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Analysis of the performance of a hybrid hydraulic Pump/Motor using MATLAB Simulink

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Abstract

The MISER hydraulic hybrid technology is an innovative approach to kinetic energy recovery, storage and re-application for any form of vehicle. This technology makes use of a hydraulic system to reduce the fuel consumption of the vehicle. MISER achieves this by means of a combination of regenerative braking, hydraulics and using gas compression to provide an almost loss-free medium for fast storing and fast release of energy that contributes to optimized engine performance. The system uses a hydraulic Pump/Motor (P/M) and nitrogen filled accumulators to store the excess and unwanted kinetic energy and reuse the stored energy at the latter stage. The hydraulic Pump/Motor (P/M) is a critical component in the system and very little is known of its performance characteristics. This study provides clarity on the development of the system model and the performance of the hydraulic system P/M. The system model consists of a Nitrogen-filled hydraulic accumulator, a MISER P/M, a reservoir and a flywheel which is used to represent the inertia of the vehicle. The model has been developed and implemented in MATLAB Simulink. An integration Solver is used to simultaneously solve the governing equations and predict the system performance. The study aims to make a partial contribution to environmental impact savings in the field of sustainable development.

Keywords: Hydraulic Hybrid; Pump/motor; efficiency; Simulink;

1. Introduction

The MISER project makes use of a hydraulic regeneration system. The projects primary goals are to introduce fluid power into the transportation sector as a means of dramatically increasing efficiency and decreasing vehicle emissions. The MISER design makes uses of a hydraulic P/M coupled to the power take-off (PTO) to the gearbox, a hydraulic accumulator and a reservoir as shown in Fig. 1 [1].

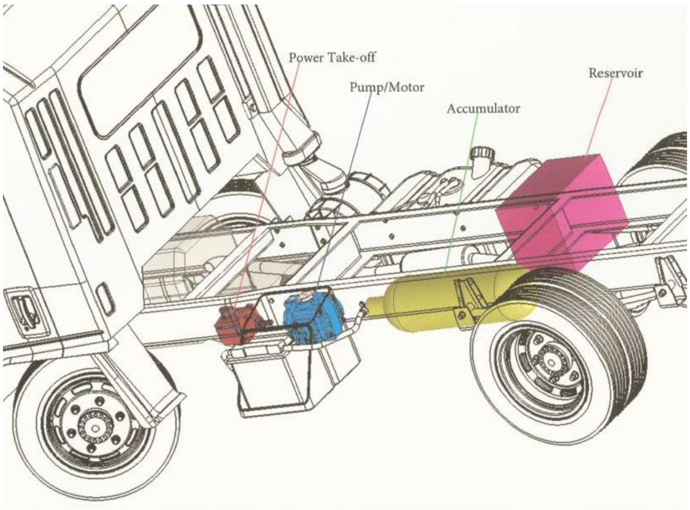

Fig. 1- MISER System layout (Adapted from Ref. [1])

The hydraulic accumulator serves as a hydraulic energy battery, the accumulator stores energy in the form of compressed nitrogen which is separated from the oil by bladder inside the accumulator. The P/M transfers energy between the diesel engine and the hydraulic accumulator depending on the system requirements. The reservoir contains the hydraulic oil. The electronic controller monitors the vehicle's performance and controls hydraulic P/M accordingly. The controller system engages the P/M as a pump when the vehicle transmission has excess kinetic energy, the P/M then applies a negative braking torque on the transmission as the pump fills the accumulators. When the vehicle is accelerating, and there is a need for additional kinetic energy. The control system engages the P/M as a motor, the P/M then applies a positive driving torque to the transmission as the motor converts the stored energy in the accumulators back into kinetic energy in the vehicle.

The hydraulic Pump/Motor (P/M) is a critical component in the system and very little is known of its performance characteristics. This study provides clarity on the development of the test system model and the performance characteristics of the hydraulic P/M. Hydraulic pumps and motors are almost fully positive displacement devices. They use a moving boundary to trap a packet of fluid and then force the fluid into the outlet. Unfortunately, hydraulic pumps and motors experience losses due to internal leakage. This loss is known as the volumetric loss. Hydraulic pumps and motors are also mechanical devices, with many moving parts operating at high loads. Consequently, friction develops between the moving parts. This loss is known as the mechanical or torque loss. The total efficiency of the system could be calculated by combining these losses.

Manring [2] constructs a mathematical model that takes into consideration all the imperfections in the testing equipment used to calculate the pumps efficiency. The study stressed the importance of selecting the correct testing equipment. The results of the tests were most accurate when measuring across the entire measurement range of the sensor. Similar experimental studies have been conducted on regenerative systems. Ho [3] designed and built a closed loop test bench in order to study a regenerative system. A flywheel was used to represent the inertia of the vehicle. The flywheel's speed was increased by the hydraulic unit when operating as a motor and decreased when operating as a pump. This study reveals that the overall efficiency of the system changes from 22% to 59% depending on system parameters. A comparison between simulated results and experimental results was done by Pourmovahed [4, 5]. In this experiment, energy was converted from Hydraulic Potential, which was stored in the accumulators, to rotational kinetic energy stored in the spinning flywheel. The decay rate of the peak speed was found to be an indicator of total system efficiency. A model of a "typical" hydraulic energy storage system was developed by Wang [6]. The model consists of a hydraulic accumulator, hydraulic pump/motor, reservoir, connecting lines and controller.

In this paper, the performance of a hydraulic P/M has been investigated using MATLAB Simulink. A model has been developed. Four system variables parameters associated with the test bench model namely the accumulator size, the flywheel Inertia, the maximum pressure and the accumulators pre-charge pressure have been studied. A description of the system model is provided in section 2. The detailed results of the simulation conducted are given in section 3.

2. System Model

This section describes the MATLAB Simulink model that was developed to simulate the test system. The MATLAB/Simulink model consists of four subsystems namely; hydraulic powerpack, test bench subsystem, control systems and data acquisition subsystem. The subsystems are connected as shown in Fig. 2 and simulated together. The model was used to simulate a test system and evaluate the performance and full cycle efficiency of the hydraulic P/M.

2.1. Test system procedure

The layout of the test system is shown in Fig.2. The Variable-Displacement Hydraulic Machine or P/M is connected to a flywheel by means of a shaft. The hydraulic accumulator is connected to the P/M's A port. The hydraulic reservoir supplies oil to the P/M and is connected to the P/M's B port. The hydraulic accumulator is used as a hydraulic energy battery and the flywheel is used as the mechanical energy battery. Initially, the hydraulic accumulator is charged using an external hydraulic supply while the flywheel is at rest.

An external power pack charges the accumulators to maximum system pressure. When the systems maximum pressure is reached, the controller sends a signal to the P/M commanding the unit to act as a motor. The motor then applies a positive torque to the flywheel accelerating the flywheel under the energy of the accumulator. The pressure in the accumulator will fall as the P/M converter hydraulic potential energy in the accumulator into mechanical energy in the flywheel. When the minimum system pressure is reached all the system energy is stored in the flywheel. Triggered by the pressure drop, the control system sends an electronic signal to the P/M commanding the unit to act as a pump. The pump then applies a negative torque to the flywheel, absorbing the mechanical energy and converting it back into Hydraulic potential energy.

This cycle is repeated until the energy in the systems dissipates. The speed and torque of the flywheel and the flow rate and pressure of the hydraulic system have been recorded. These system parameters are later used to calculate the instantaneous power of the P/M. The cycle efficiency of the system is then measured by comparing the total amount of energy in the system at the end of a cycle. This is discussed in detail in section 3.2.

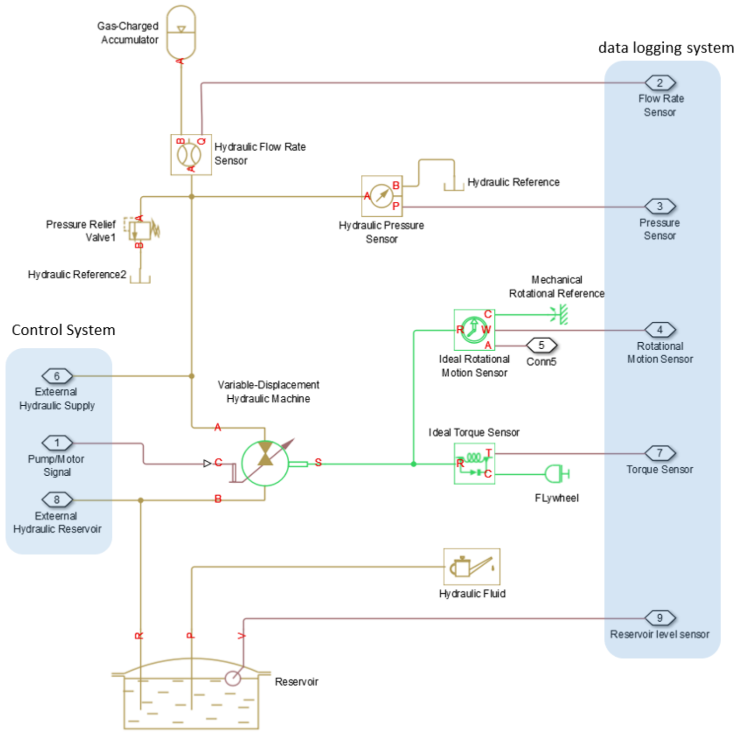

Fig. 2- layout of the test system

2.2. System Components

The following sections include the Equations used for the calculation of the performance of the hydraulic pump, the motor, the accumulator and the flywheel [7, 8].

2.2.1. Pump efficiency model

The hydraulic P/M component acts as a pump in pump mode or as a motor in motor mode depending on the control signal. The MATLAB Simulink model makes use of a Variable-Displacement Hydraulic Machine, as depicted in Fig. 2.

The overall efficiency of the pump is comprised of two components, volumetric efficiency, η_v , and torque efficiency, η_t . This combination is represented by the following Equation:

$$\eta = \eta_v \times \eta_t \tag{1}$$

The volumetric efficiency is expressed as follows:

$$\eta_v = \frac{Q_p}{V_p\ \omega} \tag{2}$$

Where Q_p is the flow rate, V_p is the volumetric displacement and ω is the rotational speed of the pump.

The torque efficiency is expressed as:

$$\eta_t = \frac{V_p P_d}{T} \tag{3}$$

Where P_d is the hydraulic pressure generated and T is the torque on the pump shaft.

According to Manring [9], "although there have been many attempts to model pump efficiency with some degree of accuracy, there is no accurate way to predict pump efficiency characteristics. Therefore, experimental coefficients are still required in the modelling process"

The hydraulic power delivered to the system by the pump is expressed as follows:

$$P_h = Q_p P_p \tag{4}$$

And the hydraulic energy stored in the system is given by the following Equation:

$$E_h = \int_{t1}^{t2} P_h \, dt \tag{5}$$

2.2.2 Motor efficiency model

Pumps and motors can be classified as the same machine operating in opposite modes. So, Equation 1 may also be used to describe the overall motor efficiency. Since the motor operates inversely of the pump, the torque and volumetric efficiencies are respectively given by:

$$\eta_t = \frac{T_{out}}{V_d \, P_i} \tag{6}$$

The torque efficiency is expressed as follows:

$$\eta_v = \frac{V_d \, \omega}{Q_i} \tag{7}$$

Where V_d, is the volumetric displacement, T_{out} is the output torque on the motor shaft, ω is the angular velocity of the motor, P_i is the inlet pressure, and Q_i is the volumetric flow rate into the motor. It is important to note that the efficiency equations of the motor are essentially the reciprocal of the efficiency equations of the pump.

2.2.3. Flywheel

The instantaneous values of the shaft power absorbed/delivered of the flywheel is expressed as:

$$P_f = \frac{2\pi NT}{60} \tag{8}$$

Where P_f ,is the shaft power of the flywheel, T is the shaft torque and N is the rotational speed of the shaft

A flywheel stores energy in a rotating mass. Depending on the inertia and speed of the rotating mass, a given amount of kinetic energy is stored as rotational energy. The kinetic energy stored in a flywheel is proportional to the mass and to the square of its rotational speed as follows:

$$E_f = \frac{1}{2} I \omega^2 \tag{9}$$

Where E_f is the kinetic energy stored in the flywheel, I is the moment of inertia and ω is the angular velocity of the flywheel.

In reality, available energy is lost in flywheel due to viscous shearing of the air in contact with the flywheel (also referred to as drag). Bearing friction would account for other loses in the flywheel system. Simulink models the flywheel using an ideal inertia which experiences no losses. Due to our interest in the performance of the P/M the other losses associated with the flywheel will not be modelled.

2.2.4. Hydraulic accumulator

Available energy is lost in hydraulic accumulators through the irreversible heat transfer and friction. The thermal loss in a gas-charged accumulator is caused by variations in the gas temperature during compression and expansion. It is equal to the amount of available energy dissipated through heat transfer to the accumulator wall and eventually to the outside world. The Simulink hydraulic accumulator model considered the charging and discharging of the accumulator to be an "adiabatic" thermal process and the losses caused by thermal conductivity are considered negligible. Due to our interest in the performance of the P/M only, the practically "loss free" accumulator model will be ideal for the system model. Simulating with a "loss free" accumulator results in fewer calculations required when investigating the performance of the P/M and overall system efficiency.

2.3. Simulink Model

The Simulink model developed in the study simulates a hydraulic P/M test bench as shown in Fig. 2. In addition to the physical test bench, a control system is developed to control the P/M during the tests. A data acquisition sub-system is introduced to record parameters and analyze the data. The model test procedure as described in section 2.1 is then simulated.

The purpose of developing this model is to simulate a test cycle and evaluate the full cycle efficiency of the hydraulic P/M. Based on the principle equations for the hydraulic pump and motor efficiencies, discussed in section 2.2, the following parameters are required to calculate the performance of the P/M:

- System flow rate;
- system pressure;
- P/M shaft speed and
- P/M shaft torque.

Sensors are introduced into the model to record the required parameters. The controller receives the sensors readings and commands the P/M to act as a pump or motor depending on the cycle requirements. The data logging system stores the data from the sensors and performs the calculations required to measure the efficiencies of the P/M. System simulation variables include maximum and minimum system pressure, flywheel inertia, accumulator size and gas pre-charge pressure.

The focus of this study is the performance of the hydraulic P/M only. All other components are modelled as ideal components and the losses associated with the components are not modelled. The P/M is modelled using the Variable-Displacement Hydraulics Machine block as shown in Fig. 2.

2.3.1. Control System

The control system contains a state flow control system shown below in Fig. 3. The state flow control system is responsible for the control logic of the test system. The control system's input parameters are the rotational speed of the P/M and the system pressure. The outputs from the control system are P_M Signal and the starter signal which controls the external hydraulic charging unit used to prime the system before the test is simulated.

The control system makes use of a state machine. The blue text represents the input condition required to change states and the black text inside of the blocks represents the output of the controller while the state is active.

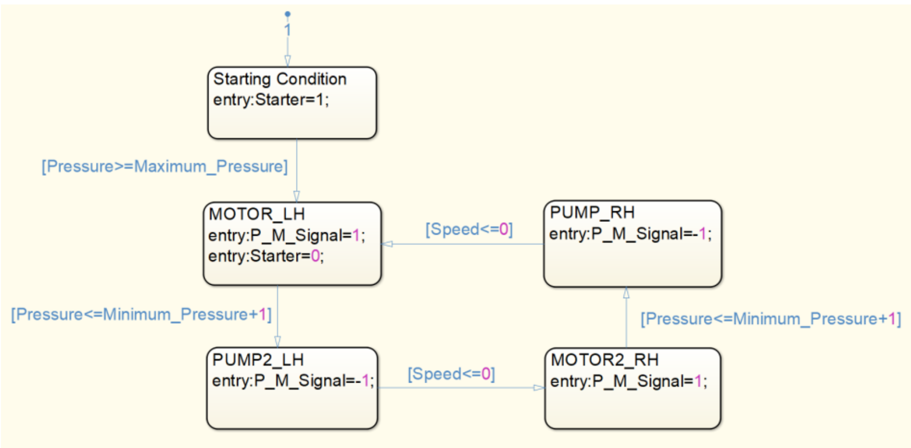

Fig. 3- State Flow Controller

2.3.2. Data Acquisition Subsystem

The data acquisition system is responsible for recording the performance of the system during the simulation. The recorded data from the model is then used to calculate the energy stored in both the flywheel and the accumulator. The Power Calculator blocks, shown in Fig. 4, use equation 4 and 8 to calculate the respective powers. The calculated powers are then integrated with respect to time by the integrator block to produce the stored energies. The Unit Delay block samples the energy reading and holds it with one sample period delay. This delay determines the data recording frequency. The unit delays are set to 0.01 which means the Data Acquisition Subsystem measures and calculates the system energies every 0.01 seconds.

The data acquisition system employs data scopes to record the system's sensor measurements. The scopes also record the performance characteristic of the model and log the data. The functionality of the control system is confirmed by studying the behaviour of the shaft connecting the flywheel to the hydraulic P/M and the system pressure as shown in Fig. 5. This Figure shows that initially, the flywheel is at rest when the system is fully charged.

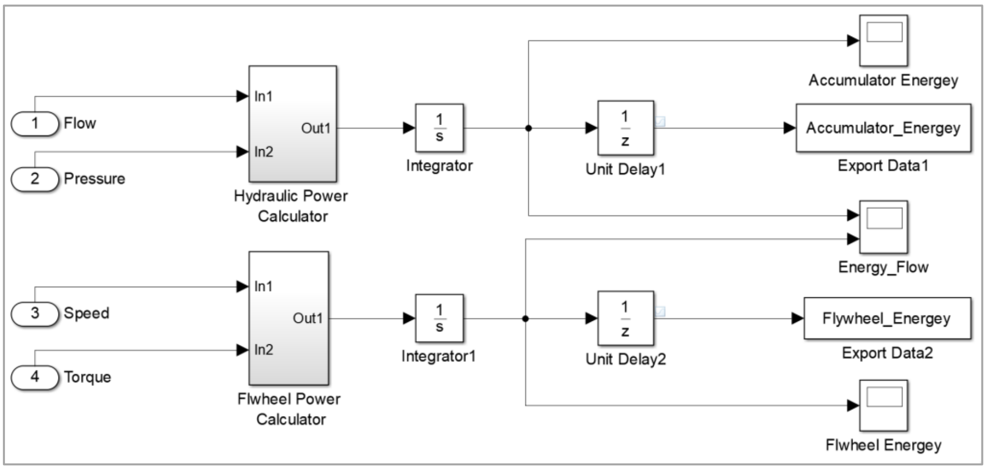

Fig. 4- Data Acquisition Subsystem

3. Results/Discussion

In this section, the results of the simulations are presented and briefly discussed. The model's input parameters are varied individually, the influences of the changes on the performance of the P/M are then investigated.

3.1. Benchmark simulation sensor measurements

The first simulation is performed as a benchmark test. The results obtained from this simulation have been compared to simulations performed with different randomly selected inputs parameters. The benchmark input variables are shown in Table 1.

Table 1 -Benchmark input parameters

	Accumulator size (Litres)	Flywheel Inertia (kg/m^2)	Maximum Pressure (bar)	Pre-Charge (bar)
Run 1 Benchmark	110	32	350	90

Fig. 5(a) illustrates the Flow rate in the systems as a function of time. Positive values present the flow rate of oil from the P/M into the accumulator and negative values represent flow from the accumulators to the P/M. Fig. 5(b) illustrates the hydraulic system pressure as a function of time. Fig. 5(c) illustrates the shaft's rotational speed as a function of time. Positive values present clockwise rotation and negative values represent anti-clockwise rotation. Fig. 5(d) illustrates the shaft's Torque as a function of time. Positive values present positive torque accelerating the flywheel in a clockwise direction. When the input variables are adjusted, these results will differ but only by magnitude and frequency the general shape of the cycles will remain the same.

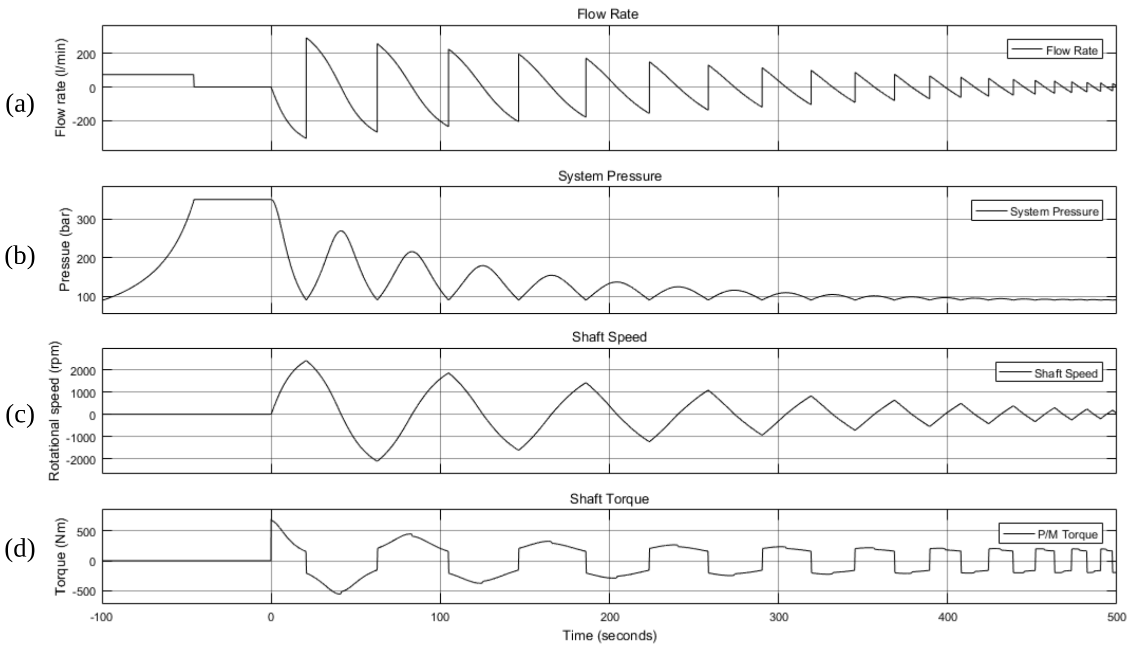

Fig. 5- Benchmark Model output data as functions of time

3.2. System Energy Flow

The transformation or flow of energy between rotational kinetic energy, stored in the flywheel, hydraulic potential energy stored in the nitrogen accumulators, is a critical parameter to measure when evaluating the performance of the hydraulic P/M, therefore when constructing the model and sizing the hydraulic components, it is critical that the amount of energy transferred within the system is known.

Fig. 6 illustrates the hydraulic and flywheel energy as a function of time, the data acquisition system calculates the energies using equations 4 and 8. The parameters used, to calculate energy, are both positive and negative. The data acquisition system applies an RMS function to translate the data from the negative y-axis to the positive y-axis. The recordings of the energy can now be plotting against each other in the same time domain. Fig. 6 show both the hydraulics and flywheel energies on the same axis. The red line spanning from the initial hydraulic energy level to the peaks of the hydraulic energy represents the energy loss in the system.

When comparing the peaks of the hydraulic energy to the previous peaks, it appears that there has been energy lost due to the P/M's inefficiencies. To evaluate cycle efficiency the data in Fig. 6 is divided into cycles, the "findpeaks" function was used inside MATLAB to attain the peak hydraulic pressure readings during the simulation. Each peak represents a starting and ending point of a test cycle. The cycle efficiency is percentage ratio between the energy stored in the accumulators at the end of the cycle and the initial energy stored in the accumulators at the beginning of the cycle.

$$\eta_{cycle} = \frac{E_{h_2}}{E_{h_1}} \qquad (12)$$

Where, E_{h_1} is the energy stored in the accumulators at the beginning of the cycle, E_{h_2} is the energy stored in the accumulators at the end of the cycle. The cycle efficiency represent a round trip efficiency for the P/M.

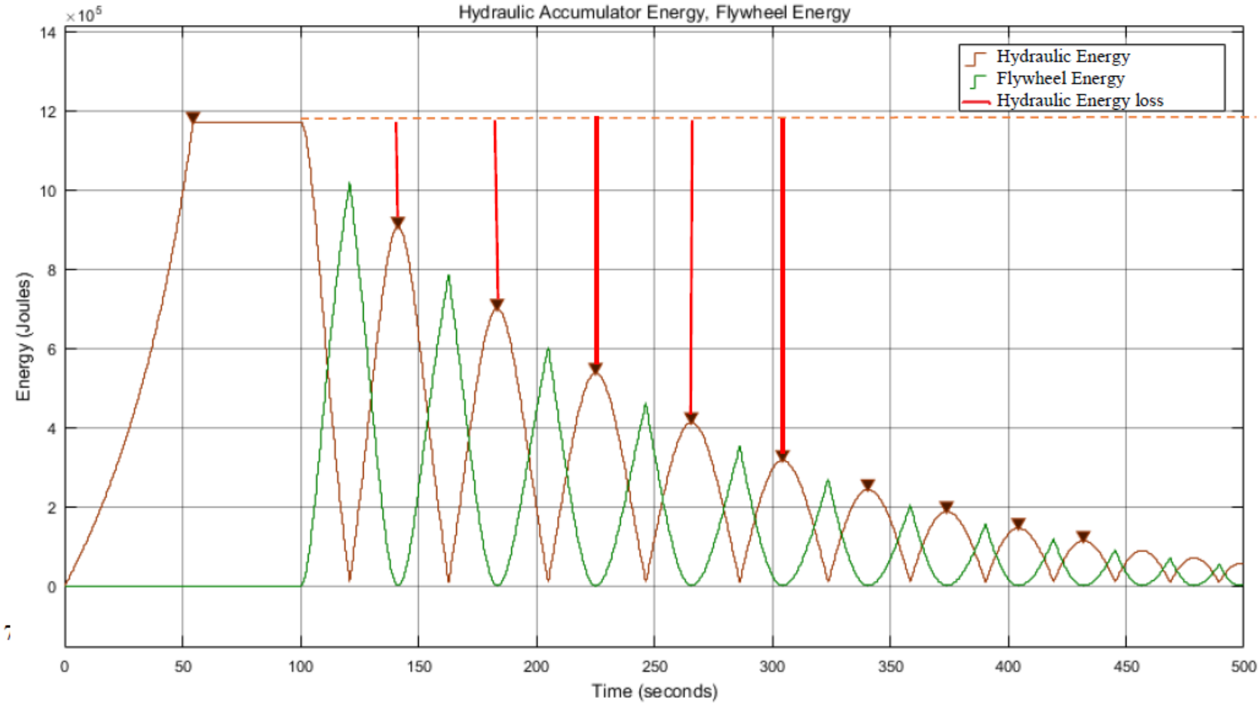

Fig. 6- Energy Flow Diagram

3.3. Test Cycle

Cycle 1, shown in Fig. 7, starts at the beginning of the test after the hydraulic accumulator has been fully charged. At point 1 the hydraulic energy stored in the accumulators is at its maximum value and the flywheel kinetic energy is zero. The energy is then transferred from the accumulator into the flywheel by the P/M. At the cycles mid-point, between 1 and 2, all the hydraulic energy has been dissipated and the flywheel kinetic energy is at maximum. Point 2 represents the end of the cycle. All the kinetic energy stored in the flywheel has now been converted back to hydraulic energy by the P/M and the system has completed one full cycle. In Fig. 8 the first 11 peaks are shown.

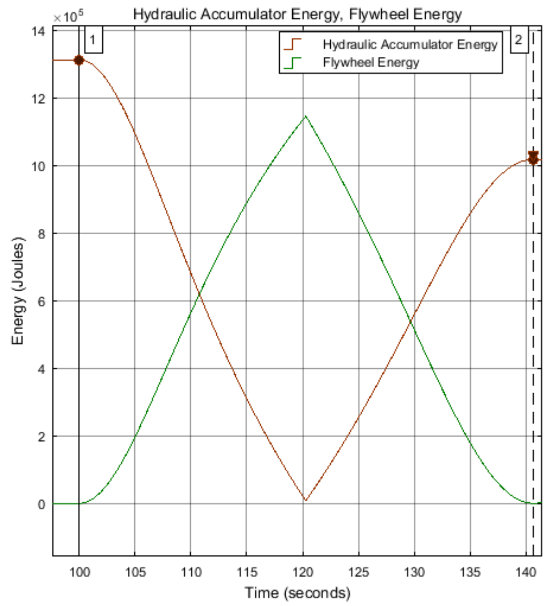

Fig. 7-Cycle 1

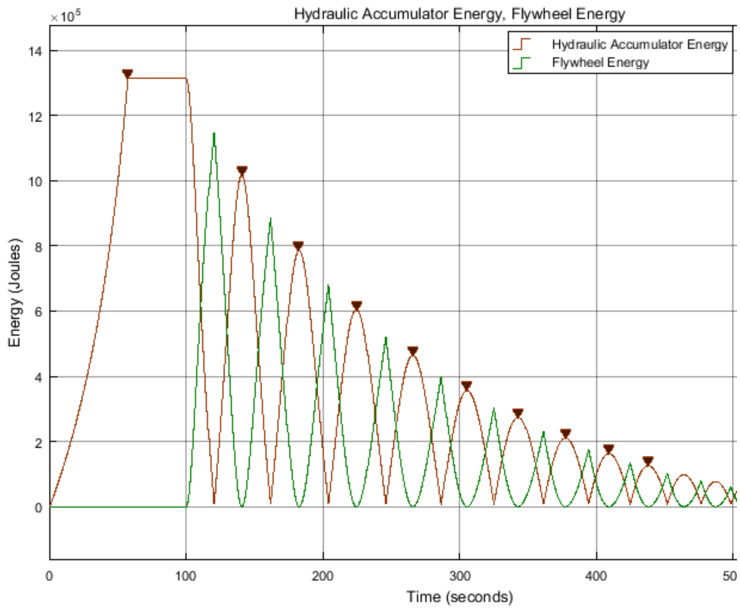

Fig. 8- First 10 cycles

3.4. Benchmark Cycle Efficiency

In Fig. 9, the cycle efficiency per cycle is plotted against total energy stored. The cycle efficiency decreases as the initial energy of the system dissipated. By the 5th cycle, the energy in the system has reduced to 30% of the initial energy. The cycle efficiency then begins to increase with each passing cycle and after 9 cycles the efficiency reached a new maximum but the residual energy remaining in the system is insignificant. Although the P/M is now very efficient it would be unable to develop any work.

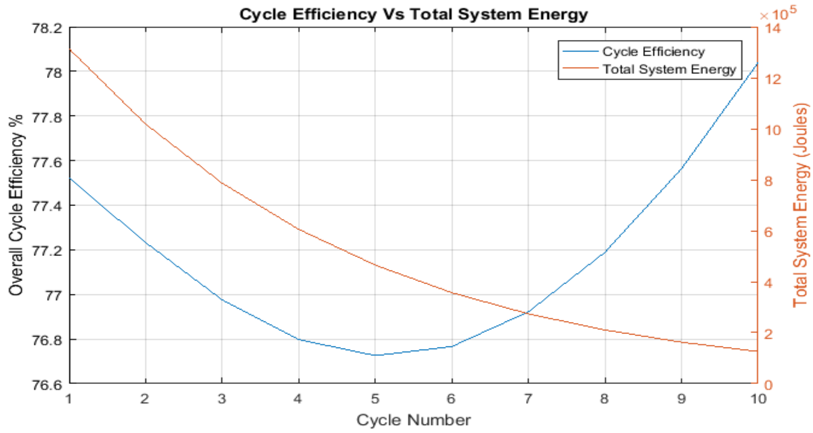

Fig. 9- Benchmark Cycle Efficiency Vs System Energy

3.5. Effects of System Variables

There are 4 system variables parameters associated with the test bench model namely the accumulator size, the flywheel Inertia, the maximum pressure and the accumulators pre-charge pressure. In this section, these parameters are adjusted one at a time (Table 2/number in bold) and the corresponding effects on the cycle efficiency are compared.

Table 2 - Varied Maximum System Pressure input parameters

	Maximum Pressure (bar)	Flywheel Inertia (kg/m^2)	N_2 Pre-Charge (bar)	Accumulator Volume (litre)
Run 1 Benchmark	*350*	*32*	*90*	*110*
Run 2	**300**	32	90	110
Run 3	**400**	32	90	110
Run 4	350	**27**	90	110
Run 5	350	**37**	90	110
Run 6	350	32	**75**	110
Run 7	350	32	**105**	110
Run 8	350	32	90	**90**
Run 9	350	32	90	**130**
Run 10 Optimized	**400**	**37**	**105**	**90**

3.5.1. Effects of the variation of the maximum system pressure and the flywheel inertia

Fig. 10(a) shows the results of runs 2 and 3 in which the maximum pressure was set to 300 bar and 400 bar respectively, the other input parameters have been kept constant. While a higher pressure (400 Pa) is beneficial during the first five cycles, with respect to the cycle efficiency, reducing the maximum pressure appears to result in a higher performance during the last 5 cycles (Fig. 10(a)). This could be attributed to the relationship between the P/M's volumetric efficiency and the system's pressure and speed. When the system pressure is increased, the initial hydraulic energy of the system increases as well, resulting in longer cycle times and increased speeds. The P/M's volumetric efficiency improves with higher pressures and higher speeds. The increased cycle time results in the P/M experiencing high pressure and high flow rates for a longer period of a time. This shifts the efficiency to the right on the x-axis with the shape of the efficiency curve being similar for all three simulations.

Fig. 10(b) shows the results of runs 4 and 5 in which the flywheel's inertia was set to 27kg/m^2 and 37kg/m^2 respectively, the other input parameters were kept constant. An increase in flywheel inertia results in a minor increase in cycle efficiency.

Fig. 10 Cycle efficiency as a function of (a) Maximum system pressure, (b) Flywheel inertia

3.5.2. Effects of the variation of the Nitrogen pre-charge pressure and accumulator volume

Fig. 11(a) shows the results of runs 6 and 7 in which the Nitrogen pre-charge pressure was set to 75bar and 105bar respectively, the other input parameters were kept constant. An increase in pre-charge pressure resulted in a significant increase in cycle efficiency. This could be attributed to the relationship between the P/M's volumetric efficiency and the system's pressure. The accumulator pre-charge pressure is the minimum system pressure. Hence, a cycle with a relatively higher pre-charge pressure will result in a higher average volumetric efficiency. Fig. 11(b) shows the results of runs 8 and 9 in which the Accumulator volume was set to 90Litres and 130Litres respectively, the other input parameters were kept constant. The graphs show an inverse relationship between the accumulator volume and the cycle efficiency. An increase in accumulator volume resulted in a minor decrease in cycle efficiency.

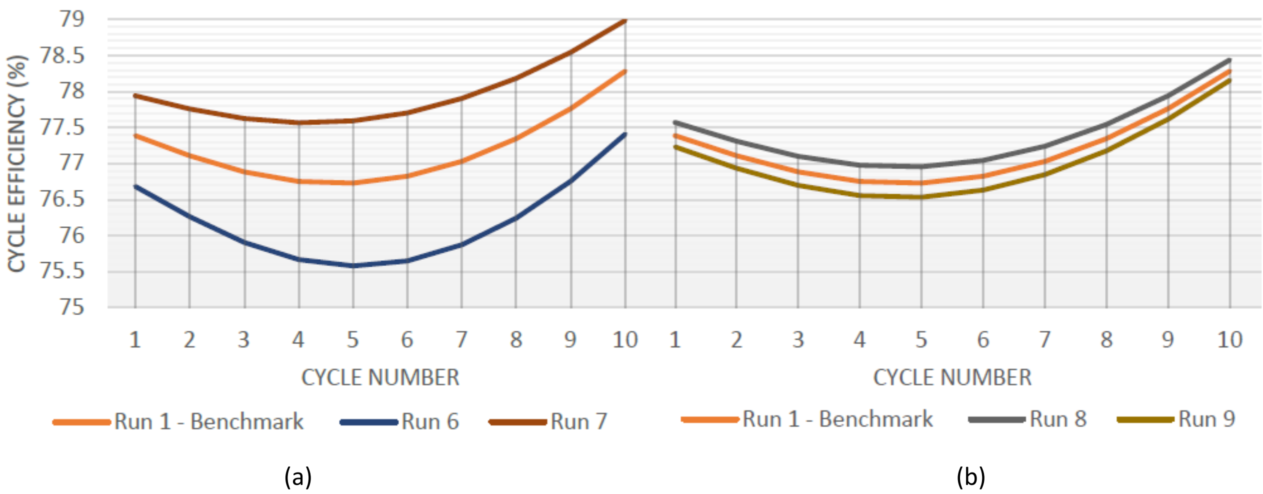

Fig. 11. Cycle efficiency as a function of (a) Nitrogen pre-charge pressure and (b) Accumulator volume

Conclusion

In this paper, a hybrid hydraulic Pump/Motor model has been developed using MATLAB Simulink. The full cycle efficiency of the hydraulic P/M has been analyzed. Four system variables parameters namely; accumulator size, flywheel Inertia, maximum pressure and the accumulators pre-charge pressure have been considered to investigate the performance. Considering that the kinetic energy stored in the flywheel is converted to hydraulic energy by the P/M during one full cycle, the following summarize the results obtained from this investigation:

- Increasing the maximum system pressure improves the cycle efficiency during the first half of the test (made of 10 cycles) but decreases the cycle efficiency during the second half of the test;
- Increasing the size of the flywheel inertia results in a relatively minor improvement of the cycle efficiency of the system;
- Increasing the volume of the accumulator results in a drop of the cycle efficiency of the system;
- An increase in pre-charge pressure results in a significant increase of cycle efficiency of the system;

In order to improve the accuracy of the test bench model developed, the incorporation of hoses, accumulator and flywheel losses and reservoir heating and heat dissipation is necessary. This forms part of the future work that will supplement this preliminary investigation.

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