Introduction

The world's electricity consumption increases at a faster rate every year due to increase in use of more electrically powered devices in the world. The global electricity consumption in 2012 was 20, 900 TWh [1]. Despite energy efficiency improvements in electrical devices, power demand has grown around the world. In 2017, the average annual electricity consumption for a U.S. residential utility customer was 10,399 kWh, an average of 867 kWh per month. Louisiana had the highest annual electricity consumption at 14,242 kWh per residential customer, and Hawaii had the lowest at 6,074 kWh per residential customer [2].

Washing machines and dryers, one of the common electrically powered devices in every home, draw the most energy relative to other home appliances, with an averaged 700W in operation. With these power consumption facts, the problem to tackle is the power required for washing machines in public areas such as gyms. A washing machine is an appliance that doesn't use continuous power throughout the day, which allows modelling a system that can be broken down into 3 main stages:

1. Energy generation
2. Energy storage
3. Energy consumption.

From these three main stages, all components are broken down to their minimal forms for further examination and simulation.

Design Specification

The wasted energy comes from work out machines such as stationary bikes, rowing machines or similar cabled machines. The main source of energy focused on for modeling purposes was a single stationary bike. All values could be increased to account for a gym with multiple bikes and/or the use of the rowing machines.

Design Objectives

The objectives of system design are listed below:

1. We plan for the end-system to be mechanically powered using a renewable source and have the effect of reducing grid electrical energy demand.
2. Have the system installable in a residential home.

Alternative Concepts

These solutions use the energy generated by humans during workouts by utilizing machines such as bicycles, rowing machines and other similar devices which require weight to be pulled in repeated continuous motion. This energy will be harnessed for the purpose of turning laundry loads for friction washing and/or tumble drying.

Use of Pressurized Water flow

Energy from the exercise machine is used to pump water into a tank, when the tank is filled to a predetermined height, the tank is emptied, to drop water into a drum filled with clothes to be washed. The potential energy stored in the tank is used to rotate the drum and supply water for laundry. Once the energy is dissipated, the water is then pumped back up to the tank via pressure difference, the motion is repeated for a predetermined number of cycles. During the drying phase, the potential energy in the water is used to rotate the drum, but the water is not allowed to enter the drum.

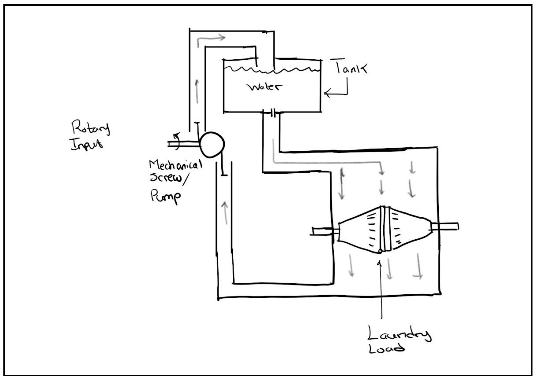


Figure 1: Proposed system 1

Use of Kinetic Energy

In this solution, a flywheel will be used to store kinetic energy from exercise machines. The stored kinetic energy is then converted to electrical energy, which powers an electrically powered washing machine. Additionally, we can have carpets with a piezoelectric material that can produce an extra amount of electricity to power the washing machine.

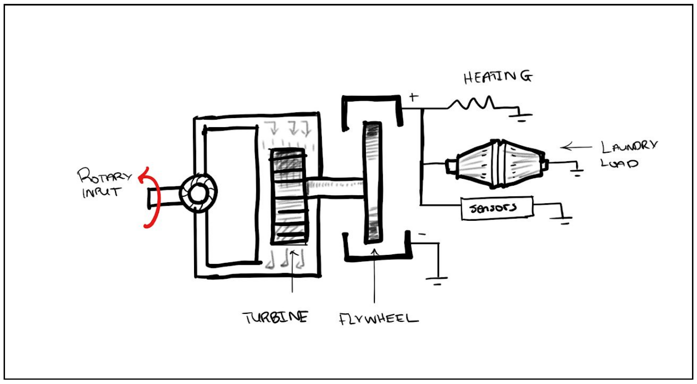


Figure 2: Proposed system 2

Use of Elastic Potential Energy

A common motion used in washing machines is the oscillation of the drum clockwise and anticlockwise for washing and drying. This solution uses the elastic potential energy of an oscillating linear spring with the help of mass, to rotate the drum. The rotary input from the exercise machine is then used to raise the mass, which compresses a linear spring attached to the mass. The linear springs elastic potential energy is used to oscillate the drum filled with clothes. This system meets the design objectives by not being powered by the grid and is completely mechanical. It can also be installed in the garage of a home.

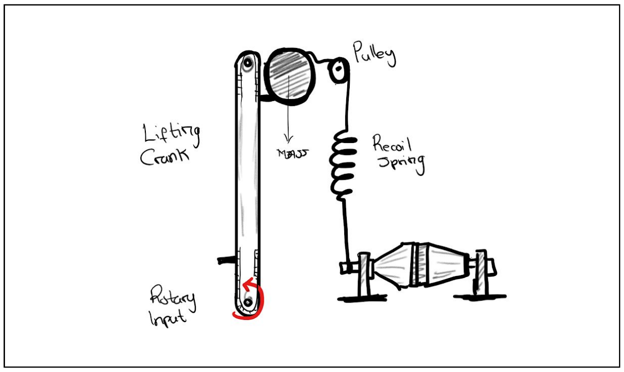


Figure 3: Proposed system 3

Design Selection

The final design is a combination of the first and second solution - the primary solution. This system described is more efficient compared to others as it saves energy when the washing machine is not in use. Also, the system is able to generate electrical energy for use, which makes room for addition of sensors into the machine, to make it smarter. Consumers can choose the way to power the washing machine through different sources - using the different exercise machines.

System Details

The exercise machine used for this project will be a rowing machine. However, different exercise machines can be employed to achieve the same input. The rowing machine is modeled using torsional springs and an inertia element.

Rotational energy from a rowing machine will be used to elevate a bucket of water to a predetermined height. As the bucket is being elevated, a spring is being compressed, storing elastic potential energy. At the maximum height, the loaded spring is used to empty the bucket of water.

Gravitational potential energy of the water is used to turn a turbine. The turbine is connected to a flywheel via a flexible shaft/link. The turbine is modeled as a rotational element with torsional springs and an inertia element.

The system is further complicated by taking into account the efficiency and friction losses to maximize energy generation.

Modeling

Input Variable

The input for the system - torque provided by a human cyclist.

Source

For the mechanical system to be realistic, data for the average torque which an individual can generate with an exercise machine will be used for our simulation. This data was obtained from research papers on the peak torque generated by a human cyclist[3] and estimating the torque variation from pedal motion in cycling.[4]

A graph obtained from literature is depicted below:

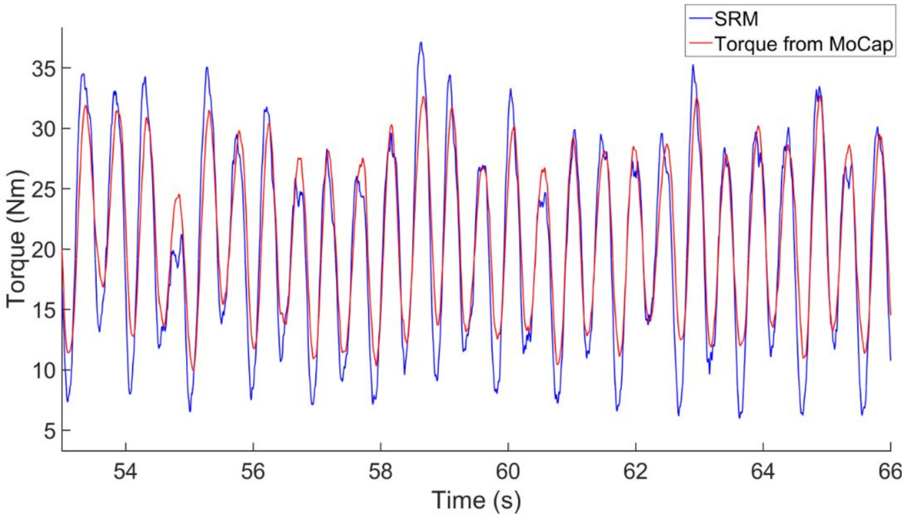


Figure 4: Graph of torque vs time[4]

Extracting torque input value from the graph between 54 and 56, results in the following values

Torque (Nm)	15	30	17	25	20	10	30	25	15	29	13
Time (s)	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0

Table 1: Interpolated torque generated by a cyclist measured via mocap

Mathematical Models

The system is made up of a combination of system types and element types. The following section highlights the elements which constitute the complete system and describes them using their state equations.

System and Element Model

For simplicity, the input in our system is assumed to be a single cyclist producing a torque by cycling in a gym. However, the input torque can be provided by several exercising machines in a gym. The following text presents the different subsystems employed and further breaks down each subsystem to its elements with their respective governing state-equations.

Note: The parameters for each stage are provided with reasonable justification under Design Parameters section.

Energy Storage and Consumption

Recalling that the input to our system is assumed to be torque from an individual cycling or rowing. The torque produced by this individual is used to store energy in a flywheel.

Figure 5 is a graphical representation of the energy storage subsystem.

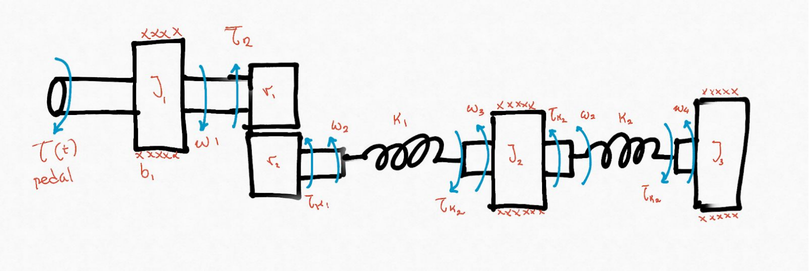
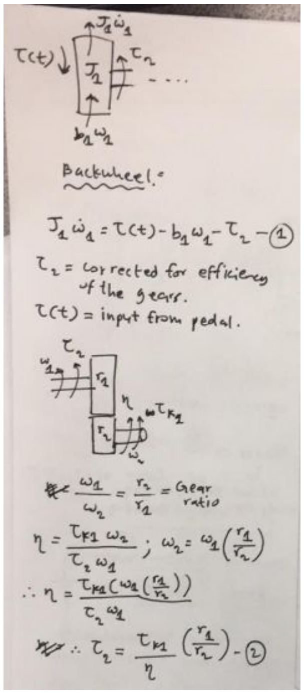


Figure 5: Energy Generation System - Pedal-Generator Mechanical System

The energy storage subsystem constitutes multiple stages, energy being transferred from the point of action (i.e. the input torque) to the Flywheel, energy is stored here for later use.

To magnify the input torque applied to the backwheel of a cycle/rowing machine, the subsystem utilizes a gear train with a predetermined efficiency.

Figure 6 is a detailed graphical representation with the respective governing equations to depict how a gear train is being utilized.



Backwheel:-

$$J_1\dot{\omega}_1 = \tau(t) - b_1\omega_1 - \tau_2 - ①$$

τ_2 = corrected for efficiency of the gears.

$\tau(t)$ = input from pedal.

$$\frac{\omega_1}{\omega_2} = \frac{r_2}{r_1} = \text{Gear ratio}$$

$$\eta = \frac{\tau_{K1}\,\omega_2}{\tau_2\,\omega_1}\,;\ \omega_2 = \omega_1\left(\frac{r_1}{r_2}\right)$$

$$\therefore \eta = \frac{\tau_{K1}\left(\omega_1\left(\frac{r_1}{r_2}\right)\right)}{\tau_2\,\omega_1}$$

$$\therefore \tau_2 = \frac{\tau_{K1}}{\eta}\left(\frac{r_1}{r_2}\right) - ②$$

Figure 6: Gear train - Backwheel and Gear

The back-wheel in figure 6 is a Type-A energy storage element. It is modelled as an inertia element and its angular velocity is a state variable of our subsystem. In addition, to account for friction losses, friction is added to the backwheel. The state-equation of the back wheel is given below as equation 1.

$$J_1\overline{\omega}_1 = \tau(t) - b_1\omega_1 - \frac{T_{k_1}}{\eta}\left(\frac{r_1}{r_2}\right) \quad (1)$$

The magnified torque produced at the output of the gear train is used to turn a Flywheel.

Figure 7 is a detailed graphical representation, with the respective governing equations, to depict how the output torque of the gear train is being utilized to store energy in the Flywheel.

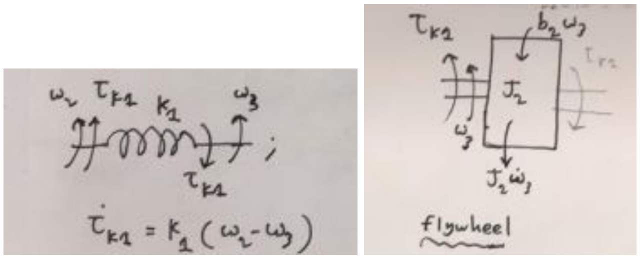


Figure 7: Spring and Flywheel

The torsion spring in figure 7 is used to store energy produced by the gear train. The flywheel is modelled as an inertia element. In addition, to account for friction losses, friction is added to the Flywheel. The state-equations of the Torsion Spring and the Flywheel are given below as equations 2 and 3, respectively.

$$\overline{\tau}_{k1} = k_1\left[\omega_1\left(\frac{r_1}{r_2}\right) - \omega_3\right] \quad (2)$$

$$J_2\overline{\omega}_3 = \tau_{k1} - \tau_{k2} - b_2\omega_3 \quad (3)$$

The energy stored in the flywheel is used to pump water from a well to an overhead tank. The torque needed to pump water from the lower reservoir (i.e. the well) is generated using the energy stored in the flywheel to power a generator**.**

Figure 8 is a detailed graphical representation, with the respective governing equations, to depict how the energy stored in the flywheel is being harnessed to power a generator.

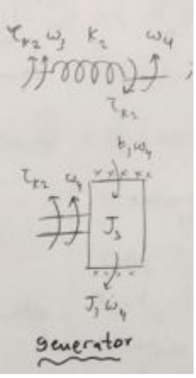


Figure 8: generator

The torsion spring in figure 8 is used to store energy produced by the flywheel as elastic potential energy. The Generator is modelled as an inertia element. In addition, to account for friction losses, friction is added to the generator. The state-equations of the Torsion Spring and the Generator are given below as equations 4 and 5, respectively.

$$\overline{\tau}_{k2} = k_2\left[\omega_3 - \omega_4\right] \quad (4)$$

$$J_3\overline{\omega}_4 = \tau_{k2} - b_3\omega_4 \quad (5)$$

The torque given as input to the generator is used to turn a motor which produce a back-emf. The generated back-emf is used to pump water from the lower reservoir (i.e. the well) to the overhead tank.

The following figures provide a detailed graphical representation with the respective governing equations to depict how water is pumped to an overhead tank by utilizing the energy stored in the flywheel.

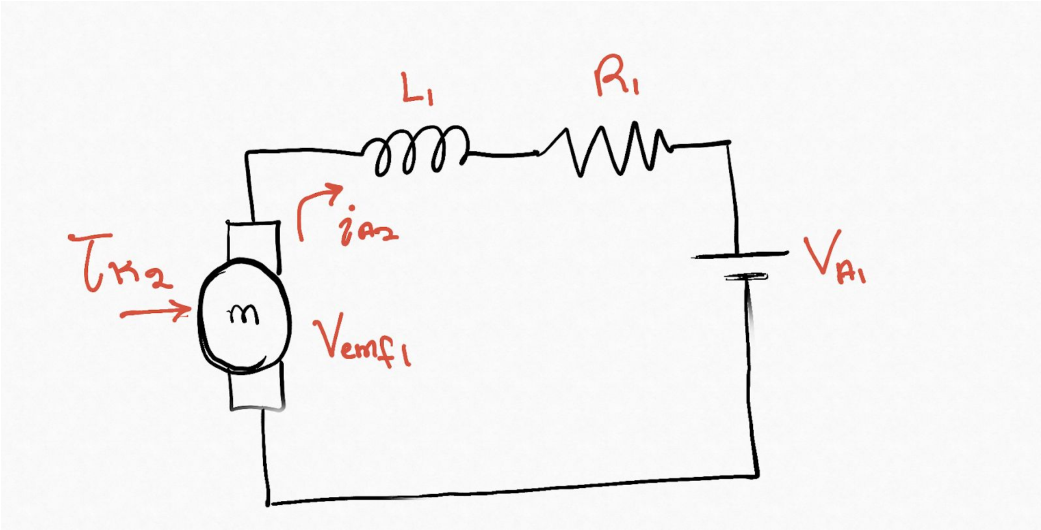


Figure 9: Generator - Electrical System

The energy stored in the flywheel is used to generate back-emf, as shown in figure 9. The state-equation of the armature current of the Generator is given as equation 6.

$$\bar{i}_{L1} = \frac{V_{emf1} - V_{R1} - V_{A1}}{L_1} \quad (6)$$

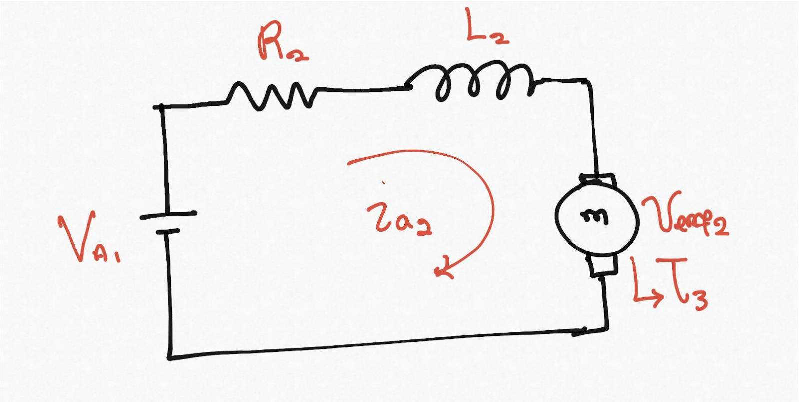


Figure 10: Electric System - Pump

Figure 10 shows the circuit setup to produce a torque using the generated back-emf of the generator. This produces a pressure difference between the lower-reservoir (i.e. the well) and the overhead tank. The state-equation of the armature current of the motor is given as equation 7.

$$\bar{i}_{L2} = \frac{-V_{emf2} - V_{R2} + V_{A1}}{L_2} \quad (7)$$

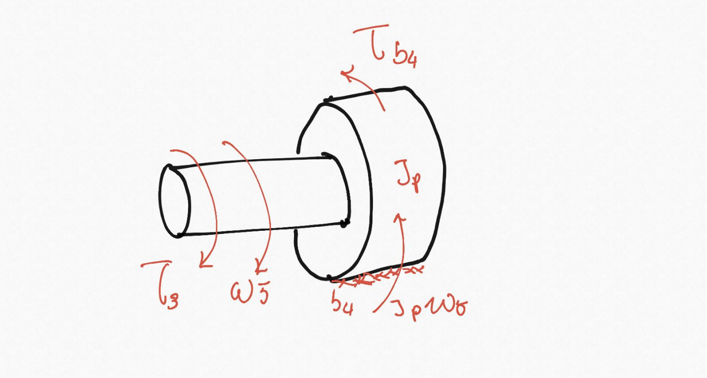


Figure 11: Pump - Mechanical model

The torque produced by the generated back-emf of the generator, is used to pump water to an overhead tank. The pump is modelled as an inertia element. In addition, to account for friction losses, friction is added to the pump element. The state-equations of the pump and the corresponding pressure-head developed in the overhead tank is are given as equations 8 and 9, respectively.

$$J_p \overline{\omega}_5 = \tau_{k3} - b_4 \omega_5 \quad (8)$$

$$\overline{P}_{3A} C_f = \frac{P_{in}}{R_{ef}} - \frac{P_{3A}}{R_{f1}} \quad (9)$$

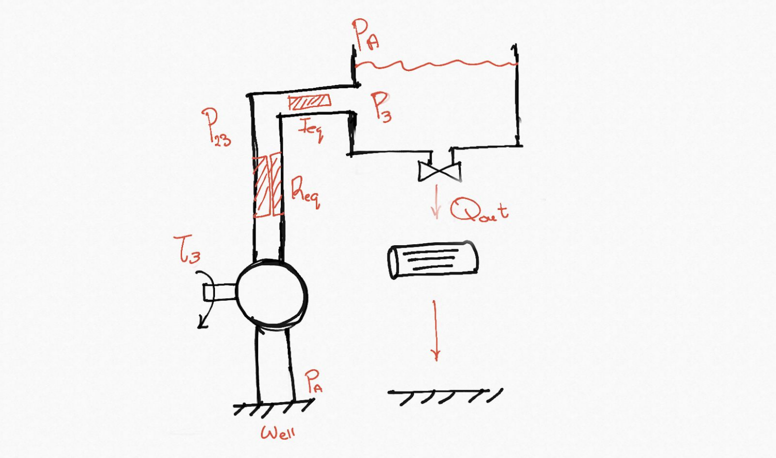


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Figure 12: Fluid system model

Figure 12 is a graphical representation of the pressure-head developed in the overhead tank due to the pressure difference created by the pump. The rate of flow of water from the lower-reservoir to the overhead tank is modelled using the state equation 10.

$$\overline{Q_{in}} I_{eq} = P_{in} - Q_{in} R_{eq} - P_{3A} \qquad (10)$$

The pressure-head developed in the overhead tank stores energy as a fluid capacitor. The energy stored in the tank is used to drive a drum, by periodic actuation of a valve. The period is predetermined and depends on the weight of the drum and the torque needed to rotate it - heavier the drum, the more torque needed to complete a cycle. Hence, the higher the frequency of valve actuation.

The water flowing out of the tank periodically, drives the drum and returns to the lower-reservoir. The torque produced by the energy stored in the flywheel helps pump water back to the overhead tank. The energy stored in the overhead tank is consumed by the drum as it rotates. Therefore, the output of our system is the torque across the drum. The plot for the power of the drum is included in the Simulation section under Energy Consumption for your reference.

Design Parameters

The system being modelled has a handful of unknown parameters that are to be determined through research and calculations, to ensure feasibility of the system. All parameters are summarized in table 2.

Energy Generation

Within the energy generation portion of the system we had to determine the masses and constant relating to the torsion bars and gears.

The first mass being the backwheel was determined to be 20[Kg] as that was found to be a standard flywheel mass of a high resistance stationary bike, with a radius of 0.3[m] [9].
The gear ratio was chosen to be 20:1, used to increase the torque from the input. A torsion bar connecting the gears to the flywheel was calculated to have a spring constant value of 363.1 [N/m] [8].

Energy Storage

The Energy storage element of our system is the flywheel which from research we found to have a mass of 270 [Kg], and a radius of 0.65 [m] [5]. We also found the flywheel to have a damping coefficient of 0.2[5].

Energy Consumption

Consumption starts with the generator attached to the output shaft of the flywheel via a torsional bar, with a spring constant of 363.1 [N/m][8].

The generator was modeled as an emrax bldc motor, referencing the datasheet we were able to find all relevant parameters such as resistance, inductance, V/rpm, mass and radius which are summarized in table 2.

Following the parameterization of the generator, we move to modeling the washer. From research and assumptions on the required power-output, it was established we need a 6 [m] pipe with a diameter of 0.0191 [m].

The motor used to model the pump is an emrax bldc motor [7], referencing the datasheet we were able to find all relevant parameters such as currents, resistance, and inductance. This pump transports water through the designed pipes to the open overhead tank.

Using a cross section area of 0.785 [m^2] and a height of 0.4 [m], the overhead tank has a volume of 300[L] and a fluid capacitance of 8×10^{-5} [$m^4\cdot s/Kg$] using the equation $C_f = \frac{A}{\rho g}$.

Using density of water as 997 [kg/m^3] and viscosity of water as 8.9×10^{-4} [Pa], pipe inertance and resistance were calculated using equations $I_{eq} = \frac{\alpha\rho L}{A}$ and $R_{eq} = \frac{128\rho L}{\pi d^4}$, respectively.

Finally, the drum was found to have a radius of 0.25 [m] and a loaded mass of 30 [kg]. The weight of the drum was assumed to account for the weight of material, water, and clothes. The washer was modeled with having a damping coefficient of 0.5[6]

Parameter Table

Parameter Name	**Variable Name**	**Value**	**Unit**
Back wheel mass	m_1	20	Kg
Flywheel mass	m_2	270	Kg
Generator mass	m_3	40	Kg
Pump mass	m_4	7	Kg
Drum mass	m_5	30	Kg
Back wheel radius	r_1	0.3	m
Flywheel radius	r_2	0.65	m
Generator radius	r_3	0.174	m
Pump radius	r_4	0.094	m
Drum radius	r_5	0.25	m
Back wheel resistance	b_1	0.7	NA
Flywheel resistance	b_2	0.2	NA

Generator resistance	b_3	0.39	NA
Damping on drum	b_4	0.5	NA
Back wheel inertia	J_1	0.9	Kg m^2
Flywheel inertia	J_2	57.04	Kg m^2
Generator inertia	J_3	0.61	Kg m^2
Pump inertia	J_p	0.031	Kg m^2
Drum inertia	J_d	0.9375	Kg m^2
Gear 1 ratio	R_1	1	NA
Gear 2 ratio	R_2	20	NA
Gear efficiency	n	0.9	NA
Spring coefficient	k_1	363.1	N/m
Spring coefficient	k_2	363.1	N/m
Generator EMF	k_{emf1}	1.4	V/rpm
Pump EMF	k_{emf2}	1.4	V/rpm
Generator resistor	R	28	mΩ
Generator inductor	L	380	μH
Pump	k_4	0.67	Nm/A
Fluid capacitance	C_f	8×10^{-5}	m^4·s/kg
Fluid resistance	R_f	89.93	Pa·s/m^3
Pipe resistance	R_{eq}	5.50×10^6	Pa·s/m^3
Pipe inertance	I_{eq}	20.87×10^6	Kg/m^4
Pipe length	L_1	6	m
Pipe diameter	d_1	0.0191	m
Valve length	L_2	0.1	m
Valve diameter	d_2	0.00635	m
Tank radius	r_6	0.5	m
Tank height	d_3	0.4	m

Tank volume	V_1	300	L

Table 2: System parameters[5][6][7][8]

Simulation

Energy Storage

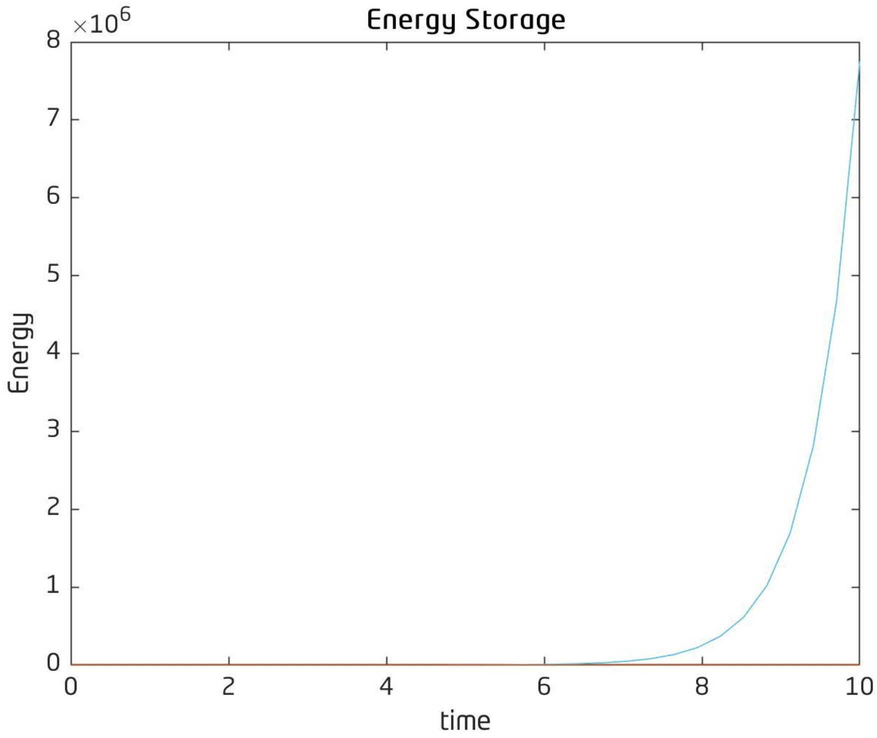

Figure 14: Energy Storage-Time Plot

The energy is generated by pedalling and/or rowing, transferring energy to the spring and then to the flywheel. Before the energy is transferred to the generator, a spring stores the energy in itself as elastic potential energy. The input is provided to the system for a short duration - i.e. an impulse, which results in the huge spike shown in figure 14.

Energy Consumption

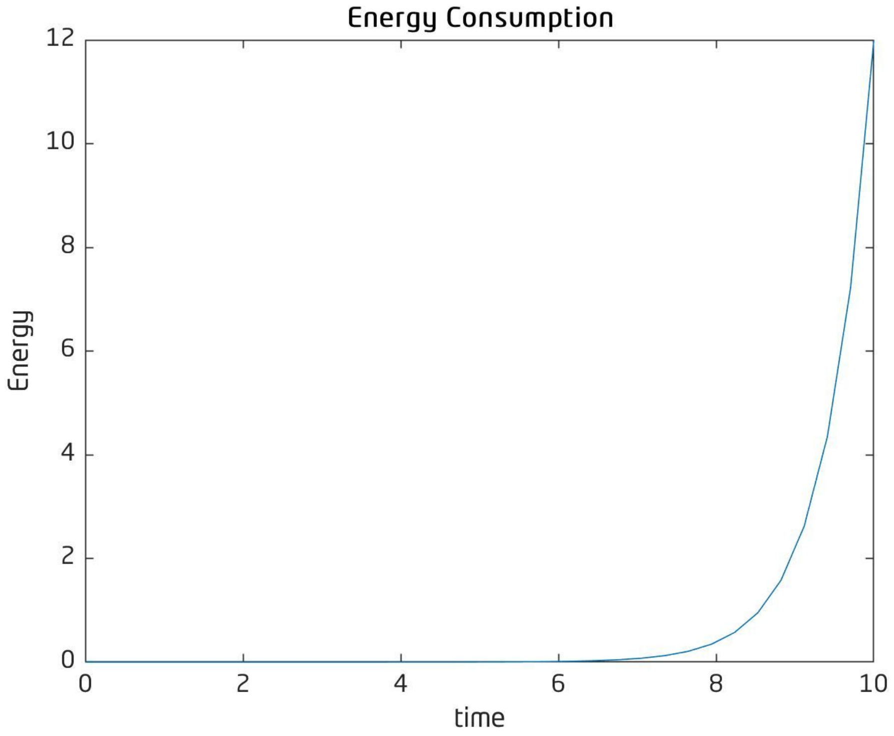

Figure 15: Energy Consumption-Time Plot

Following the final energy storage element, the generator starts producing energy that is provided to the rest of the system. According to figure 15, the energy consumption is less than the energy produced and stored. The lost energy can be accounted for by simulating the heat and friction losses.

Linearization model

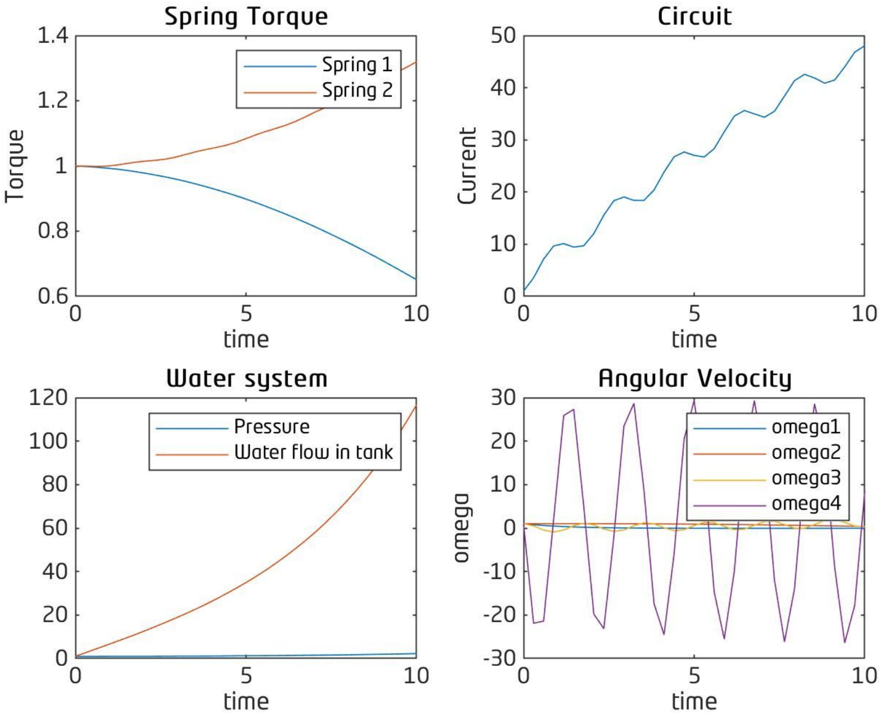

Figure 16: Linearized model

The main feature to observe in the linearized model of the system is that all the models are linear. The operating point of the linear model is calculated by equating the state equations of the system to zero and solving for the all state variables.

The system is linearized about the operating point as shown in figure 16, where omega1- 4 are the rotational energy of the backwheel, the flywheel, the generator and the pump, respectively.

Non-linear model

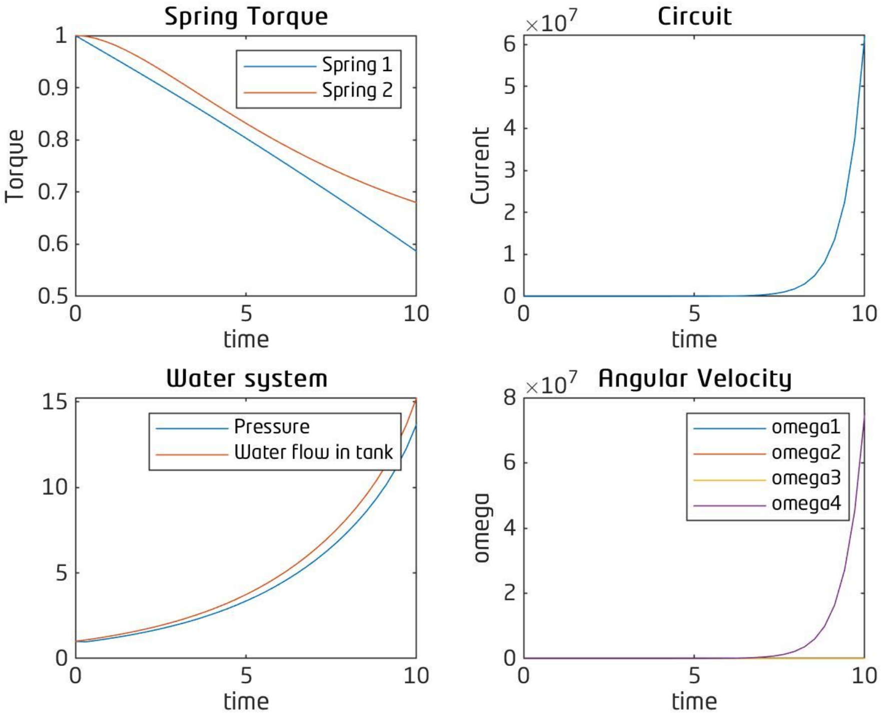

Figure 17: Non-linear model

The spring has a non-linear ‘K’, resulting in a non-linear system and low amounts of energy being passed to the system from the input as shown by figure 17.

Design Reflection

Simulation

For some parts of the system, data is scaled, to observe changes in the system. We believe the scaling of these parameters caused the spikes in our simulations. The spikes in our simulation could be a result of a human error in the calculations of the system. It is to be noted that the system designed in this report is not a perfect system. The imperfections of the system are not entirely accounted for in the simulations in MATLAB.

Conclusion

Based off the simulations of our designed model, we are able to establish that the system was able to output the required power to run the washing machine for a complete cycle, using only renewable energy from an exercise machine. It is to be noted that this system is not as ideal or efficient as the power transmission and consumption of a conventional washing machine powered from grid power. However, the objective of this model was not to make a more efficient design but to make a system that had a lesser impact on our energy consumption.

References

[1] FrequencyCast, FrequencyCast - The UK Tech Radio Show, 2018. [Online]. Available: https://www.frequencycast.co.uk/

[2] U.S. Energy Information Administration, “How much electricity does an American home use?” 2018. [Online]. Available: https://www.eia.gov/tools/faqs/

[3] Abbiss Chris, Peiffer Jeremiah, and Laursen Paul, “Optimal cadence selection during cycling,” 2009.

[4] J.-C. Quintana-Duque, T. Dahmen, and D. Saupe, “Estimation of torque variation from pedal motion in cycling,” vol. 14, 2015.

[5] ActivePower, CLEANSOURCE, 2017 [Online] . Available: http://www.activepower.com/en-US/5066/.

[6] K. Takayuki, T. Nobutaka, and N. Yutaka, Modeling and Vibration Analysis of a Drum type Washing Machine, 2016. [Online]. Available: http://semimac.org/wp-content/uploads/2016/03/

[7] E. I. E-Motors, User’s Manual for Advanced Axial Flux Synchronous Motors and Generators, 2016. [Online]. Available: http://emrax.com/wp-content/uploads/2016/12/

[8] MITCalc, SpringsCalculation, 2016. [Online]. Available: http://www.mitcalc.com/doc/springs/help/en/

[9] Indoor Fitness , Why Is The Flywheel Weight Important For Spin Bikes?, 2015. [Online]. Available: https://indoorsfitness.com/flywheel-weight-important-spin-bikes/