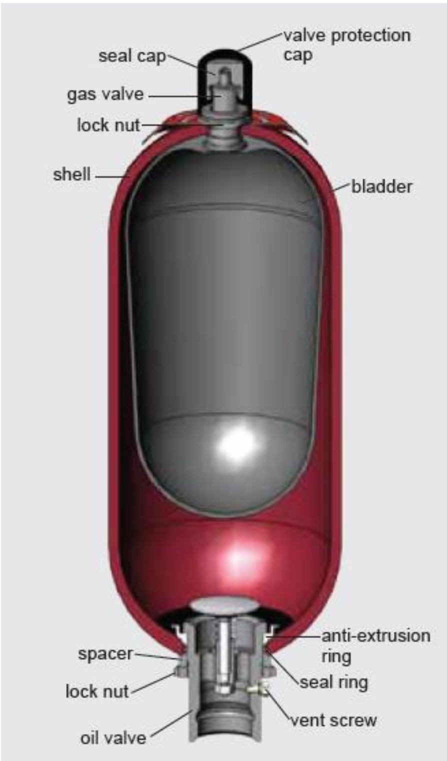

Figure 2.8: Cross-Sectional View of Hydraulic Bladder Accumulator (HYDAC).

2.4.4 Hydraulic Tank/Reservoir

In this project, the hydraulic reservoir is used as the low pressure hydraulic oil storage where the volume of oil being kept must be sufficient to be used for the whole hydraulic system. The reservoir must be serviced by changing the oil after being used for several times to avoid contamination (Busch, 2015). The criteria for reservoir volume selection can be based on the volume of accumulator and the minimum oil volume to be used. It is suggested that the reservoir volume to be about five times of the accumulator volume (Yuken Kogyo Co., 2006). Also it is advisable that the reservoir volume to be at least three times of the minimum oil volume required for the whole hydraulic system operation (Yuken Kogyo Co., 2006) as the oil level in the reservoir will be fluctuating during the pumping and motoring actions of hydraulic system. The internal view of hydraulic reservoir with its sub-components is shown in Figure 2.9 (Divedi, 2017).

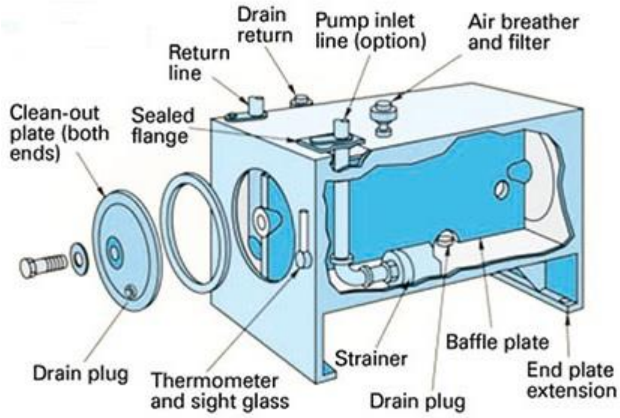

Figure 2.9: Internal View of Hydraulic Reservoir with its Sub-Components (Divedi, 2017).

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

This chapter describes the processes involved to design the HRB system configuration and the test bench. Design process will comprise of understanding the operation of HRB, selection of suitable specifications for hydraulic components, the finalized hydraulic components to be used in HRB system, regenerative braking control system, the layout of HRB system on the test bench, and analysis of HRB performance and V-belt selection for regenerative braking part. The fabrication will be based on the design layout of HRB system on the test bench made by using Solidworks software. The sequence of design processes for HRB test bench development is shown in Figure 3.1.

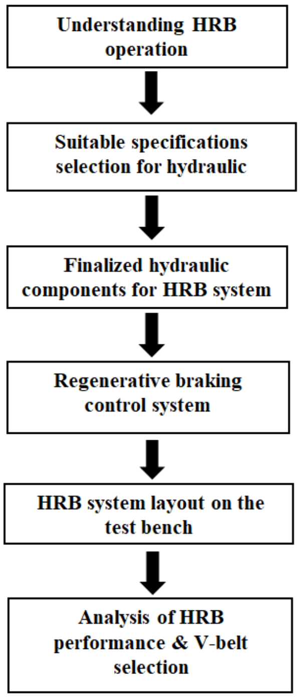

Figure 3.1: Flow of Design Processes for Developing HRB Test Bench.

3.2 Hydraulic Regenerative Braking (HRB) Operation

As stated in literature review at the end of section 2.2.1, the parallel-through-the-road architecture is selected to be implemented in this HRB system development project. This is due to its architecture similarity with the test vehicle which is Perodua Myvi and only involves less complex modification on the existing vehicle drive train.

After studying the previous related work on the HRB test bench development, some ideas have been gathered for the execution of regenerative braking system development in this project. For the regenerative braking system, the operation will be initiated by pressing the brake pedal where the vehicle starts slowing down through exertion of braking torque by the front wheels and right rear wheel to stop the vehicle, resulting in losses of kinetic energy. Based on this input from brake pedal, the electromagnetic clutch will engage to couple the shaft of hydraulic pump to the right rear wheel shaft, recovering some of the kinetic energy losses from that wheel by using the pump. Using that recovered kinetic energy, the pump will transfer the hydraulic oil from the reservoir into the high pressure accumulator (accumulator charging). Between the pump and the accumulator, there will be a pressure relief valve which will be used to regulate the pressure of the system to the safe condition and an inline check valve which serves a purpose to ensure the oil flow in one direction (pump to accumulator). As the accumulator charging reached slightly below its maximum pressure (90% State of Charge/SOC), the electromagnetic clutch will immediately disengage to decouple the connection between drive wheel and pump which in consequence stops the transfer of oil and ends the accumulator charging. The accumulator is now filled with pressurized oil that will be used to assist the vehicle acceleration.

3.3 Selection of Hydraulic Component Specifications

The selection of hydraulic component specifications will be based on the optimization simulation done by using Matlab software. In this simulation, the hydraulic specifications that could achieve the maximum fuel economy of HHV will be selected. The hydraulic specifications consist of the pump size, motor size, accumulator size, gear ratio for pump and gear ratio for motor. Each specification have various configurations which will form various sets of hydraulic configurations. Every set of configurations will be executed inside the simulation to obtain their respective HHV fuel economy. Among the fuel economies obtained, the maximum value will be chosen which lead to the selection of its set of hydraulic configurations. The general coding for this simulation inside Matlab is shown in Figure 3.2.

```
for pump size = [PM_size 1, PM_size 2, PM_size 3, ….]    %pump size, mass, operating speed
    for motor size = [M_size 1, M_size 2, M_size 3, ….]    %motor size, mass, operating speed
        for accumulator size = [Acc_size 1, Acc_size 2, Acc_size 3, ….]    %accumulator size, mass
            for pump gear ratio = [GR_PM 1, GR_PM 2, GR_PM 3, ….]
                for motor gear ratio = [GR_M 1, GR_M 2, GR_M 3, ….]
                    [Simulation Model]
                    end
                    [Display maximum fuel economy value            % configuration set of hydraulic component specs
                     Display a set of hydraulic                    % fuel economy unit in km/L
                     configurations corresponding
                     to that max fuel economy]
                    end
                end
            end
        end
    end
end
```

Figure 3.2: General MATLAB Simulation Code for Selection of Hydraulic Component Configurations.

Based on the simulation performed, the maximum fuel economy of HHV obtained with its hydraulic component specifications are listed in Table 3.1.

Table 3.1: Finalized Specification of Hydraulic Components from MATLAB Simulation.

Pump Displacement	25 cc/rev
Motor Displacement	50 cc/rev
Pump Gear Ratio	5.5:1
Motor Gear Ratio	2:1
Accumulator Volume	10 L
Fuel Economy of HHV	18.2787 km/Liter

The finalized hydraulic components that will be used for HRB test bench development will be based on those specifications.

3.4 Finalized Hydraulic Components for HRB System

The hydraulic components model that have been finalized were purchased from Standco Company which is among a trusted hydraulic company in the northern region of Malaysia. They not just provide service of supplying hydraulic components for this project, but also they included together with the service of installation of the components. They also provide professional advices regarding the hydraulic components and the suitable hydraulic circuit configuration for this project. The list of finalized components to be used in this HRB test bench development is shown in Table 3.2.

Table 3.2: Finalized Components with Detail Specifications for HRB Test Bench.

Hydraulic Gear Pump 	**Function** -Used to pump the hydraulic oil from hydraulic reservoir into the hydraulic bladder accumulator. -Also used to convert the recovered mechanical power into fluid power.	**Model**	Standco SGP-3A-F25RCC
		Mass	3.5 kg
		Displacement	25 cc/rev
		Minimum Operating Speed	500 rev/min
		Maximum Operating Speed	3000 rev/min
Hydraulic Gear Motor 	**Function** - Used to convert the potential energy of pressurized oil from the accumulator into kinetic energy to drive the left rear wheel.	**Model**	Standco HYD Motor 50 CC
		Mass	10 kg
		Displacement	50 cc/rev
		Maximum Operating Speed	750 rev/min
Hydraulic Accumulator 	**Function** -Used to store the potential energy in the form of pressurized oil with the nitrogen gas being compressed inside the accumulator. -Releases the pressurized oil (potential energy) during vehicle acceleration.	**Model/ Type**	Standco Hydraulic Bladder Type Accumulator
		Mass	48 kg
		Capacity	10 Liter
		Minimum Operating Pressure	7 MPa @ 70 Bar
		Maximum Operating Pressure	14 MPa @ 140 Bar

<u>Pressure Relief Valve</u> 	**<u>Function</u>** -Used to regulate the pressure of the hydraulic system to the operating pressure of accumulator.	**Model**	Oil Control Aluminium Pressure Relief Valve (3/4”)
<u>Inline Check Valve</u> 	**<u>Function</u>** -To ensure the oil flow in one direction from the reservoir to the accumulator. -To prevent the backflow of oil in the hydraulic hose.	**Model** **Mass**	CIT-06 (3/4”) 0.5 kg
<u>Hydraulic Pressure Gauge</u> 	**<u>Function</u>** -Used to measure and display the current pressure inside accumulator.	**Model** **Mass**	(BTM 2 1/2”) 0-250 Bar 0.2 kg

Pressure Gauge Safety Valve Complete with Adapter 	**Function** -Used to protect the pressure gauge from excess pressure.	**Model**	GCT-02
Solenoid Normally-Closed Valve 	**Function** -Used to block the oil flow from accumulator during braking and allow the oil flow from accumulator to the drive wheel during acceleration.	**Model**	V2067 NC-06 AC220 (200 Bar) Coil ID 13mm
		Mass	0.4 kg
Flow Control Valve 	**Function** -Used to regulate the flow rate of oil from accumulator to the drive wheel and into the reservoir.	**Model**	KC-06 (3/4")
		Mass	0.75 kg
Hydraulic Hose 	**Function** -Used to channel the oil flow from hydraulic component to another hydraulic component. -Connect all hydraulic components to form a complete hydraulic circuit.	**Model**	Standco Hydraulic Hose SAE 100 R2AT/DIN EN 853-2SN-3/4" (215 Bar)

<table>
<tr><td rowspan="5"><u>Three Phase Induction Motor</u>
</td><td rowspan="5"><u>Function</u>

-Serves a purpose to initiate the propelling of the wheel at the test bench before commencing the HRBS operation.</td><td>Model</td><td>TEC Y2-A112M-4</td></tr>
<tr><td>Operating Speed</td><td>1440 rev/min</td></tr>
<tr><td>Operating Power</td><td>4 kW/
5.5 HP</td></tr>
<tr><td>Operating Frequency</td><td>50 Hz</td></tr>
<tr><td>Operating Voltage</td><td>415 V</td></tr>
</table>

3.5 Regenerative Braking Control System

The control system of regenerative braking consists of an input which is brake pedal, two states which are accumulator pressure/state of charge (SOC) and wheel rotational speed, and an output which is electromagnetic clutch mode. The control system begins by pressing the brake pedal where the next two conditions need to be satisfied in order to engage the electromagnetic clutch. The next condition is the wheel rotational speed ranging between its minimum and maximum speeds (90.9 <= wheel speed <= 545.45 rpm). If the current wheel rotational speed is in the range, then only the control system will proceed to the next condition. The last condition is the accumulator pressure lesser than or equals to 133 bar (SOC <= 90%). If the current accumulator pressure is lesser than or equals to that critical value, the magnetic clutch will finally engage but if the current pressure exceeds the critical value, the magnetic clutch will remained disengage. The magnetic clutch will remained in engage mode as long as the input and two conditions are all satisfied. The flow chart of regenerative braking control system and the summary of the control system are shown in Figure 3.3 & Table 3.3 respectively.

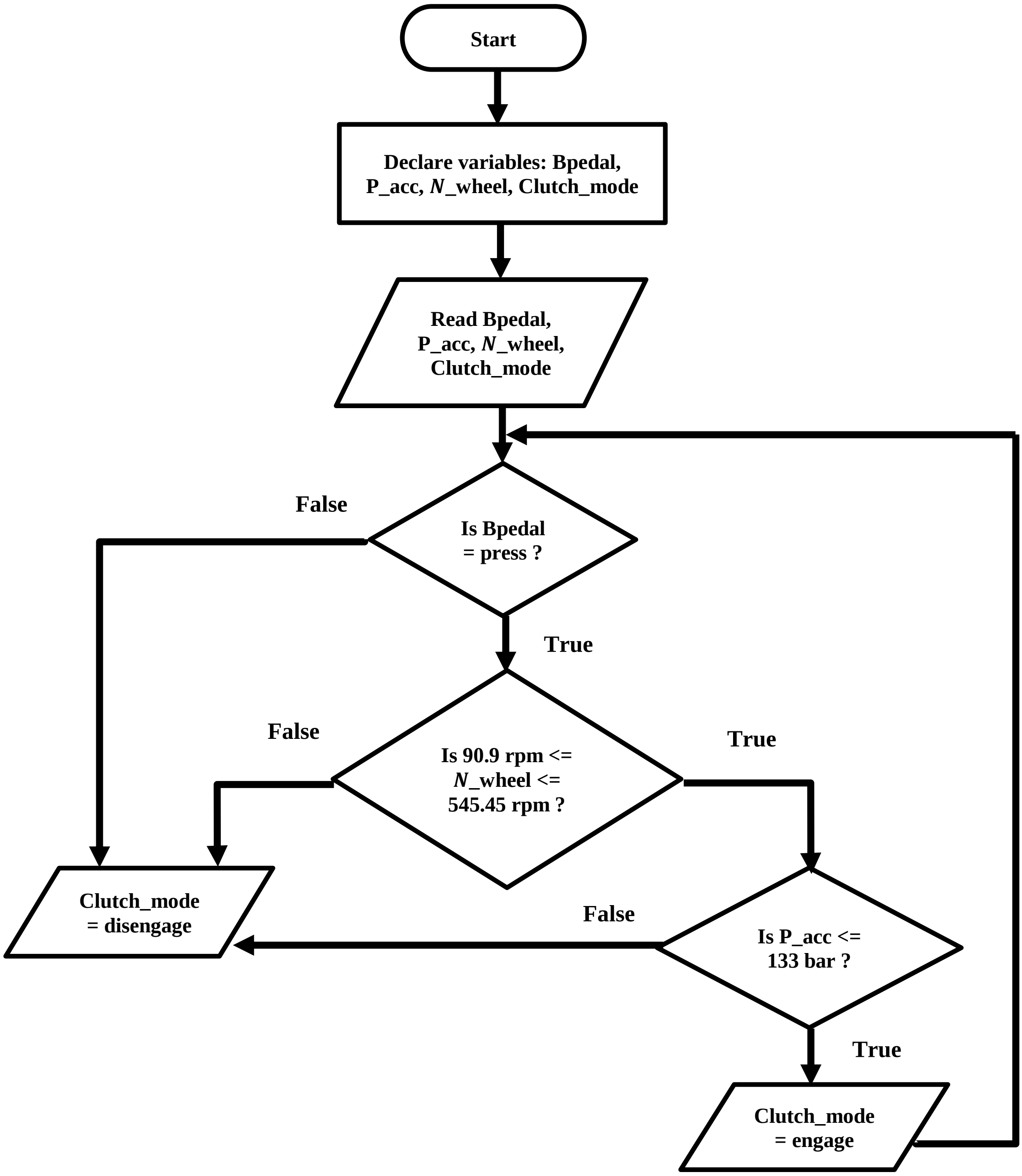

Figure 3.3: Flow Chart of Regenerative Braking Control System.

Table 3.3: Summary of Regenerative Braking Control Strategy.

Brake Pedal	Wheel speed Condition	SOC Condition	Magnetic Clutch Mode
Pressed	90.9 <= wheel speed <= 545.45 rpm	<= 90%	Engage
Pressed	> 545.45 rpm	<= 90%	Disengage
Pressed	90.9 <= wheel speed <= 545.45 rpm	> 90%	Disengage
Not pressed	90.9 <= wheel speed <= 545.45 rpm	<= 90%	Disengage