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University Honors Program Research Project

APPROVAL PAGE

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College: College of Electrical and Computer Engineering

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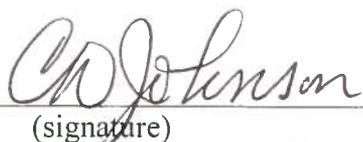
Full title of project as it should appear in Graduation Program and transcript:

Speed Control for Simple Heat Engine

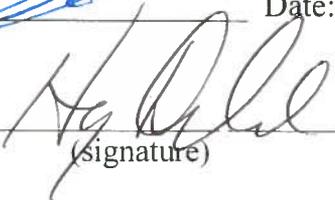
Abstract:

There are many different types of clean efficient engines. One example is a Gamma Stirling engine, which uses a power piston and a displacement piston to as part of a system to produce power. One problem with a Stirling engine though is the external heat causes the engine to fluctuate in speed, which in turn will cause noticeable differences in voltage output. I will attempt to implement a circuit to control the speed of the Stirling engine.

Approved by:

Project Advisor:  Date: Nov. 18, 2010
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Department Chair:  Date: 11/23/2010
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University Honors Program Director:  Date: 11-30-10
(signature)

Speed Control for Simple Heat Engines

by

Kat DeVirgilio

Honors Thesis

**Submitted in partial fulfillment of the requirements
for Honors
for
The University of Alabama in Huntsville**

Chapter 1

Introduction

There are many different types of Stirling engines. The Stirling engine that was used was a Gamma type Stirling engine, which used a power piston, a displacement piston and a small connection tube between the two pistons. The piston casings are air tight, and the heat differential changes the pressure inside the Stirling engine. The air inside the Stirling engine is heated by an external heat source. When the displacement piston moves toward the cool side, the air inside the heat differential case heats up and the pressure inside the engine is high. This pushes out the power piston. When the displacement piston moves toward the hot side, the air inside the engine is on the cool side of the heat differential case and causes low pressure. The low pressure pulls the power piston in. Figure 1.1 shows the Stirling engine used in the experiment.

There are a few drawbacks to using a Stirling engine. A Stirling engine requires a large constant external heat source. After a period of time, the heat and cold differential will saturate and there will be no heat differential and the Stirling engine will stop. The saturation is not a problem with larger Stirling engines, but small engines will saturate easily. The Stirling engine does not scale well. A smaller Stirling engine will not be as efficient or easy to use when

compared to a larger Stirling engine. Overall though, the Stirling engine is a viable alternative source to clean power.

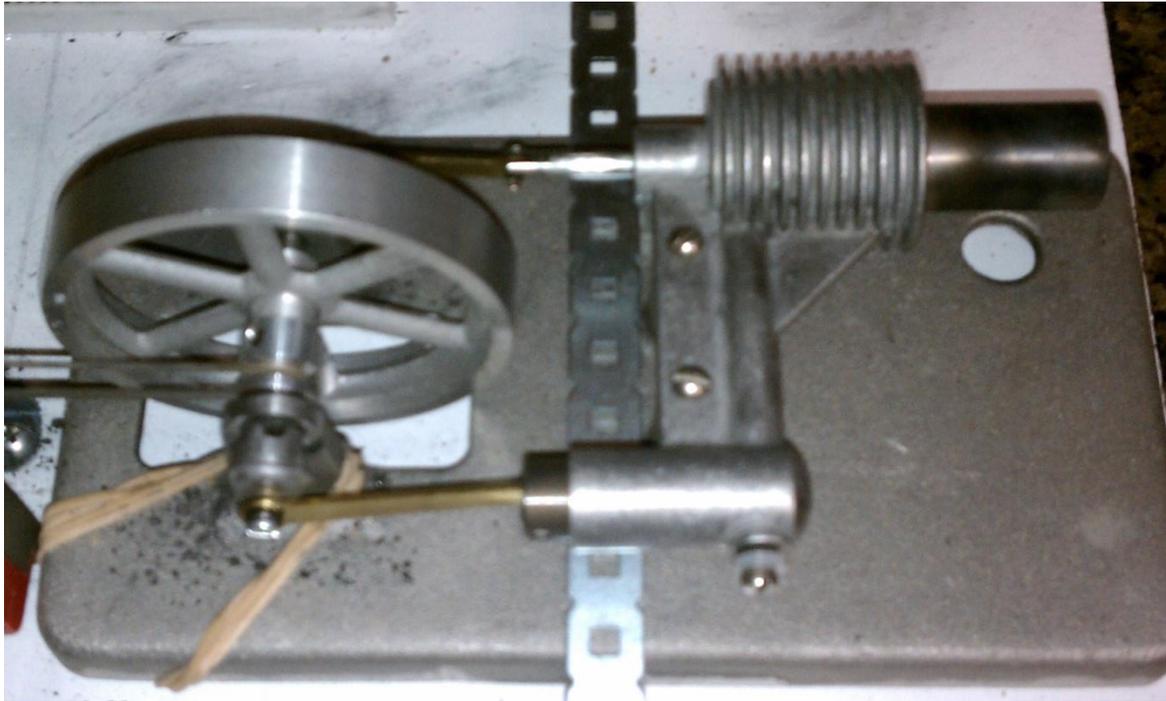


Figure 1.1 Stirling Engine

One concern about Stirling engines is the rotational speed problem. As the Stirling engine uses an external heat source, the speed of the Stirling engine will vary with the heat differential. The purpose of this project is to control the speed of the Stirling engine. There is a torque peak on a rotational engine, and any speed past a given torque peak will start to decrease power and lower efficiency. In order to avoid wasting power and to increase efficiency, this project will use a circuit and microcontroller to control the speed of the Stirling engine. A bang-bang or on and off control system, which was common a century ago will be attempted.

Chapter 2

Background and Literature Review

Stirling engine technology is used in a wide variety of applications today. Stirling technology applications include powering homes as a clean energy source, powering submarines used for naval defense, and possible space applications. A Stirling engine can be completely self-contained with a variety of external heat sources to power its internal heat cycle. There are many different types available they are nice and clean alternative power sources when compared to internal combustion engines and their nitrogen oxides pollutants.

One current application for Stirling engine technology combines the power of the sun with the clean running Stirling generator. A solar collector mirror array focuses the sun on the heat end of a Stirling engine. The heat is used to expand hydrogen gas, which drives the piston of the Stirling engine, which in turn powers an electric generator (Allan, 2005). Stirling Energy Systems claims their solar-Stirling combination is nearly twice as efficient as other solar energies currently in use. Southern California Edison signed an agreement with Stirling Energy Systems for 500 MW of clean power which could result in adding 20,000 dish systems (Allan). Stirling engine technology is clearly marketable and is a cleaner power generation alternative.

Another application for Stirling engines is using them as air-independent propulsion (AIP) systems on submarines. As nuclear power is not available for many countries, alternatives must be found. The Knockums AIP system on Swedish submarines use diesel fuel and liquid oxygen. The combustion gases are hot enough that the exhaust does not need a compressor for discharge from the submarine(Ross, 1995). As the Stirling AIP is vibration free and the infrared signature is extremely low, Swedish submarines are virtually invisible to sensor detection of the snorkel and hydrophone detection of the engine (Ross).

Even the National Aeronautics and Space Administration, more commonly known as NASA, has looked into Stirling engines as space technology. The free-piston Stirling engine is highly reliable, is highly efficient, is durable, and has a lot of potential to meet the requirements for space applications (Shaltens, 1987). Several companies are working with the Department of Energy's requirements for a low cost, long term Stirling engine to try and provide 25 kW of electricity to a utility power grid (Shaltens). There are many applications for Stirling engines and a lot of potential to grow.

From the depths of the sea to the far out reaches of space, Stirling engines can be applied to many facets of everyday technology. California combines solar energy with the clean running Stirling engine to produce clean electricity for millions of people. The Swedish use the Stirling engine as a propulsion system for submarines making them virtually undetectable by common technology. Controlling the speed of the engines without manipulating their heat sources is a challenge.

Chapter 3

Calibration of Tools

The overall system consisted of a Stirling engine, a digital optical shaft encoder, a small on-board motor, a breadboard, and a Vex microcontroller. The Stirling engine was connected with a belt to a shaft that was inserted into the digital optical shaft encoder, which read the rotations of the Stirling engine. The other side of the shaft was connected to the small on-board motor that acted as a generator. The output voltage from the generator was read by the Vex microcontroller A/D input. This is shown in Figure 3.4.

In order to determine the rotational count of the Stirling engine, the digital optical shaft encoder sensor had to be calibrated. This digital sensor used two interrupts to send quadrature data. Only one channel was used in my setup. The shaft encoder used 90 notches evenly spaced around a circle and an infrared sensor to count each time a notch passed by the sensor. In Appendix A, an example of the power calibration Vex code is shown. The Vex sensor was preset to zero using the `PresetEncoder` command and was sampled from interrupt port one on the Vex microcontroller. The interrupt ports are used for data that the microcontroller needs to process immediately (VEX). The `StartEncoder` command was necessary to start using the optical shaft encoder, as shown in the code. The shaft encoder was connected to the Stirling engine by

a pulley and belt, so every time the engine turned, it would turn the sensor in a one-to-one ratio. The elastic belt may have affected the coupling, but the effect was judged to be minimal.

In order to determine the power output of the Stirling engine, a small on-board motor was connected to the Stirling engine by a pulley. The electrical output of the motor was connected to analog port two of the microcontroller. The Vex microcontroller produced a count, which had to be converted into voltage. Every 200 counts from the microcontroller was one volt and on average, the motor could output about 100 millivolts unloaded.

The on-board motor was connected to a breadboard and to several different control circuits. The first load circuit was used to find the torque peak of the Stirling engine. The torque peak was when the Stirling engine reached its maximum power output versus rotations and faster rotations above the peak saw the power flutter or drop. The formula for torque is as follows:

$$T = P/2f\pi \quad (3.0)$$

With an electric drill as a mechanical power source, the torque remained constant. Thus rearranging the problem produces the following:

$$P = 2\pi f T \quad (3.1)$$

$$P = kf \quad (3.2)$$

The power depends directly on rotational frequency where $k = 2\pi T$.

By changing the resistor, it is possible to change the power output by the following:

$$P = V^2/R \quad (3.3)$$

To find the torque peak, different resistors were added in series with the generator and an electric drill was used to turn the shaft connecting the digital optical encoder and the generator. The data was imported into MATLAB, where the code in Appendix B was used to generate several graphs that included the RPS versus time, voltage output versus time, power spectral density, and the power versus RPS. By populating and examining different regression lines, the two ohm resistor was chosen, as it allowed the most power at 6.5 rotations per second. In Figure 3.1, the 2 ohm resistor graph showed a maximum power output of 0.6mW. In Figure 3.2, the 10 ohm resistor graph showed a maximum power output of 0.28mW. In Figure 3.3, the 200 ohm resistor graph showed a maximum power output of 0.015mW. The 2 ohm resistor allowed double the power output of the 10 ohm resistor and four times the power output of the 200 ohm resistor. Lower resistances were tried, but the voltages were too low to view accurately.

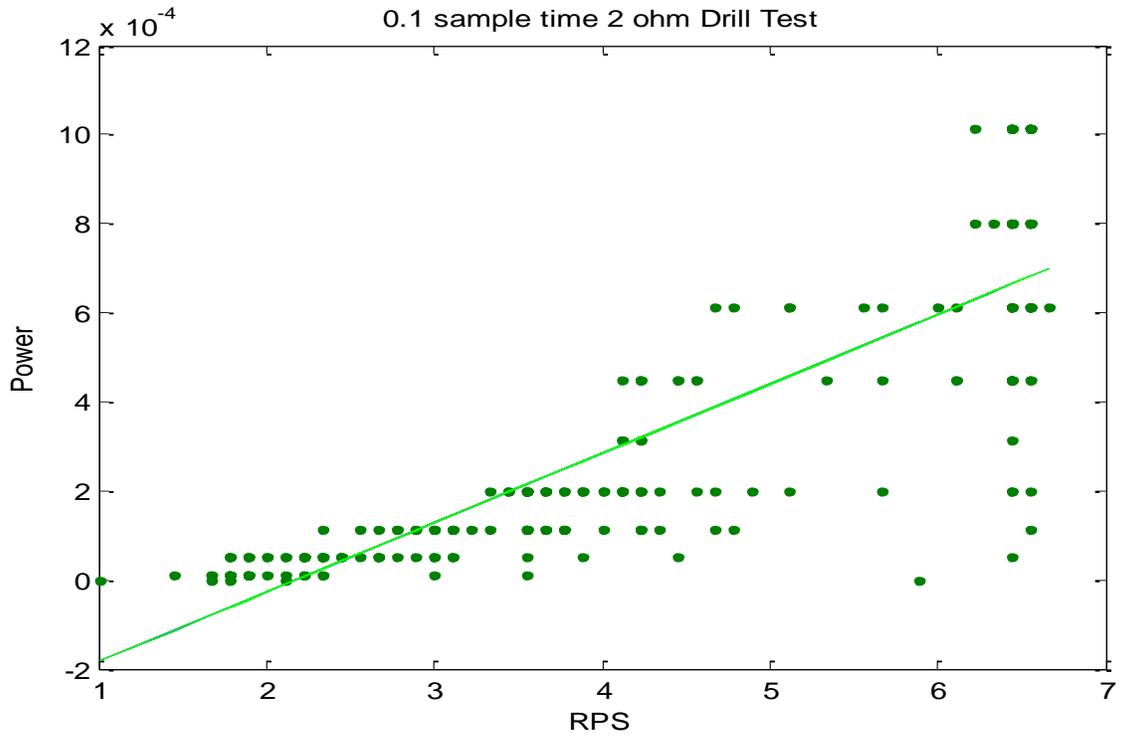


Figure 3.1 2 ohm Drill Test

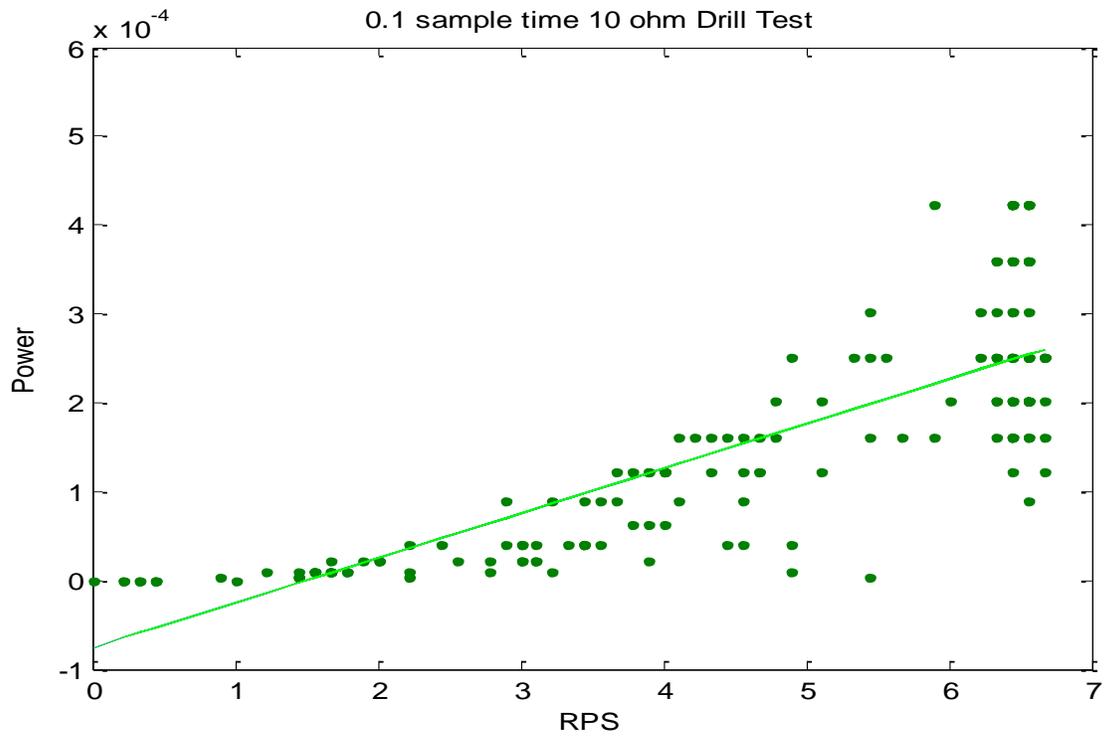


Figure 3.2 10 ohm Drill Test

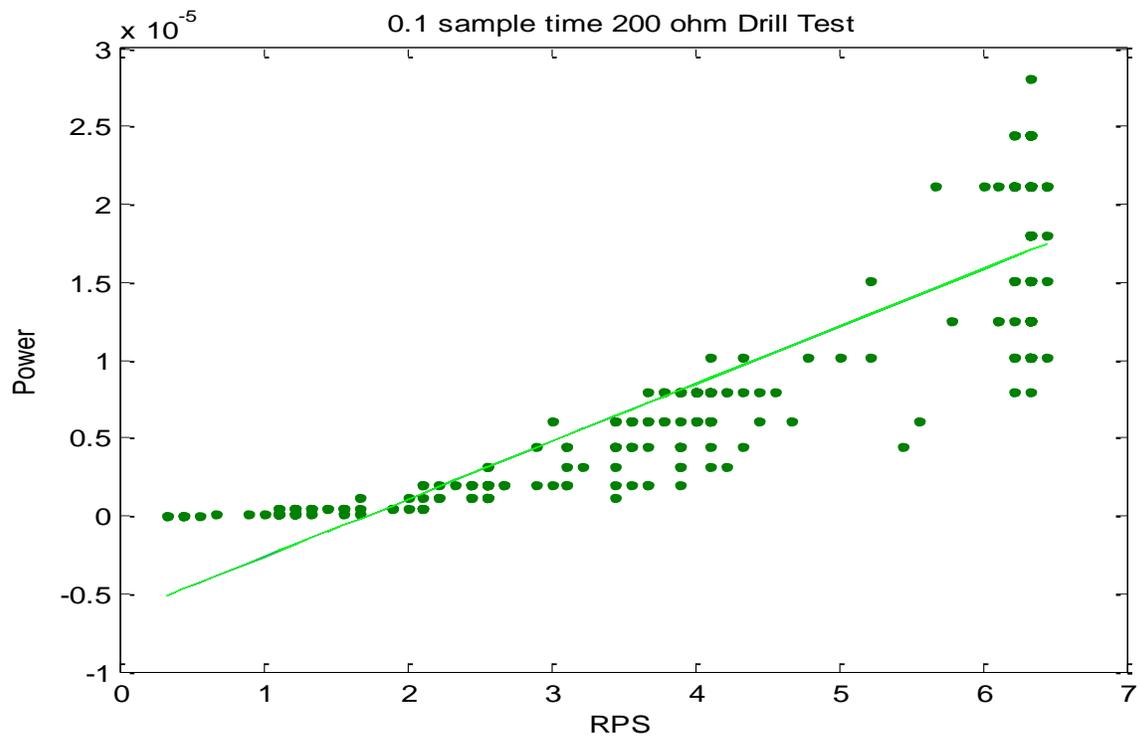


Figure 3.3 200 ohm Drill Test

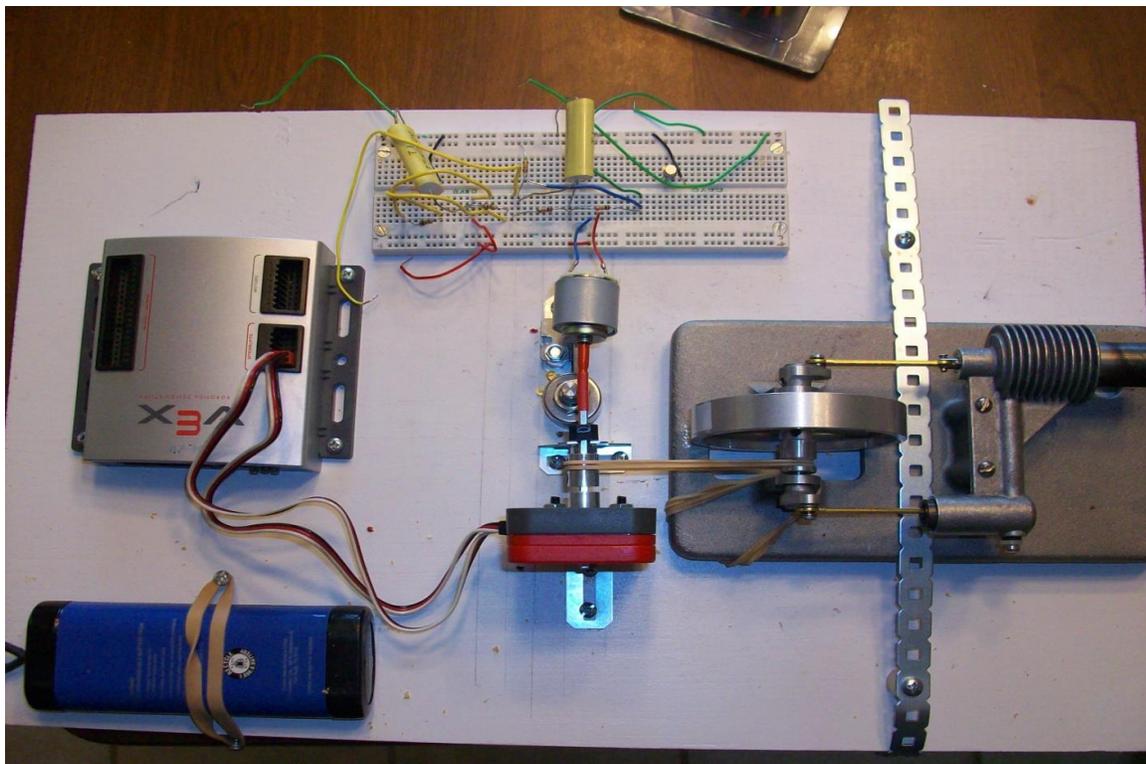


Figure 3.4 Project Set-up

Chapter 4

Experiment

By varying the control circuit, it is possible to control the power output of a Stirling engine. The basis for comparison was the open loop control circuit with the output of the generator going straight to the microcontroller for measurements. Then by varying the loads, it was possible to control the speed output of the Stirling engine.

One of the first tests performed was using a butane heat source only and no control circuit or basically an open-loop. In Figure 4.1, the butane open-loop test showed that without some sort of control or load, the rotations of the Stirling engine fluctuated wildly between 7 and 11 rotations per second. The first 2 seconds of the data were ignored as the motor was coming up to speed. The period varied over 1.5 seconds and could have possibly been from a varying heat source or just due to using a Stirling engine and the heat differential over time going down. The purpose of this project was to try to smooth out the wild fluctuations in speed.

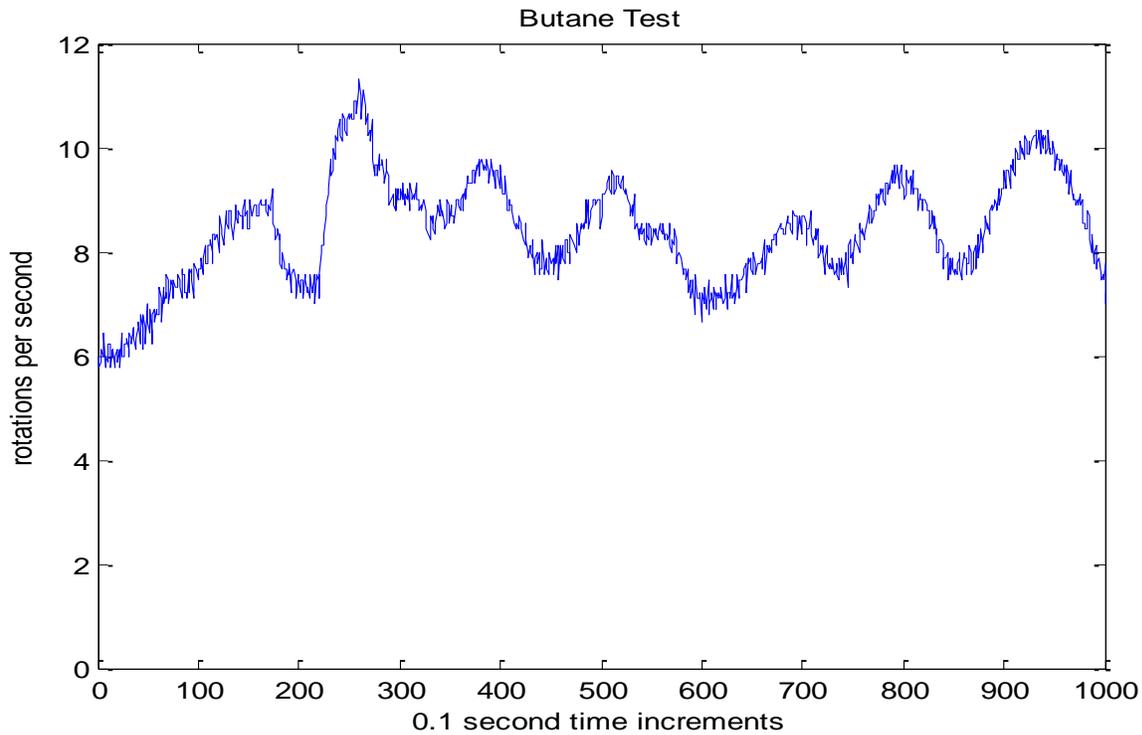


Figure 4.1 Butane Test

In addition, as the time sampling was fast enough, it is possible to view the intra and inter-stroke properties of the Stirling engine. The sharp up slant was the power stroke when the Stirling engine piston was accelerating the wheel and doing work. The rotations per second went up since the motor's energy goes into the wheel energy. The sharp downward slant was the compression stroke when the Stirling engine piston was coming back around and required work, so the rotations per second went down slightly. As the 0.1 second sampling time caused aliasing with the 10 rps motor speed, a special run was done at 0.01 second sampling time. An exploded view of the intra and inter-stroke oscillations is shown in Figure 4.2. The rotational speed changes between the power and compression strokes are clearly evident. The interstroke oscillations could be the residual effects of the dual elastic drive belts used in the test.

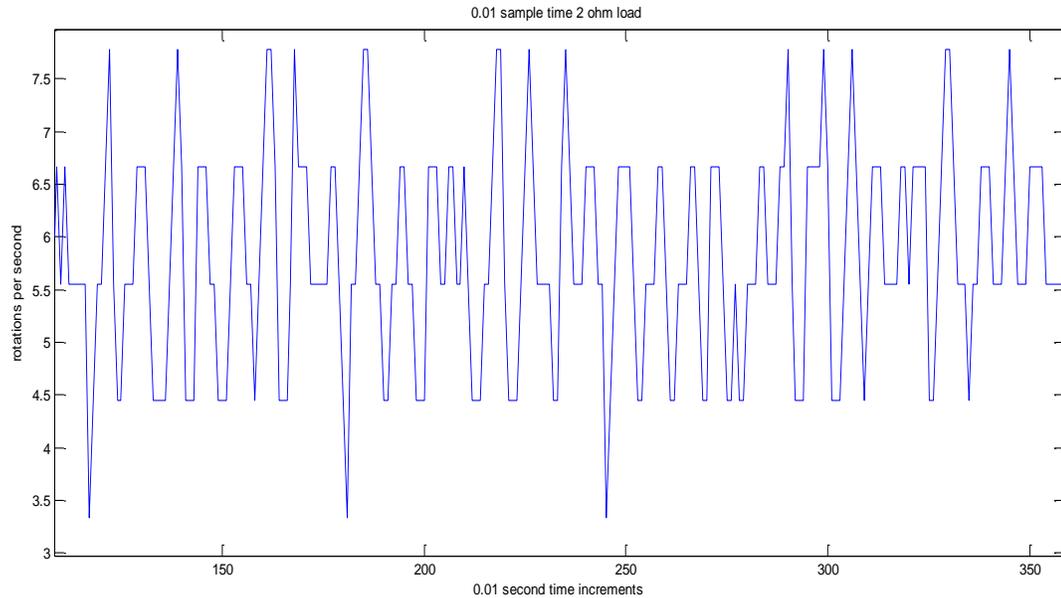


Figure 4.2 0.01 second Sampling Time

In Figure 4.3, a 2 ohm resistor was added in series with the generator in order to try to control the speed of the Stirling engine as the load was optimal; the average speed represented the torque peak of the Stirling engine. By just adding a passive component, the rotations per second did not vary as wildly as an open loop system. In addition, the 1.5 second periodic components were reduced, but the intra and inter-stroke oscillations remained.

Other passive components were used in order to see their effects on the speed of the Stirling engine. A 4700 μF electrolytic and 0.47 μF mylar capacitor were used in series with the generator with interesting results. The electrolytic capacitor has high capacitance per volume, but high dielectric loss. The mylar capacitor has a lower capacitance per volume, but much less dielectric loss. The small 0.47 μF capacitor did not change the speed of the Stirling engine significantly. This was expected as the energy stored in the capacitor is small when compared to

the energy of the engine. The 4700 μF capacitor caused the Stirling engine speed to increase dramatically as shown in Figure 4.4. The speed of the Stirling engine increased from an average

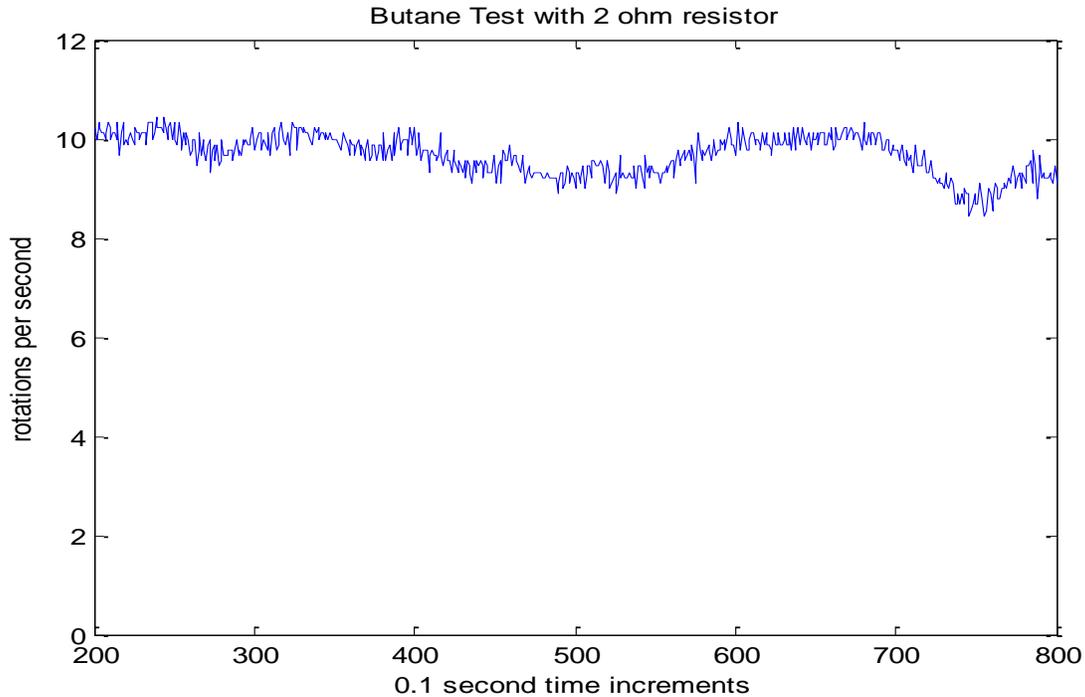


Figure 4.3 Butane with 2 ohm resistor

of 8 rotations per second up to 14 rotations per second. There was also a visible increase in speed of the Stirling engine to the point of concern for the mechanical parts of the engine. The capacitor stored up charge on the power stroke of the Stirling engine and discharged on the return stroke. Instead of slowing down on the return stroke like normal, the capacitor would discharge into the circuit and power the motor which was connected to the Stirling engine. This quickly returned the stirling engine to its power stroke. In effect, the Stirling engine was able to have a faster compression stroke instead of an alternating between slower compression and quicker power stroke. The type of material in the 4700 μF capacitor had a high dielectric loss and it was difficult to view the voltage. The capacitor used later in the full passive circuit was a

100 μF tantalum electrolytic capacitor. The tantalum material has a low dielectric loss and therefore did not cut the voltage like the standard electrolytic capacitor.

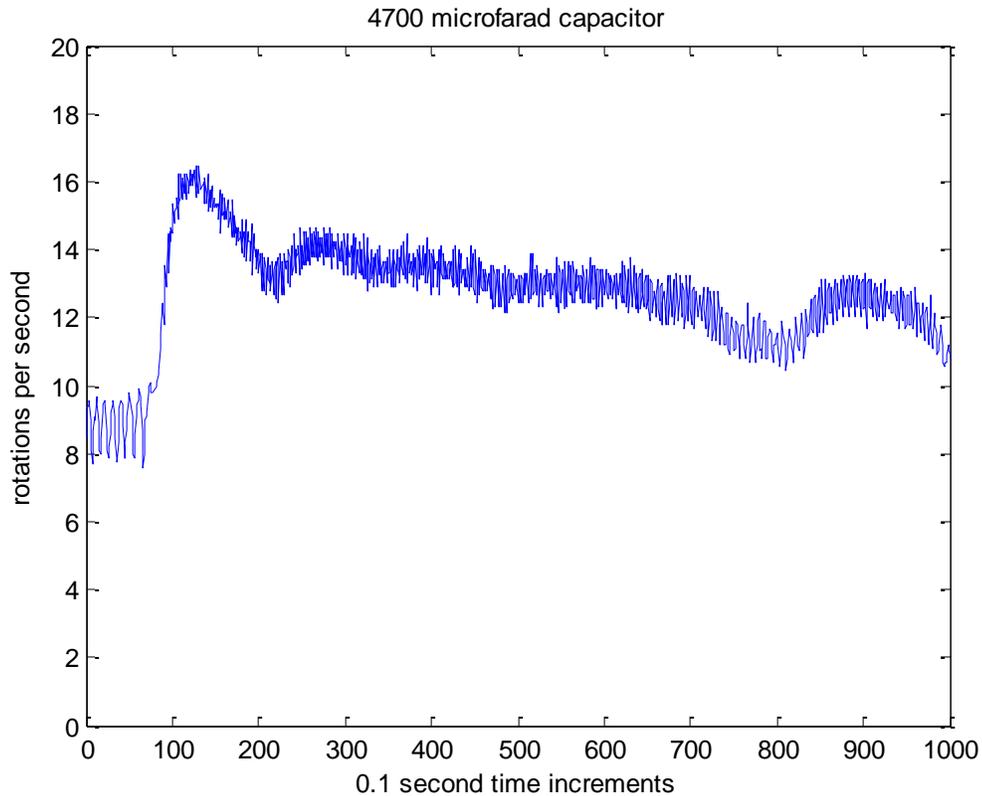
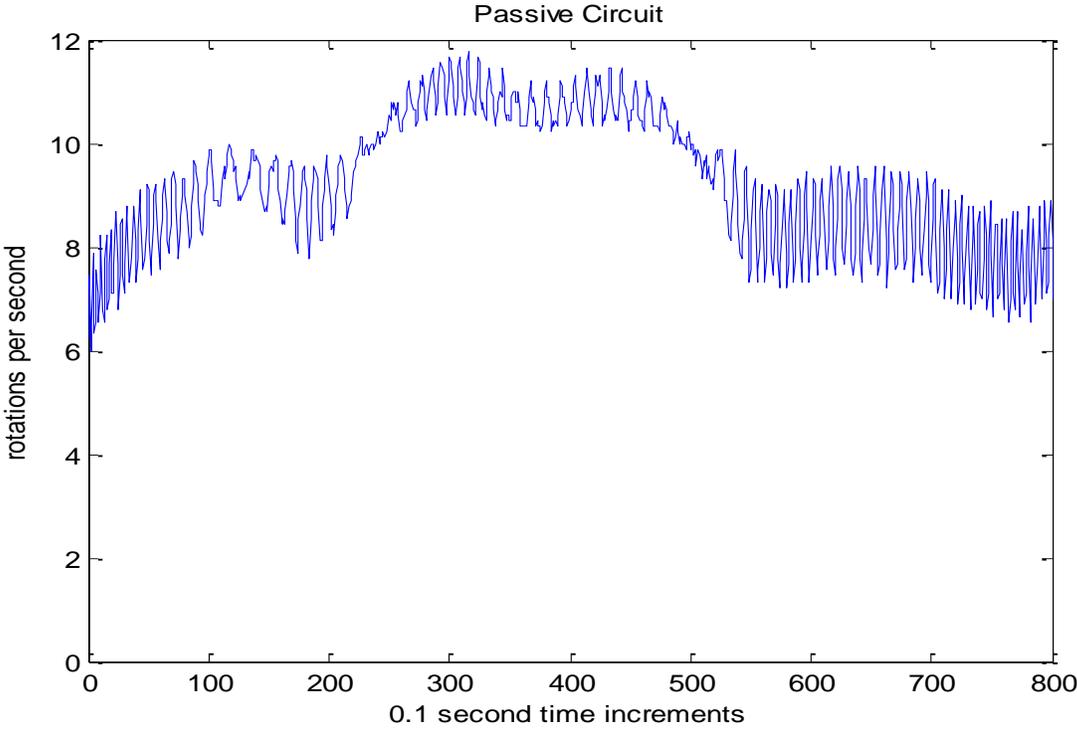


Figure 4.4 4700 μF Capacitor

The passive control circuit, as shown in Figure 4.6, consisted of a 2.0mH inductor in series with a 10 ohm resistor and a 100 μF tantalum capacitor in parallel. The combination of an inductor and capacitor made an LC circuit and formed a choke and capacitor filter found in tube power supplies of the past. The capacitor-inductor would at resonance filter out higher frequencies from reaching the load. Unfortunately, it was not possible to get inductors of the right size and with low series resistances. The next best choice was an inductor with a series resistance of 0.7 ohms and an inductance of 2 millihenrys. In the case of the Stirling engine, higher frequencies would be produced at higher rotation speeds and by the commutation of the

generator's armature. The 10 ohm load resistor was chosen in part because the 2 ohm resistor suppressed the voltage to levels too low to read. The 10 ohm resistor could act like a reasonable load, and the microcontroller would still be able to read the voltage. The passive control circuit



also affected the power and compression strokes making them longer and more visible as shown in Figure 4.5. The capacitor still caused a rotational speed surge to about 10 rps.

Figure 4.5 Passive Circuit

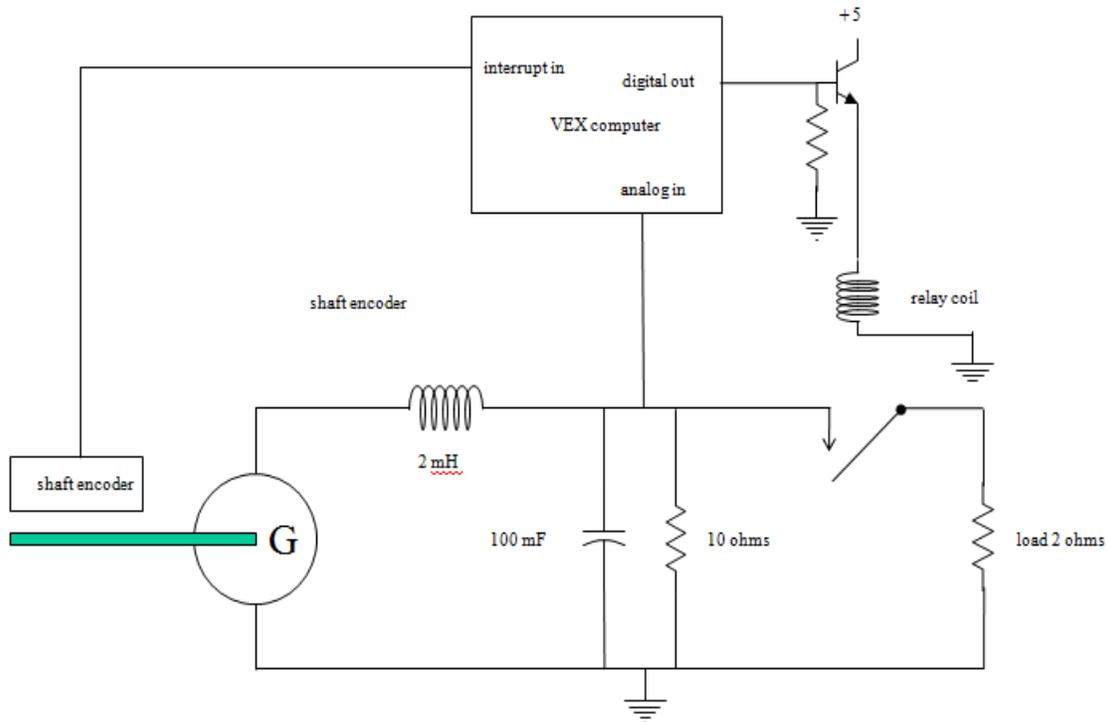


Figure 4.6 Inductor in Series with Parallel Capacitor Resistor

A single-pole single-throw relay was connected to the Vex microcontroller, and every time the logic dictated, as in the code shown in Appendix B, the relay was thrown. The relay would switch in a 2 ohm optimal load resistor. The resistor would load down the generator and slow the rotational speed of the Stirling motor. The average rotation per second of the non-loaded Stirling engine varied from about 7 rps to 11 rps. The speed of the Stirling engine with a passive circuit was around 7 rps to 13 rps. Every $1/10^{\text{th}}$ of a second, the code would check the current rotations versus a set number of 7.7 rotations per second. If the Stirling engine was above the 7.7 rotations per second, the relay would trigger and two ohms would be added into the circuit to load down the Stirling engine and slow the rotations. In Figure 4.7, the Stirling engine kept trying to speed up above 9 rotations per second, but the logic kept the speed well

fairly constant at 8.3 rps with a standard deviation of 0.66. The average rotation per second with the passive circuit and relay was a flatter line versus the fluctuations of the loop system.

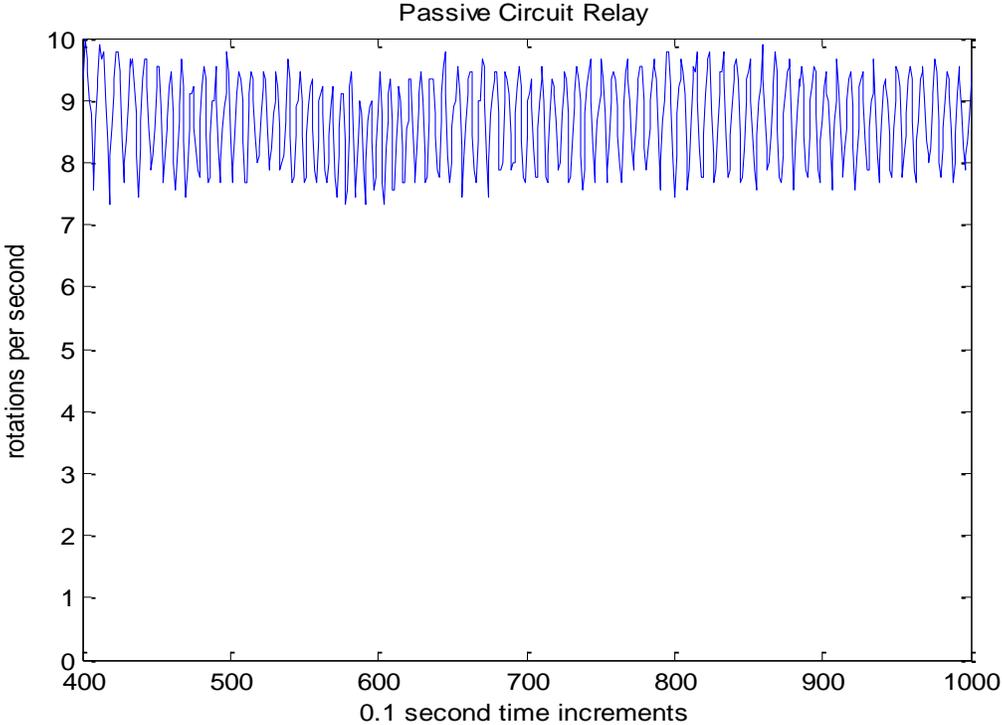


Figure 4.7 Passive Circuit with Relay

Chapter 5

Results and Discussion

By bang-bang control of the circuit, it was possible to stabilize the rotations of the Stirling engine. It was possible to vary the set number to pulse the circuit at any declared number. The 7.7 rotations per second number was low enough to demonstrate control over the Stirling engine and high enough to still allow the Stirling engine to do work. A close up view in Figure 5.2 shows an expanded view of the relatively straight line of the RPS. By comparing Figure 5.2 with Figure 5.1, it is possible to see that the RPS line has been smoothed out. The mean RPS with the passive circuit and relay was 8.7 rps compared to the mean rps of the Stirling engine with the 4700 μ F capacitor at 10.5 rps. The passive circuit and relay RPS was the closest to the set goal of 7.7. The passive circuit and relay also had the lowest standard deviation at 0.66 compared to the 4700 μ F capacitor at 7.4 and the open circuit at 10.1.

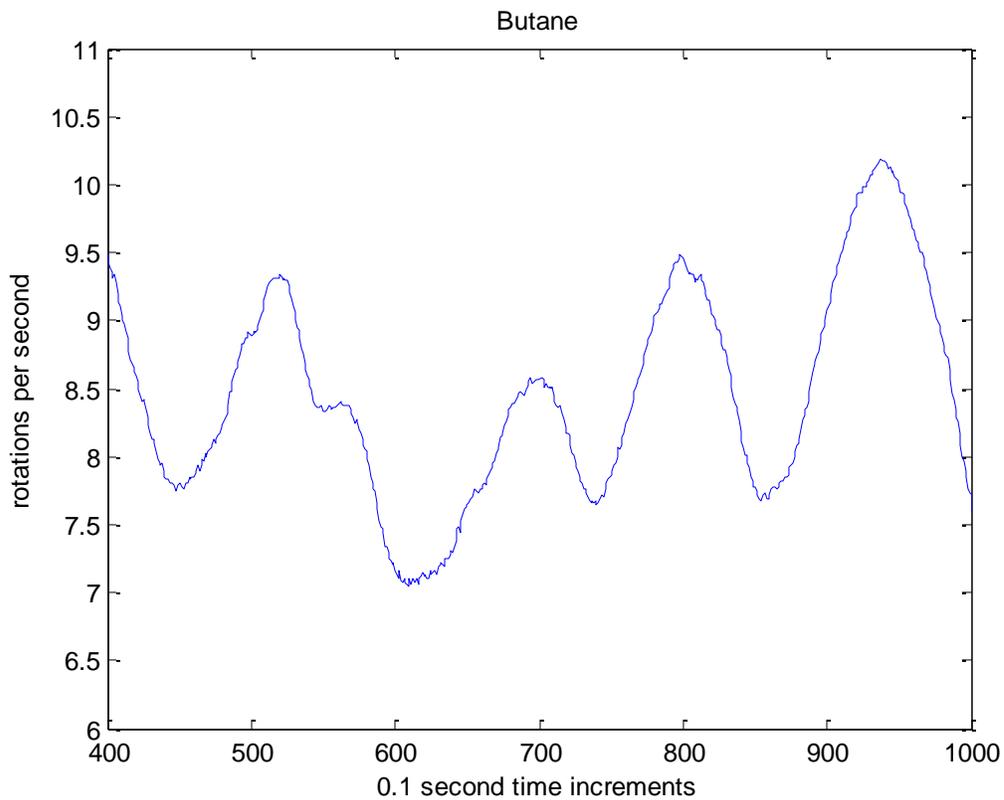


Figure 5.1 Butane

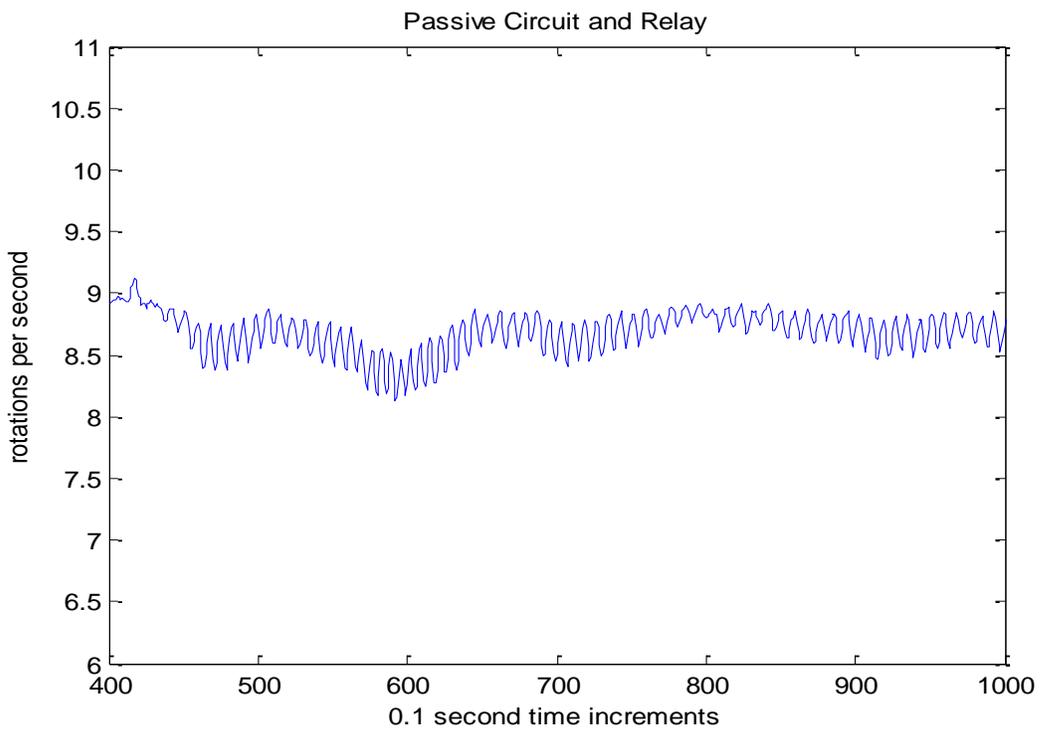


Figure 5.2 Passive Circuit and Relay

Another way to look at the system is in Figure 5.3. The Stirling engine works as an input into the system in part 2. The output of part 2 goes is the actual rps from the Stirling engine, which feeds into part 1. Part 1 subtracts the actual output from the Stirling engine from the desired output and outputs a difference. If the difference of part 1 is too high, a control algorithm toggles a load on. Otherwise, the control algorithm does not toggle the load and the output of part 1 feeds into part 2. Part 2 adds the Stirling engine output and the corrected difference from part 1 and starts the cycle again.

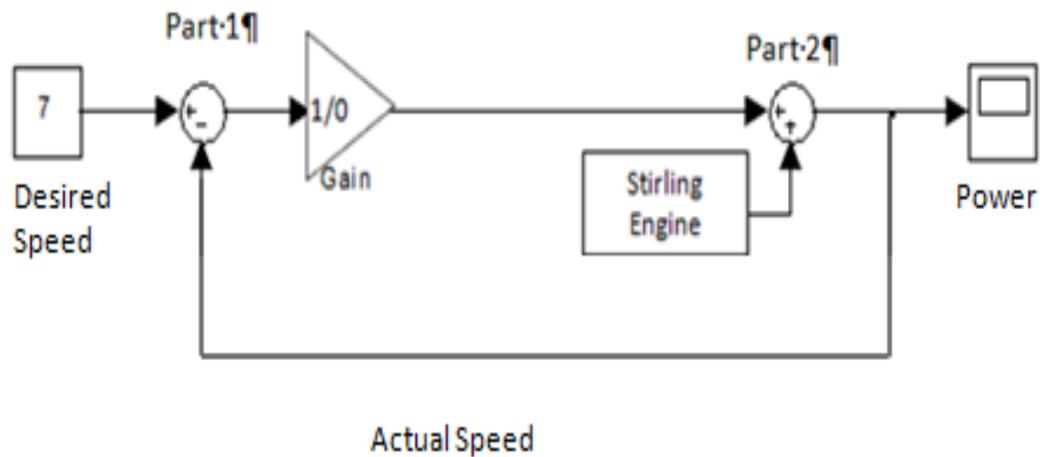


Figure 5.3 Feedback Loop

Chapter 6

Acknowledgements

I would like to thank a few people who made my project possible. First of all, I would like to thank my mother for playing editor for me. She put up with a lot of variations by the time I finally finished. Next, I would like to thank my father for helping run some of the tests so I would not burn down the house balancing a butane torch. Also for helping troubleshoot the MATLAB code and offering up plenty of suggestions in format. Lastly, I would like to thank Dr. Johnson who whose enthusiasm and stories in class about control systems prompted me to try and apply controls to a Stirling engine and for being an invaluable mentor for my project.

Appendix A: Code for Rotation and Voltage Count and Control

```
1 #include "Main.h"
2
3 void main ( void )
4 {
5     int rev = 0;
6     int loop = 0;
7     int test;
8     int rotation = 0;
9     int clock = 0;
10    int rpm = 0;
11    int voltage = 0;
12    int voltage_average = 0;
13    int voltage_counter = 0;
14    int old_rotations = 70;
15    int rotation_clock = 0;
16
17    // connect to port
18    while ( loop < 15000 )
19    {
20        PresetEncoder ( 1 , 0 ) ; // Connects encoder to microcontroller
21        StartEncoder ( 1 ) ; // starts optical encoder
22        PresetTimer ( 1 , 0 ) ; // Preset timer 1 to 0
23        StartTimer ( 1 ) ; // Initiate timer 1
24        clock = 0 ; // Clear clock
25        while ( clock < 100 ) // Goes on for 1/10 of a second
26        {
27            clock = GetTimer ( 1 ) ; // Gets the time and puts it in clock variable
28            rev = GetEncoder ( 1 ) ; // Get info from optical encoder
29            rotation = rev ; // Counts one full rotation
30            voltage = GetAnalogInput ( 2 ) ; // Gets voltage from analog port 2
31        }
32        voltage_average = voltage_average /5 ; // Finds the average of the 5 voltages
33        PrintToScreen ( "%d" , (int)rotation ) ; // How many revolutions the optical encoder is reading
34        PrintToScreen ( " , %d\n" , (int)voltage ) ; // Voltage coming from analog port 2 (motor)
35        voltage_counter = 0 ; // Resets voltage to 0 for next loop through
36        voltage_average =0 ; // resets voltage average to 0 for next loop through
37        loop = loop + 1 ; // iterates a loop
38        StartTimer ( 2 ) ;
39        if ( rotation >= old_rotations ) // compares rotations to set number
40        {
41            rotation_clock = GetTimer ( 2 ) ;
42            SetDigitalOutput ( 12 , 1 ) ;
43        }
44        SetDigitalOutput ( 12 , 0 ) ;
45    }
46 }
```

```
33 PrintToScreen ( "%d" , (int)rotation ) ; // How many revolutions the optical encoder is reading
34 PrintToScreen ( " , %d\n" , (int)voltage ) ; // Voltage coming from analog port 2 (motor)
35 voltage_counter = 0 ; // Resets voltage to 0 for next loop through
36 voltage_average =0 ; // resets voltage average to 0 for next loop through
37 loop = loop + 1 ; // iterates a loop
38 StartTimer ( 2 ) ;
39 if ( rotation >= old_rotations ) // compares rotations to set number
40 {
41     rotation_clock = GetTimer ( 2 ) ;
42     SetDigitalOutput ( 12 , 1 ) ;
43 }
44 SetDigitalOutput ( 12 , 0 ) ;
45 }
46 }
```

Appendix B: Code for generating Power v. RPS

```
% data measurement tool
v=[];
r=[];
cal=[];
%input data
% sampling rate
ts=0.1;
fs=1/ts;
q=butane4700mf;
%see how many rows of data
data_count=size(q,1);

%data massage
for k=1:data_count
    r(k)=q(k,1)./90.0;
    v(k)=q(k,2)./200.0;
    cal(k)=0.05*sin(2*pi*(k-1)*ts);
end

% use 10 ohm for load and 100 ohms for open
p = (v.*v)./10;
%time plot
t_index=1:data_count;
subplot(4,1,1)
plot(t_index-1,r*fs);
% Annotate time plot
axis ([0 1000 6 11]);
title('Passive Circuit Relay');
xlabel('0.1 second time increments');
ylabel('rotations per second');
figure;

subplot(4,1,2)
plot(t_index-1,v);
% Annotate time plot
axis ([0 250 0 .05]);
title('Voltage v. Time Butane Test');
xlabel('0.1 second time increments');
ylabel('voltage');
figure;

[z_f,f]=periodogram(v,[],[],fs);
subplot(4,1,3)
plot(f,z_f);
axis ([0 .4 0 0.014]);
```

```
title('Power Density Spectrum Butane Test');  
xlabel('frequency (hz)');  
ylabel('power (watts/hz)');  
figure;
```

```
subplot(4,1,4)  
[pp,ErrorEst] = polyfit(r*fs,p,1);  
[pop_fit,delta] = polyval(pp,r*fs,ErrorEst);  
plot(r*fs,pop_fit,'-',r*fs,p,'.',r*fs,pop_fit,'g-');  
title('0.1 sample time Butane Test');  
xlabel('RPS');  
ylabel('Power');
```

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