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April 25, 2014

Dr. Timothy Smith, Faculty Advisor
University of Michigan
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Subject: Final Report for appendage that generates electrical power from jet engine exhaust for Aerospace Propulsion Outreach Program Competition

Dear Dr. Smith:

Enclosed is our final report for the design and manufacture of an exhaust driven appendage to a JetCat P-80SE gas turbine that generates electrical power for the 2013-2014 Air Force Research Laboratory Aerospace Propulsion Outreach Program competition.

This report details our design and analysis of a turboprop attachment that uses the exhaust from a JetCat P-80SE to drive standard turboprop components. These components are then used to run an alternator to produce 500 Watts (W) of electrical power with no loss of thrust. With the combination of our knowledge of the subject, modern design methods, and the resources at our disposal we were able to create a very capable design. Once we completed our design using the computer software, SolidWorks, we began our manufacturing phase. We outsourced all of our component manufacturing to Precision Manufacturing Services, Inc. We then constructed our prototype using the facilities provided to us by the University of Michigan. In addition, we plan to test our design using a single-axis calibrated thrust stand provided to us by MJet. Also, we would like to report that our team of four aerospace engineering students have completed this project within the previously estimated cost of $34,364.

We would like to thank you for all of your assistance with our project this semester, including use of Bldg. 421 in order to conduct testing of our design. In addition, our team is also grateful for the useful previous project findings that you were able to share with us. We are confident that our final product will exemplify "The Michigan Difference" at the AFRL competition. Thank you for your consideration.

Sincerely,
Victor Bensoussan   Christopher Labadie

Shubhankar Mohan   Roberto Shu

encl.

Victor Bensoussan | Christopher Labadie | Shubhankar Mohan | Roberto Shu

Final Report:

Turboprop Add-on to Jet Engine for Electrical Power Generation

April 25th, 2014

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Aerospace Propulsion Outreach Program (APOP)
Professor Timothy Smith
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Abbreviations and Acronyms

GenJet	Generator Jet - Refers to JetCat P80 SE engine, Turboprop and alternator appendage
APOP	Aerospace Propulsion Outreach Program sponsored by the US Airforce
JetCat	JetCat P80-SE gas turbine engine
DC	Direct Current
RPM	Rotations per minute
FXB	François-Xavier Bagnoud
WSTPC	Wilson Student Team Project Center
MJet	Michigan Jet Engine Team

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EXECUTIVE SUMMARY

The U.S. Air Force Research Laboratory's (AFRL) Aerospace Propulsion Outreach Program (APOP) is sponsoring an intercollegiate competition that gives undergraduate students the opportunity to modify a JetCat P-80SE gas turbine engine. The purpose of this competition is to give students a better understanding of gas turbine engines throug a hands-on approach. This is achieved by giving students a simple set of requirements and allowing them to customize and fabricate with little regulation. The challenge at this year's competition is to design a device that will be used to extract 500 Watts of DC electrical power at 24 Volts from a jet engine's exhaust while minimizing the amount of stock thrust lost. This device will be designed to attach to a JetCat P80-SE small gas turbine engine. For our device, we chose to design a turboprop attachment that will use the exhaust from the jet engine to drive a power turbine. Then the torque created by the power turbine is used to drive a propeller shaft which is connected to an alternator.

Our turboprop attachment is mainly made of machined and cast stainless steel. Some components such as the gear box were made from aluminum to save weight. All of the stock metal used in the manufacture of our design was purchased from a local machine shop. Off the shelf components such as the turbine, guide vanes, bearings, gears, propeller, and gauges were purchased to complete the overall system.

The attachment we designed secures to the JetCat using a coupler. The exhaust gasses pass through the coupler into the turbine guide vanes. These guide vanes act to linearize the flow into the power turbine. Then using gear reduction the torque created by the power turbine is used to drive a propeller. Attached to the propeller shaft we have a timing belt pulley which will drive an alternator.

Unfortunately were unable to do any physical testing of our design once it was completed. However, by conducting some testing on the JetCat we were able to attain exhaust velocity values. Form there we able to conduct a theoretical analysis of the power turbine using velocity triangles. This gave us a theoretical rotation rate of 76,700 RPM for the power turbine. Then using our gear ratio of 6:1 we calculated that the propeller shaft will rotate at 13,000 RPM. These results will be used to determine whether our system is an effective, feasible, precise and affordable method of meeting the requirements of the competition. By using a pulley ratio of 1:1 with the alternator and the propeller shaft we know that this rotation rate will produce the required amount of electrical power. However, our current propeller will not produce the required thrust at 13,000 RPM. We will need to purchase a tri-propeller with an increased pitch to achieve a thrust of 22lbf

This report will discuss the process of designing, building and analyzing our turboprop attachment.

INTRODUCTION

The U.S. Air Force Research Laboratory's (AFRL) Aerospace Propulsion Outreach Program (APOP) is sponsoring an intercollegiate competition that gives undergraduate students the opportunity to modify a JetCat P-80SE gas turbine engine. This year's task is to design an attachment to a JetCat gas turbine that is capable of extracting 500 Watts of DC electrical power at 24 Volts while maintaining as much of the stock thrust as possible.

Efficiency and a proper allocation of resources are major factors in the development of all kinds of aircraft. Currently most aircraft use small auxiliary power units or APUs. These APUs are small jet engines which transforms the chemical potential energy of the fuel into heat energy through combustion. Then, with the use of a turbine, this heat energy is converted to mechanical shaft power which can then be used to produce electrical power. This electricity can then be used to run many of the important components that are used to fly the aircraft.

The aim of our study is to combine these separate processes into one. By doing so we can remove these APUs making the aircraft lighter and more efficient. In addition, this competition plays a major role in giving students a better understanding of gas turbine engines from a hands-on approach. This is achieved by giving students a simple set of requirements and allowing them to customize and fabricate with little regulation.

We have developed a turboprop attachment to a JetCat-P80 SE gas turbine engine to accomplish this task. The exhaust gasses from the JetCat are used to drive a power turbine which in turn powers a propeller shaft that is connected to an alternator. This report details the design, fabrication and testing procedure and is outlined below along with the recommended next steps.

CRITERIA RATIONALE

In order to determine whether our turboprop design is a viable solution to the problem proposed by APOP, it must meet a set of criterion standards set down by our team and sponsor. Our judgment of these standards will be based upon our testing analysis and overall evaluation of our design. We used the following criteria to justify the merit of our design.

Effectiveness In order for our design to be considered effective, it must meet the main goals outlined in the APOP competition rules. Our turboprop attachment must produce enough mechanical shaft power to produce 500 Watts of DC electrical power at 24 Volts. In addition, the turboprop must maintain the stock thrust of the JetCat P80-SE gas turbine engine which is about 22 lb-f. Lastly, our design must use only the exhaust from the JetCat in order to run and must fit within an area of 36" by 16.5".

Feasibility The feasibility of our design will be based upon its ability to be manufactured and assembled using our own skills and the resources made available to us by the University of Michigan within the allotted time period. Also, our design must be capable of withstanding the maximum exhaust temperature of the JetCat which is 863 K. In addition to high temperatures, it

must also withstand a maximum exhaust pressure of 41 kPa at the exit of the JetCat. We were able to set these benchmarks using the values attained from the testing we did on the JetCat.

Precision The precision of our design is based on the tolerances of the dimensions in our engineering drawings and the ability to hold those tolerances during manufacturing. Due to the complexity of our design and number of moving parts these tolerances must be quite high. We were able to extrapolate that we must hold a tolerance of ±0.005" which is the industry standard. We attained this value from Fundamentals of Modern Manufacturing: Materials, Processes, and Systems.

Affordability For our design to be considered affordable, we must be able to design, build, and test our attachment within a budget of $5,000. This budget is the amount given to us by our sponsor.

DESIGN

Our solution to the task presented by APOP was to convert the JetCat P-80SE jet engine into a turboprop engine and drive an alternator through a timing belt connected to the propeller shaft. To do so we use the JetCat as a gas generator, remove the nozzle and bolt on our designed power section add-on turboprop (Figure 1). This modular approach to building a turboprop is not currently used for full-size models.

We are harnessing the exhaust gases from the JetCat gas turbine and using them to drive a power turbine. By the time the gases pass the turbine there is little pressure left to create thrust. So, a propeller is coupled to the power turbine through a gear reduction train to generate thrust. The gear reduction train is required to convert the high RPM, low torque of the power turbine shaft to low RPM, high torque in the propeller shaft. The speed of the propeller has to be reduced to prevent efficiency losses if the tips of the propeller reach supersonic speeds. Further, high torque is required to pull sufficient air through to generate thrust. To generate the 500 W of electrical power required the propeller shaft will drive a timing belt connected to an alternator.

The add-on device is greatly influenced by the publicly available WREN MW54 Turboprop [1] design by WREN Turbines USA [2]. We have made substantial modifications to the design to meet our needs and manufacturing capabilities. To aid with the design process and manufacturing a computer aided design (CAD) model was created using SolidWorks™. Figure 1 shows a rendering of the CAD model with the major components labeled.
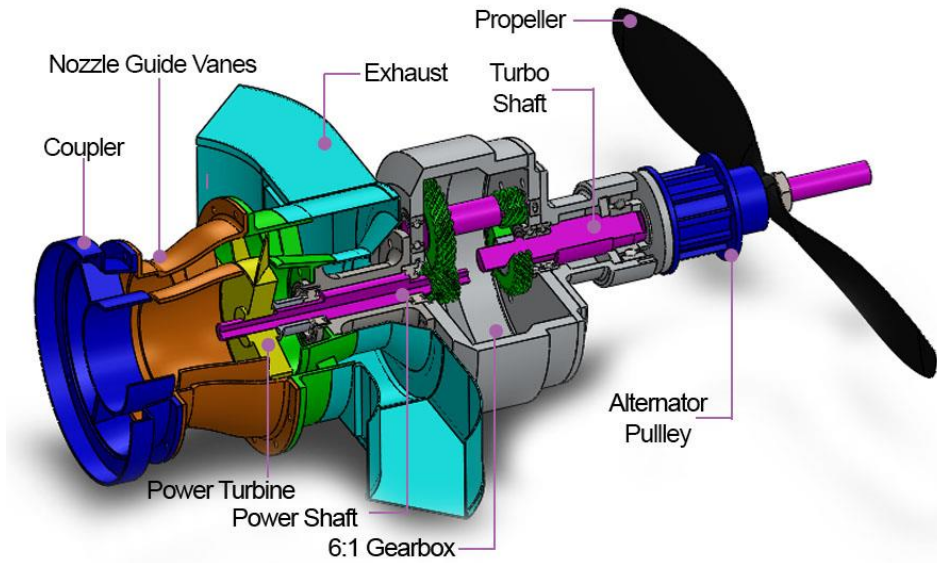
Figure 1: CAD Model of turboprop add-on. Note the alternator is not include in this model.

Gear train

The gear train purpose is to convert the high RPM, low torque of the power turbine shaft to low RPM, high torque on the propeller shaft. To generate 500 W at 24V the alternator needs to run between 15-16,000 RPM. We can use the known gear ratio formula to determine the required reduction ratio assuming that the power turbine shaft will spin at 80,000 RPM.

$$\frac{w_{out}}{w_{in}} = \frac{\prod N_{driving}}{\prod N_{driven}} \tag{1}$$

Where, w_{out} = output shaft speed, w_{in} = input shaft speed, N = number of gear teeth. From equation 1we calculate that a 5.3:1 gear reduction ratio is needed to achieve our desired 15,000 RPM propeller shaft. To achieve this we designed a gear train composed of four helical gears to achieve two reduction stages, (figure 2). Helical gears were chosen because of their capability to handle high power and quietness. The power turbine is connected by a shaft to a small 12 teeth pinion that drives a larger 30 teeth gear. This gives the first reduction stage of 2.5:1. The 30 teeth gear drives is connect by a shaft to a 10 teeth pinion that drives a 24 teeth gear in the propeller shaft. This gives the second reduction stage of 2.4:1. The overall gear reduction if of 6:1. (Calculations of the reduction ratio can be found in Appendix A). Therefore, assuming the power turbine runs at 80,000 RPM with our gear train our propeller shaft will run at 13,333 RPM, just a little lower than the 15,000 RPM required by the alternator.
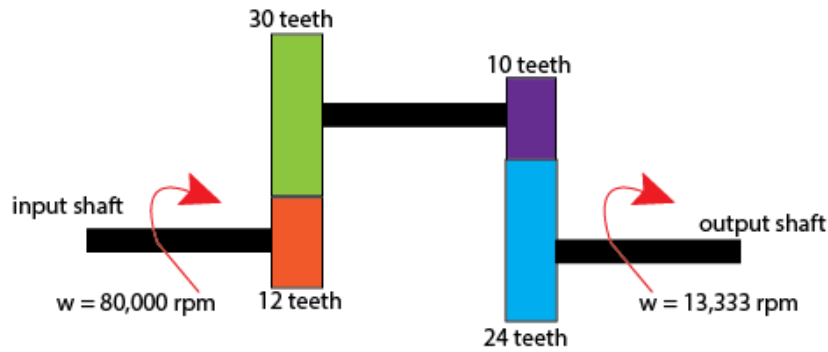
Figure 2: Schematic of gear train and respective input and output shaft speeds. Total gear train reduction is of 6:1

Propeller shaft

The propeller shaft was modified from the original WREN MW54 Turbo Prop design. We extended the propeller shaft by 1.65 inches to provide more flexibility to the design. The extended shaft allows the shaft configuration to be adjustable with minimum effort. The default configuration we set was a timing pulley to connect to the alternator and a 10" 2-blade propeller. This can be changed to include two timing pulleys that will drive 2 or 3 other shafts, opening the design space to use propellers up to 16 inches in diameter. Similarly, it can be set up to have one timing pulley to drive the alternator and several 2-blade propellers stacked in the shaft to generate more thrust.

Propeller

A turboprop generates thrust by turning a propeller. The propeller can vary in size, number of blades, and pitch. These parameters have a direct impact on the thrust produced [3]. Though, choosing the size and number of blades can depend on multiple variables our selection is simplified because we are constrained by APOP rules. Rule number 1 specifies that the add-on device must fit within a constrained area, see figure 3.

Figure 3: Diagram of constrained dimensions area set by APOP
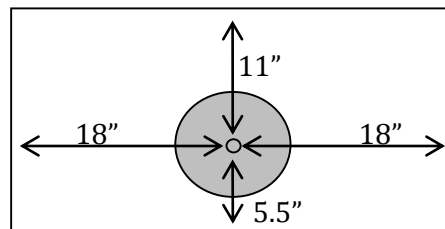
The maximum propeller diameter we can use is 11 inches. Hence, we selected a 10 inch diameter 2-blade fiberglass propeller for our solution (Figure 4). This can be easily changed to a propeller with more blades or higher pitch to get more thrust out of it. We selected the 10 inch diameter 2-blade propeller because it was the only one in stock and that would ship in time.

Figure 4: 10" diameter fiberglass propeller

Load

Our device is required to generate 500W at 24 V. Without a load cell the circuit current will be 20.83 A. This is too high of a current since most circuit can't handle it. Therefore, a load is needed on the electrical power generation circuit to drive the current down to a safe value. The Aerospace Department Technicians at the University of Michigan provided us with an 8Ω load (figure 5). Using Ohm's Law [5] we calculated that with the 8Ω load the circuit current would drop to 3A, a low enough current to be safe for the circuit components.

Figure 5: 8Ω load cell to drive electrical circuit current to 3A.

Coupler

The original plans of the turbprop add-on are designed to be compatible with the WREN MW54 gas generator. Since the original design is attached to the gas generator through the interstage nozzle guide vanes and we could not modify the size of the guide vanes, we designed a coupler. The coupler increases the diameter of the inlet of the nozzle guide vanes to be compatible with the outlet of the JetCat gas generator (figure 6).

Figure 6: Picture of interstage nozzle guide vanes on the left attached to the coupler in the right

FABRICATION/MANUFACTURING

One of our design criteria was precision, which implied a tolerance of ±0.005 inches. Our manufacturing skills and capabilities were not advanced enough in order to meet this standard, and since our budget allowed it, we chose to outsource the manufacturing to Precision Manufacturing Services, Inc.

After designing all the parts that we wanted manufactured, we made engineering drawings with the appropriate dimensions and gave them to the machinists. Due to complexity of the parts manufacturing speed was significantly reduced. We consulted with the machinists at Precision about our design and we made modifications upon their suggestion to easy the manufacturing process. A full list of the parts that we chose to outsource to be manufactured can be found in Appendix F.

Figure 7: Turboprop add-on parts layout before assembly in the correct order

In addition to the parts that we outsourced, we chose to fabricate some of the major parts the exhaust of the turboprop ourselves since we deemed that we were capable to do that. Precision helped us to finalize and weld the whole exhaust.

TESTING

Pressure Testing

In order to examine the characteristics of the exhaust gases, our team chose to measure the static temperature, the static pressure and dynamic pressure behind the nozzle at various points along the diameter. After analyzing the data, we were able to calculate the exhaust gas velocity, mass flow rate and total pressure.

Our testing components included a jet engine stand, where the JetCat was attached on. The stand was fitted with a fuel feeding system, which was used to provide the engine with a continuous flow of kerosene and the controller used to control the engine's RPM. Our testing apparatus included a gauge measuring differential pressure in PSI, a small "L" shaped metallic tube of 2mm inner diameter used as both static and stagnation probe, rubber tubing and a temperature thermocouple used to measure the temperature of the exhaust gasses. Finally, we used a horizontal translation stage with a ruler attached on it that helped us hold the probe mentioned above in the flow of the exhaust gasses and also move it accurately. The setup can be seen in figure 6.
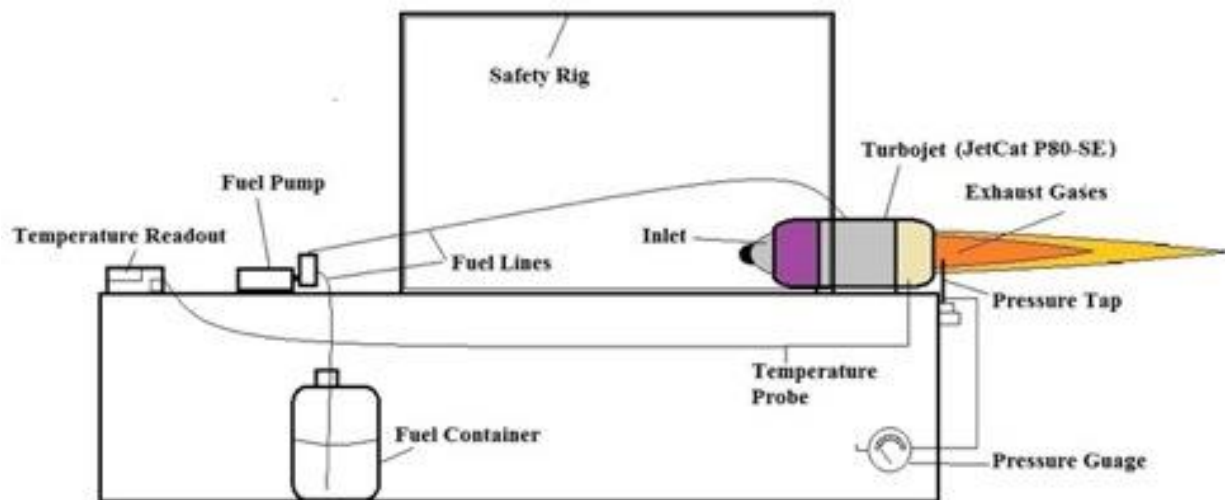

Figure 8: Schematic of setup for pressure test

In order to collect the required data, we attached the metallic tube to the translational stage and using tubing we connected it to the pressure gauge. We clamped the translational stage behind the JetCat engine and made sure that the "L" tube was 5cm away from the end of the nozzle. After connecting the engine to the fuel system, and running it at 125,000 RPM, we used the translational stage to move the "L" tube every 5 mm across the diameter of the nozzle and collect pressure readings

There were two main configurations of the "L" shaped tube corresponding to the static and stagnation pressure tests. For the static pressure test, the tube was used as a static port, with the opening parallel to the flow of the exhaust gasses, as seen in figure 7a. For the stagnation pressure the tube was used as a pitot tube, with the opening perpendicular to the exhaust flow as seen in figure 7b.
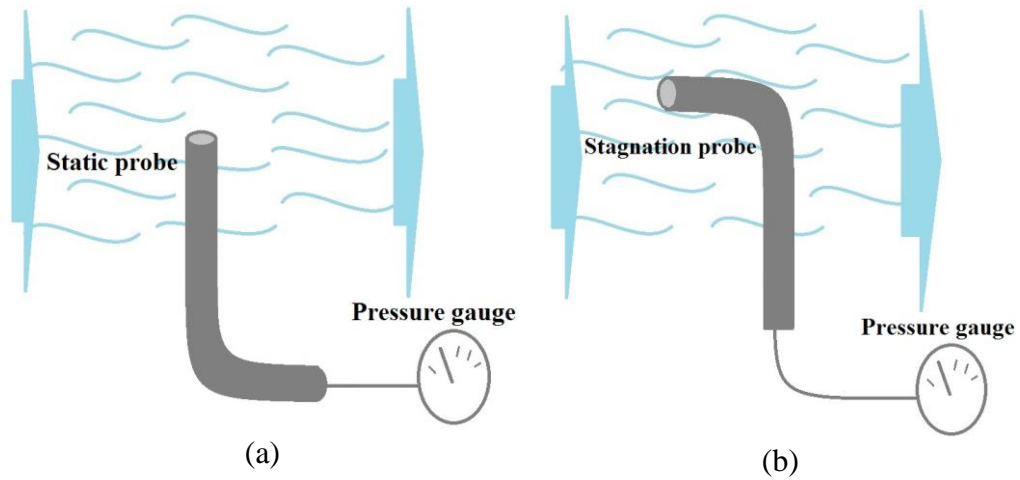
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(a)   (b)

Figure 9: Schematic of probe inlet relative to airflow to **(a)** measure static pressure **(b)** measure stagnation pressure

Finally we measured the temperature of the exhaust gasses by placing a thermocouple at the end of the nozzle in the flow of the hot gases.

Propeller Testing

For testing the performance parameter of the 10" diameter fiberglass propeller, we analyzed its torque and thrust performance using a propeller test stand. We ran the propeller at various RPM values and recorded the thrust at torque generated by the propeller using the data collection system of the stand. A schematic of the test setup is shown in figure 10 below.
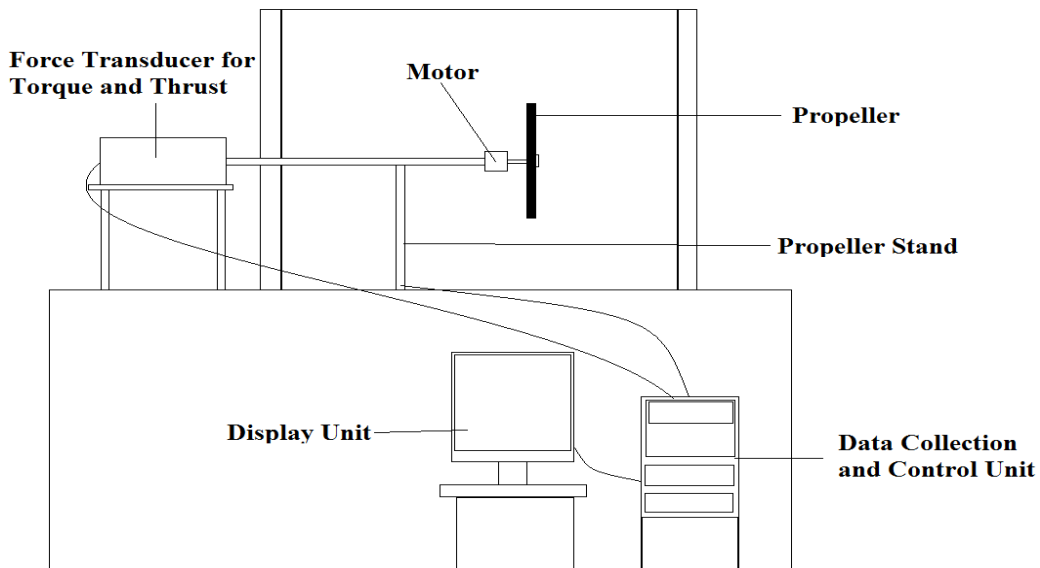
Figure 10: Schematic of setup for propeller test

TEST DATA

The graphs of our raw pressure data is displayed below. The data callouts represent the values we used for our analysis and calculation in the sections to follow.

Pressure Test Data

From the raw data in we used the Trapezoid rule to integrate the pressure values under the curves in Figure B1 and Figure B2 to calculate the a static and stagnation pressure value at the JetCat exit. The trapezoid rule equations are given in the in Appendix C.

Figure 11: JetCat P80-SE Nozzle Exit Static Pressure at 125000RPM
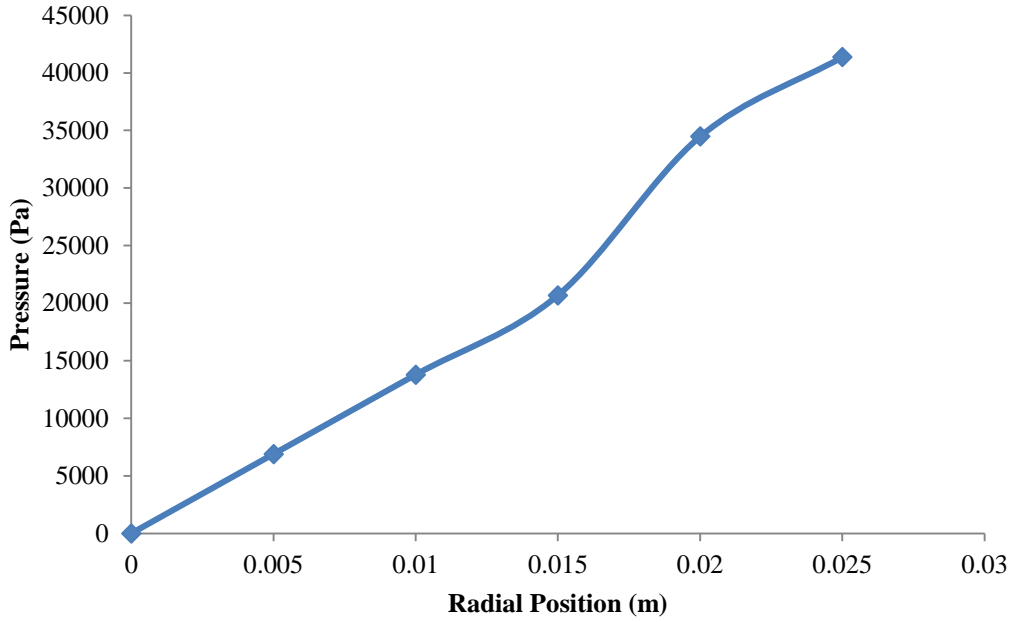
Figure 12: JetCat P80-SE Nozzle Exit Stagnation Pressure at 125000RPM
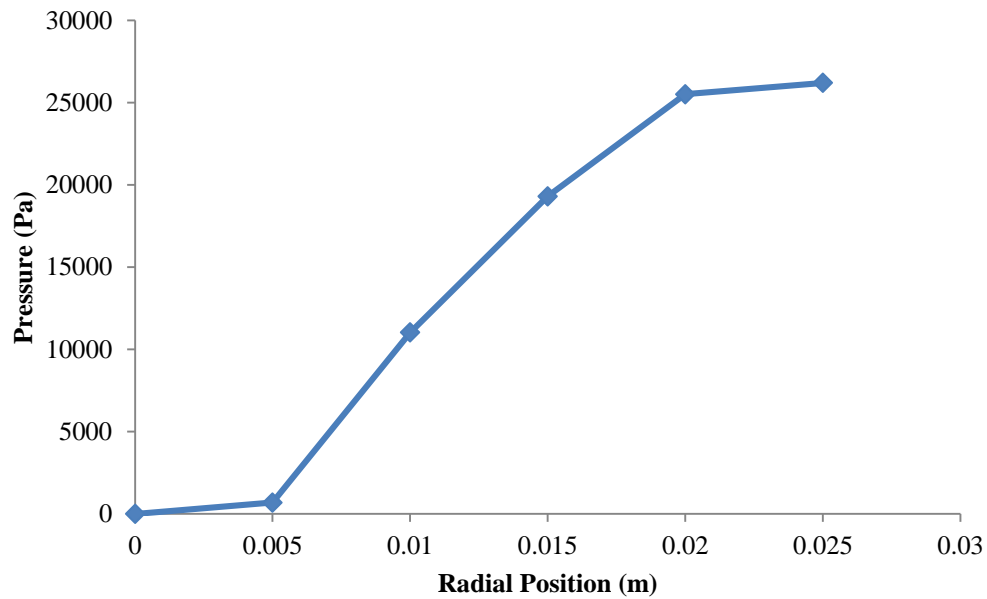
Propeller Test Data

Figure 10 depicts the thrust coefficient calculated at different propeller RPM. From the graph it can be conclude that the coefficient is plateauing at a value of 0.12 after 30000 RPM. This is probably the thrust limit of the propeller. A phenomena that we expected to see is the decrease in thrust after a given RPM when the propeller tips reach supersonic speeds, but our RPM test range was not big enough to see this. Further, we can confidently say that out test results are accurate since the three test trials we conduced generated almost the exact same values.

Figure 13: 10x8 G/F Series Propeller Thrust Co-efficient

Similar, to the thrust coefficient of the 10 inch propeller the torque coefficients seems to be plateauing. The range of our RPM 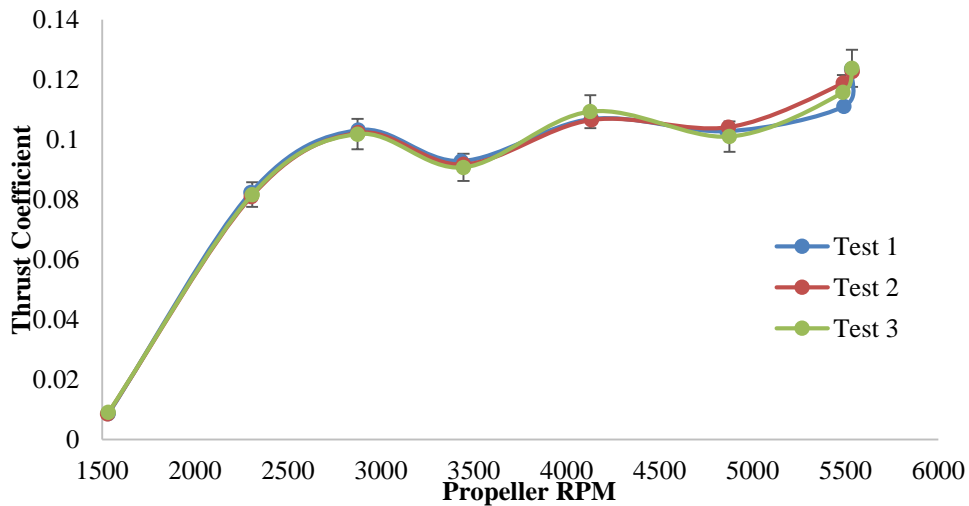test is not large enough to accurately determine the exact value where the torque coefficient settles. However, we can estimate that it will be around 0.002.
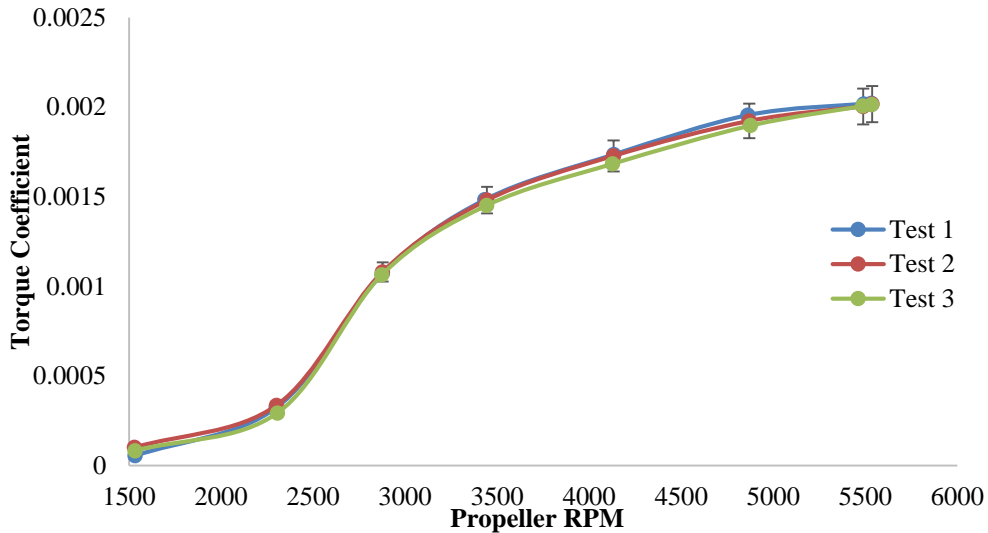

Figure 14: 10x8 G/F Series Propeller Torque Co-efficient

DISCUSSION

In order to reduce the data that we acquired from the tests to meaningful values we analyzed them based on equations obtained from known theory about jet engines.

Pressure Analysis

To calculate the exit velocity of the JetCat engine we need to calculate the dynamic pressure at the nozzle exit. Exit velocity, U_e, is given by the equation below. [7]

$$U_e = \sqrt{2 * q/\rho}$$

Where q is the dynamic pressure and ρ is the density of air at the nozzle exit conditions.

Dynamic pressure is calculated by subtracting the static pressure from the stagnation pressure at the given location:

$$q = p_0 - p$$

Where p_0 is the stagnation pressure and p is the static pressure.

The pressure values we obtain from the trapezoid rule integration are given in Table 1 below along with the air density calculated using the ideal gas law. Density was calculated using the equation given below:

$$\rho = p/RT$$

Where p is the pressure, R is the gas constant for air and T is the temperature.

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Parameter	Calculated Value
Stagnation Pressure, p_0	77954.05 Pa
Static Pressure, p	56238.28 Pa
Dynamic Pressure, q	21715.77 Pa
Air Density, ρ	0.31508 kg/m^3

Table 1: Trapezoid integration results for static and stagnation pressures

The above value for dynamic pressure was then used to calculate the exit velocity, U_e, mass flow rate, $\dot{m}$, and thrust, T. The equations for calculating the mass flow and thrust are given below.

$$\dot{m} = \rho * U_e * A, \text{ where A is the nozzle exit area.}$$
$$T = \dot{m} * U_e$$

We calculate the mass flow rate and thrust value to be 0.225 kg/s and 83.68 N respectively. These values are very close to the values given by the manufacture of 0.25kg/s and 97N.

Power turbine flow analysis

In order to characterize the rotational speed of the power turbine we need to calculate the velocity of the exhaust gasses at the inlet of the nozzle guiding vanes (stator). We calculated, in the pressure analysis section, the exhaust velocity at the nozzle to be 371.274 m/s and according to temperature graph in Appendix B, the static temperature of the exhaust gasses will be 863 K. According to the speed of sound equation.

$$u_a = \sqrt{\gamma R T}$$

Where

$$R = 286.7 \, J \, kg \, K^{-1} \text{ and } \gamma = 1.33$$

since exhaust gasses will be hot, we get

$$u_a = 573.64 \frac{m}{s}$$

and at the nozzle,

$$M_N = \frac{u_e}{u_a} = \frac{369.66}{573.64} = 0.647$$

Since we need to find the properties of the flow without the nozzle, we need to analyze the geometry of the nozzle cone.
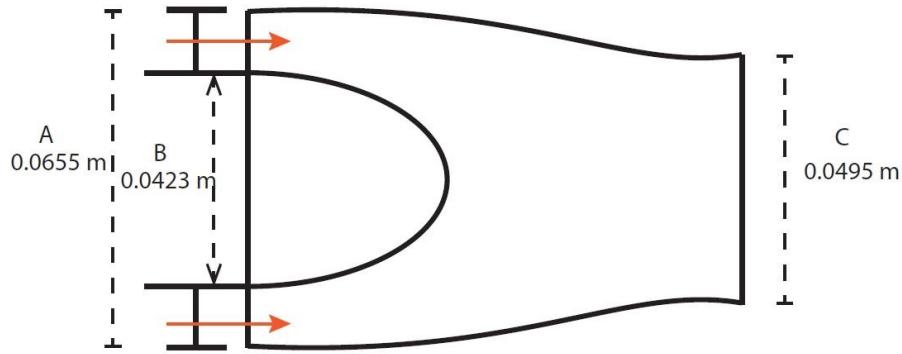
Figure 15: Exit nozzle cone geometry

Location	Area (m²)
A	0.003478
B	0.001405
C	0.001924
A-B	0.002073
(A-B)/C	1.07744 dimensionless

Table 2: Area at the different marked locations along the exit nozzle cone

Taking area ratios and using the Mach number calculated above, we are going to find the velocity of the exhaust gasses without the nozzle using isentropic relations

$$\frac{A}{A^*} = (\frac{\gamma + 1}{2})^{-\frac{\gamma+1}{2(\gamma-1)}} \frac{(1 + \frac{\gamma - 1}{2}M^2)^{\frac{\gamma+1}{2(\gamma-1)}}}{M}$$

with $M = 0.647$ and $\gamma = 1.33$, we get

$$\frac{A}{A^*} = 1.14116$$

thus applying this to area C

$$C^* = \frac{C}{1.14116} = 0.001686 m^2$$

now, using the area (A-B), where the exhaust gasses are coming out of the engine, we get

$$\frac{A - B}{C^*} = 1.2295$$

thus solving the above equation for the Mach number, we get

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$$M = 0.57$$

moreover, using the static to stagnation temperature Mach relation

$$\frac{T}{T_0} = (1 + \frac{\gamma - 1}{2}M^2)^{-1}$$

at the outlet of nozzle plane (for M=0.647 and T=863K), we get T_0=922.6K

Assuming isentropic flow throughout the appendage until the flow meets the stator blades, we can find out the velocity of the flow in the power turbine. The geometry of the nozzle guiding vanes is the following
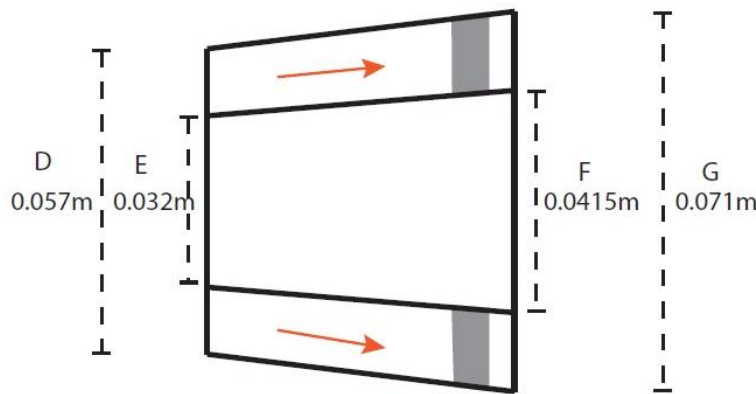
Figure 16: Interstage nozzle guide vanes geometry

Location	Area (m²)
D	0.00255
E	0.000804
D-E	0.001746
F	0.00135
G	0.00396
G-F	0.00261
(D-E)/C*	1.0356 dimensionless
(G-F)/C*	1.548 dimensionless

Table 3: Area at the different marked location in the interstage nozzle guide vanes

Since the flow will become sonic at an area of 0.001686 m², we need to make sure that it will stay in the subsonic side by exposing it to areas less than the above value. Looking at the geometry of the guide vanes we can clearly see that the flow will not become sonic at any point since both areas (D-E) and (G-F) are less than C*.

Once again using the area Mach relation we get M=0.8 for area at the inlet of the guiding vanes and M=0.416 for the outlet. Using the temperature Mach relation again, we get a static temperature at the outlet of 897K thus u_a=584.8 m/s and ultimately the axial velocity of the gasses going in the turbine wheel will be 243.3 m/s

Velocity Triangles

In order to calculate the RPM of the propeller at the end of the turboprop, we need to figure out how fast the power turbine is going to spin first. In order to do this, we need to perform a velocity triangle analysis on the turbine wheel. The configuration of the stators and rotors will be the following
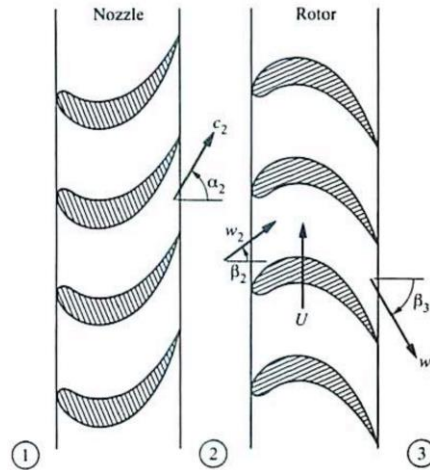
Figure 17: Turbine Rotor Stator Diagram

 with the nozzle vanes stationary and the rotor blades spinning.

We measured the angle that the outlet of the nozzle vanes make with the horizontal to be 50° upward, the angle the rotor inlet to be 20° and the rotor outlet -45°.

Then calculated that the velocity of the flow at 1 will be 243.3 m/s axial. From a stationary point of view the nozzle will direct the flow to c_2 and the rotor will direct it to c_3 coming out of it at -9.8°. From a rotating point of view, the rotor will receive the flow at w_2 and shift it to w_3. This is clearer when we look at the velocity triangles below
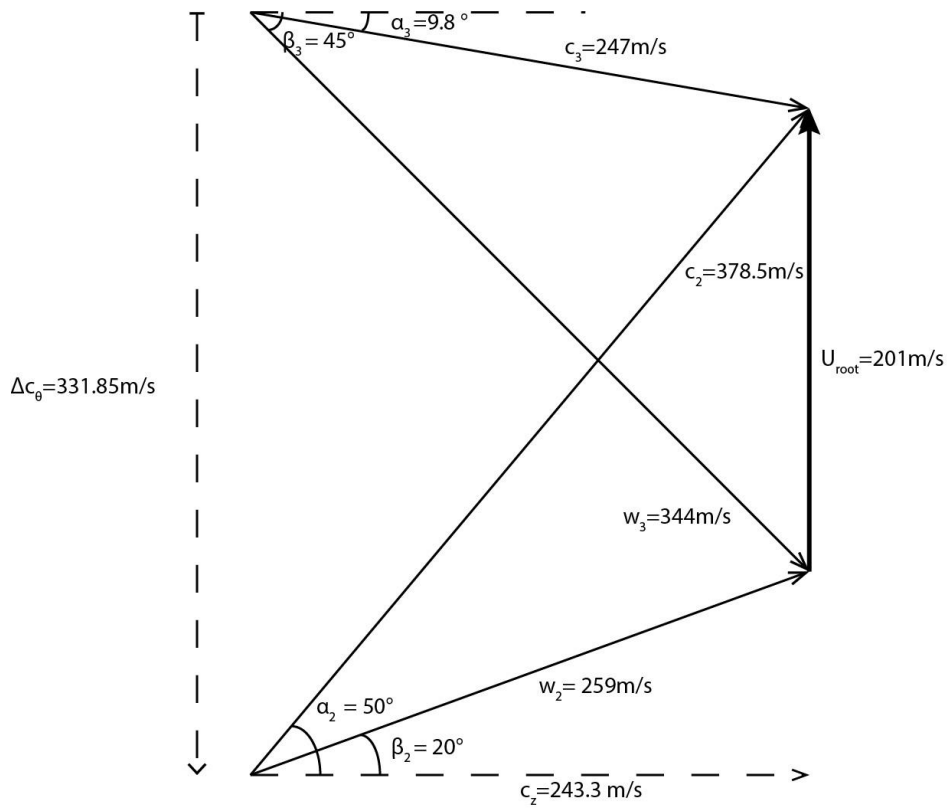
Figure 18: Turbine measured blade angles and derived velocity triangles

This leaves the flow coming out of the rotor almost horizontally at a -9.8° angle at a speed of 247m/s, with change in azimuthal velocity of 331.85 m/s while the turbine rotor will be spinning at

$$243.3(\tan 50\,° - \tan 20\,°) = 201 \; m/s$$

at a radius of 25mm from the center, at the root of the blades. This corresponds to a turbine wheel RPM of

$$RPM = \frac{60 * U}{2\pi r} = 76{,}776$$

a degree of reaction of

$$\mathbb{R} = \frac{1}{2} - \frac{c_z}{U}\left(\frac{\tan \alpha_2 - \tan \beta_3}{2}\right) = 38.4\%$$

using $\dot{m} = 0.225 \; kg/s$ which was calculated in the pressure analysis section we get a shaft power of

$$P_s = \dot{m}U\Delta_{c_\theta} = 15 \ kW$$

and finally a turbine work ratio

$$\frac{w_t}{U^2} = \frac{\Delta_{c_\theta}}{U} = 1.651$$

Propeller Analysis

We ran a thrust and torque analysis for the 10x8 propeller using a propeller test stand. We calculated the thrust coefficient (C_T) and torque coefficient (C_Q) using the equations below. **[10]**

$$c_T = \frac{T}{\rho * n^2 * D^4} \tag{2}$$

$$c_Q = \frac{Q}{\rho * n^2 * D^5} \tag{3}$$

Where T is the thrust generated and Q is the torque generated by the propeller, ρ is the air density n is the propeller speed in revolutions per second, and D is the diameter in meters of the propeller.

Since we know that the thrust coefficient plateaus after 30000 RPM at a value of 0.12 we can use equation (2) to estimate the thrust generated at the expected propeller speed. We expect the propeller to run at 13333 RPM from our power turbine flow analysis. Therefore,

$$T = C_T * \rho * n^2 * D^4$$
$$= 0.12 * 1.292\frac{kg}{m^3} * 222^2\frac{rev}{s} * 0.254^4 m$$
$$= 31.8 \ N = 7.15 \ lbf$$

Clearly, from our data thus far our design does not meet the effective criteria to maintain the original 22 lbf of thrust generated by the JetCat. We only generate a third of the desired thrust. However, our sponsors request was to maintain as much of the stock thrust a possible. Hence, it is ok if at this point we don't generate 22 lbf of thrust. Our design allows for easy adjustment of the thrust generation components, where we can add propellers or use propellers with more blades. Similarly, we can estimate the torque expected by the propeller to be 0.53 N that is equivalent to 0.12 lbf.

RESULTS

The results obtained from the testing and analysis done in the previous sections is listed in the tables below.

Parameter	Calculated Value
Power Turbine RPM	76,776
Propeller RPM	13,333
Thrust, T	7.15lbf
Torque, Q	0.12 lbf

Table 4: Results obtained from propeller test analysis

Parameter	Manufacture Value	Test Value
Exit velocity U_e	388.056 m/s	371.27 m/s
Mass flow rate $\dot{m}$	0.25 kg/s	0.225 kg/s
Thrust, T	97 N	83.68 N

Table 5: Results obtained from exhaust velocity analysis at nozzle exit of JetaCat P80-SE

Theoretically we expect to generate the required electrical power out of the alternator with our turboprop add-on. However, we will only be generating a third of the total thrust required so modification will need to be made.

PROJECT COST

The total estimated cost to design, build and test the proposed solution was $34364.00 with 10% contingency fund equivalent to $2194.00 The total estimated cost for the materials and components to build the prototype was $860.00. However, after more detail analysis on the design the cost of the prototype increased by $456.80 to $1316.80. Moreover, initially we planned to manufacture everything in house at no extra cost. However, the complexity of the design asked for professional machining. Outsourcing the manufacturing increased the cost by$3800.00. Since we outsourced our manufacturing we cut down the machinist support hours to only 5 bringing the cost down by $875.00. Overall the project cost increased by $3310.23. This is $1116.23 more than what we allocated for contingency funds. Our sponsor approved the increase in cost beforehand since it directly correlate to having a better finish product. Appendix B has a full-tabulated detail of the project cost.

SCHEDULE

The updated schedule and timeline for the project is portrayed in the Gantt Chart in Table D1 in Appendix D. We deviated from the original schedule because during concept generation and design process our sponsor decided to take a different approach to the task. This set us back two weeks in our schedule. However, we have pushed hard to have a final device that runs with compress air but has yet to be tested attached to the JetCat. Further, Precision Manufacturing made two mistakes while manufacturing our parts which delayed us two more days. From the original schedule we haven't began testing of the final device. We plan to this in the upcoming week.

CONCLUSION

Our current design did not meet all of your criteria and is thus subject to major improvements. Specifically we need to augment the power turbine RPM so that our propeller spins fast enough to produce 500W of power. Moreover we need to explore more propeller configurations so as to gain more thrust and match the stock thrust of the JetCat. Finally even though we did not meet the feasibility criterion since we did not have the necessary skills to manufacture many parts

ourselves, we managed to meet both affordability and precision by outsourcing the fabrication process.

OMISSIONS

Regarding the theoretical analysis part of our report, we chose to omit the twisting of the blades while performing the power turbine wheel analysis. Instead we measured the angles at one point and extrapolated the velocity for the whole wheel from that point.

Moreover for the propeller analysis we tested only one type of propeller on a single axis, while omitting other possible configurations of two propellers stacked on top of each other or a triple propeller. Finally due to the prolonged manufacturing time we have not yet tested the final turboprop assembly and thus we do not have actual data of thrust and power produced.

ALTERNATIVES

Instead of the turboprop power take-off approach you could place a Brayton-cycle at the exhaust of the JetCat from which we can extract shaft work and convert it to electrical power. The principle is the same to increase mass flow to recuperate the thrust lost. The basic idea is to redirect the exhaust air from the turbine into a chamber where it will be mixed with ambient air drawn in by an additional compressor. Then the mixed gas will be pushed through a second turbine that will drive a shaft connected to an alternator with a gearbox in the middle. Figure xx below is a CAD rendering of this alternative solution.
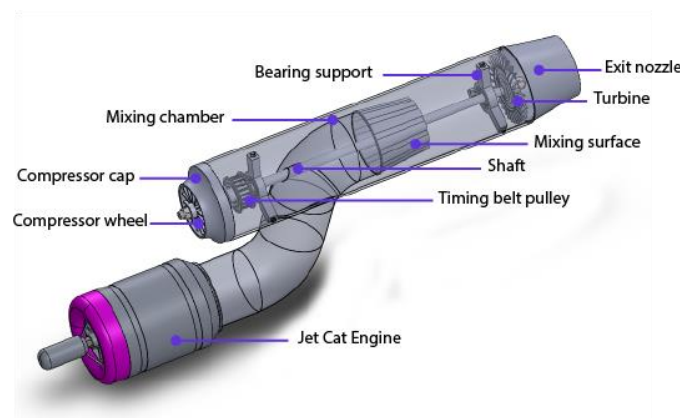
Figure 19: CAD model rendering of Brayton cycle power take-off alternative

FUTURE WORK

There is still substantial work to be done on the add-on device. Despite that we have a fully assembled turboprop add-on, we have only conducted preliminary test that demonstrate a system spinning without failure when driven by compressed air. Therefore, a thorough performance evaluation of the device has to be done to be able to claim that our device works. One of the

evaluation components will be to drive the power turbine of the add-on device with compressed air and measure how much thrust and electrical power is generated. Once, it has been proven that the system is capable of running with compressed air a similar test will be done but now driving the power turbine with the JetCat.

Further, a more in depth analysis of the thrust generation components will be done. This is to consider and analyze the use of timing belts to transmit torque to two or three other shafts to open up design space to allow for the use of propellers up to 16 inches in diameter. Additionally, look into using several two-blade propellers stacked along the propeller shaft, multi-blade propellers, or higher-pitch propellers.

APPENDICES

Appendix A – Gear Train Calculations

Calculating 1st reduction stage ratio, 12 teeth and 30 teeth gear

$$1\text{st ratio} = \frac{12}{30} = 0.4$$

Equivalent to a 2.5:1 gear ratio

Calculating 2nd reduction stage ratio, 10 teeth and 24 teeth gear

$$2\text{nd ratio} = \frac{10}{24} = 0.167$$

Equivalent to a 6:1 gear ratio

Calculating overall reduction ratio,

$$\text{ratio} = \frac{12}{30}\frac{10}{24} = 0.4$$

Equivalent to a 2.5:1 gear ratio

Calculating RPM reduction through gear train

$$
\begin{aligned}
W_{out} &= \frac{12}{30}\frac{10}{24}W_{in} \\
&= \frac{12}{30}\frac{10}{24}76776 \\
&= 13333 \; RPM
\end{aligned}
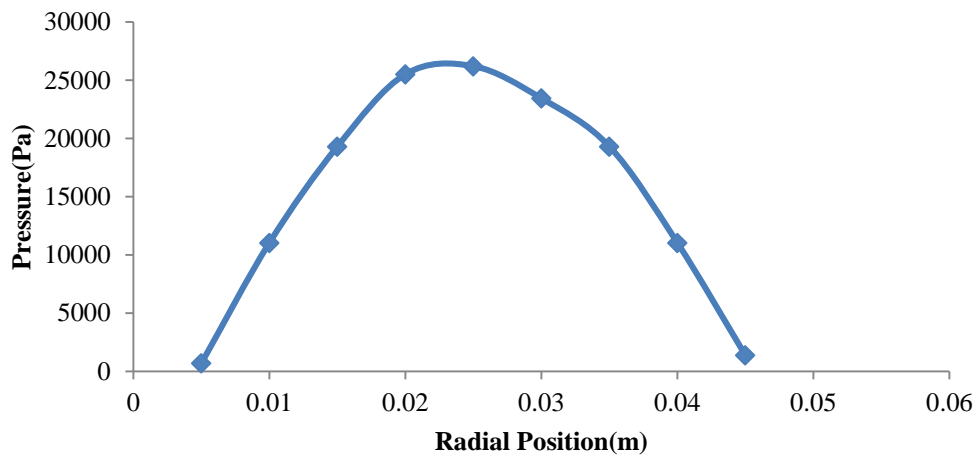$$

Appendix B – Test Raw Data

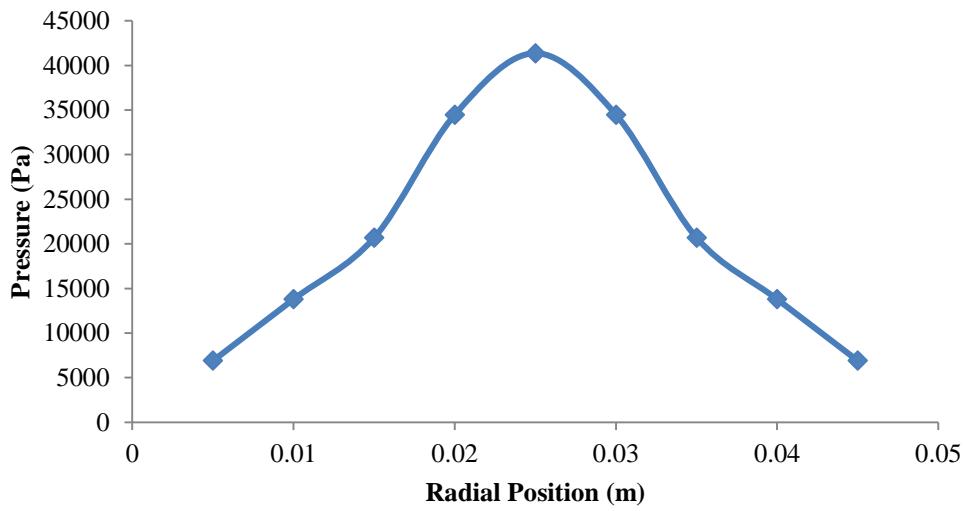**Figure B1:** JetCat P80-SE Nozzle Exit Static Pressure at 125000RPM

Figure B2: JetCat P80-SE Nozzle Exit Stagnation Pressure at 125000RPM

Position(m)	x (step)	p_0 (Psi)	p_0 (Pa)
0	1	0	0
0.005	2	1	6894.757
0.01	3	2	13789.51
0.015	4	3	20684.27
0.02	5	5	34473.79
0.025	6	6	41368.54
0.03	7	5	34473.79
0.035	8	3	20684.27
0.04	9	2	13789.51
0.045	10	1	6894.757
0.05	11	0	0

Table B1: Stagnation Pressure data for JetCat nozzle

Position(m)	x (step)	p (Psi)	p (Pa)
0	1	0	0
0.005	2	0.1	689.4757
0.01	3	1.6	11031.61
0.015	4	2.8	19305.32
0.02	5	3.7	25510.60
0.025	6	3.8	26200.07
0.03	7	3.4	23442.18
0.035	8	2.8	19305.32
0.04	9	1.6	11031.61
0.045	10	0.2	1378.95
0.05	11	0	0

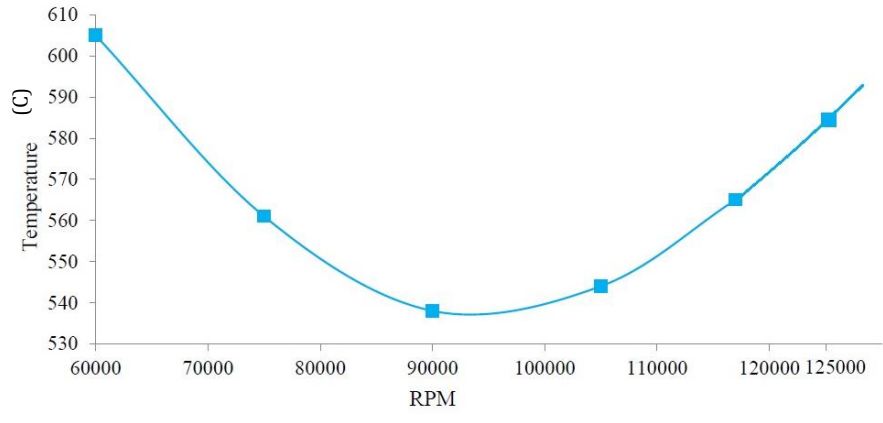**Table B2**: Static Pressure data for JetCat Nozzle

**Figure B3**: Exit temperature of JetCat Engine Turbine

Appendix C – Trapezoid Rule
E1: Trapezoid Rule

For this rule we will do the same set up as for the Midpoint Rule. We will break up the interval $[a,b]$ into *n* subintervals of width,

$$\Delta x = \frac{b-a}{n}$$

Then on each subinterval we will approximate the function with a straight line that is equal to the function values at either endpoint of the interval. Here is a sketch of this case for $n = 6$.
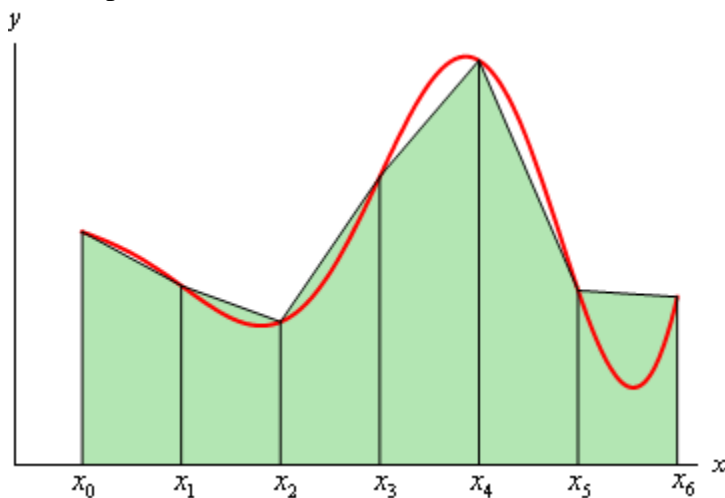
Each of these objects is a trapezoid (hence the rule's name…)

The area of the trapezoid in the interval $[x_{i-1}, x_i]$ is given by,

$$A_i = \frac{\Delta x}{2}\left(f\left(x_{i-1}\right) + f\left(x_i\right)\right)$$

So, if we use *n* subintervals the integral is approximately,

$$\int_a^b f(x)\,dx \approx \frac{\Delta x}{2}\left(f\left(x_0\right) + f\left(x_1\right)\right) + \frac{\Delta x}{2}\left(f\left(x_1\right) + f\left(x_2\right)\right) + \cdots + \frac{\Delta x}{2}\left(f\left(x_{n-1}\right) + f\right.$$

Upon simplification we arrive at the general Trapezoid Rule.

$$\int_a^b f(x)\,dx \approx \frac{\Delta x}{2}\left[f\left(x_0\right) + 2f\left(x_1\right) + 2f\left(x_2\right) + \cdots + 2f\left(x_{n-1}\right) + f\left(x_n\right)\right]$$

Appendix D - Final Budget/Project Costs

| Category	Item	Unit Cost --	Quantity --	Total Cost
Facilities	405 Workshop	$0.00		$0.00
	Wilson Student Team Project Center	$0.00		$0.00
	MJet's Thrust Stand	$0.00		$0.00
			Subtotal:	$0.00
Labor	Engineer	$30.00 /hr	500 hrs	$15,000.00
	Faculty Consulting	$150.00 /hr	10 hrs	$1,500.00
	Machinist Support	$35.00 /hr	5 hrs	$175.00
	Technician Support	$35.00 /hr	30 hrs	$1,050.00
			Subtotal:	$17,725.00
Fabrication	Student Machinist	$0.00 /hr	40	$0.00
	Precision Manufacturing Services	$200.00 /part	19	$3,800.00
			Subtotal:	$3,800.00
Equipment	JetCat P-80SE turbine engine	$2,195.00	1	$2,195.00
	Connections and Wiring	$15.00	1	$15.00
	Jet A1, 1-K kerosene	$3.00 /gallon	5	$15.00
	Alternator	$150.00	1	$150.00
			Subtotal:	$2,375.00
Prototype	72 mm Diameter Power Turbine	$182.50	1	$182.50
	Interstage Guide Vanes	$393.00	1	$393.00
	Spider Turbine Housing	$150.34	1	$150.34
	D608 Ceramic Bearing 22X8X7 mm	$96.30	2	$192.60
	D6800 Bearing 19 X 10 X 5 mm	$75.17	1	$75.17
	Steel Ball Bearing 19 x 10 x 5 mm	$8.04	4	$32.16
	Steel Ball Bearing 5/8 x 1/4 x 0.196"	$6.04	2	$12.08
	Steel Ball Bearing 3/8 x 1/8 x 5/32"	$6.11	3	$18.33
	Steel Ball Bearing 28 x 12 x 8 mm	$7.02	3	$21.06
	Steel Helical Gear 30 teeth LH	$34.35	1	$34.35
	Steel Helical Gear 24 teeth RH	$31.58	1	$31.58
	Steel Helical Gear 12 teeth RH	$40.37	1	$40.37
	Steel Helical Gear 10 teeth LH	$37.69	1	$37.69
	Timing Belt Pulley 16 teeth	$13.04	1	$13.04
	Timing Belt Pulley 10 teeth	$10.98	1	$10.98
	Timing Belt, Neoprene 3/4" wide	$25.32	2	$50.64
	10x8" Fiberglass Propeller	$2.49	4	$9.96
	Bolts + Nuts	$10.95	1	$10.95
			Subtotal:	$1,316.80
Presentations	Poster	$45.00	1	$45.00
			Subtotal:	$45.00
Other	Shipping Costs	$75.00		$75.00
	Tax	$50.00		$50.00
			Subtotal:	$125.00
			Total:	$25,386.80
Overhead			55% of total labor cost:	$9,748.75
Contingency			10% of total:	$2,538.68
Grand Total:				**$37,674.23**

Table D1: Final cost analysis

Appendix E - Schedule
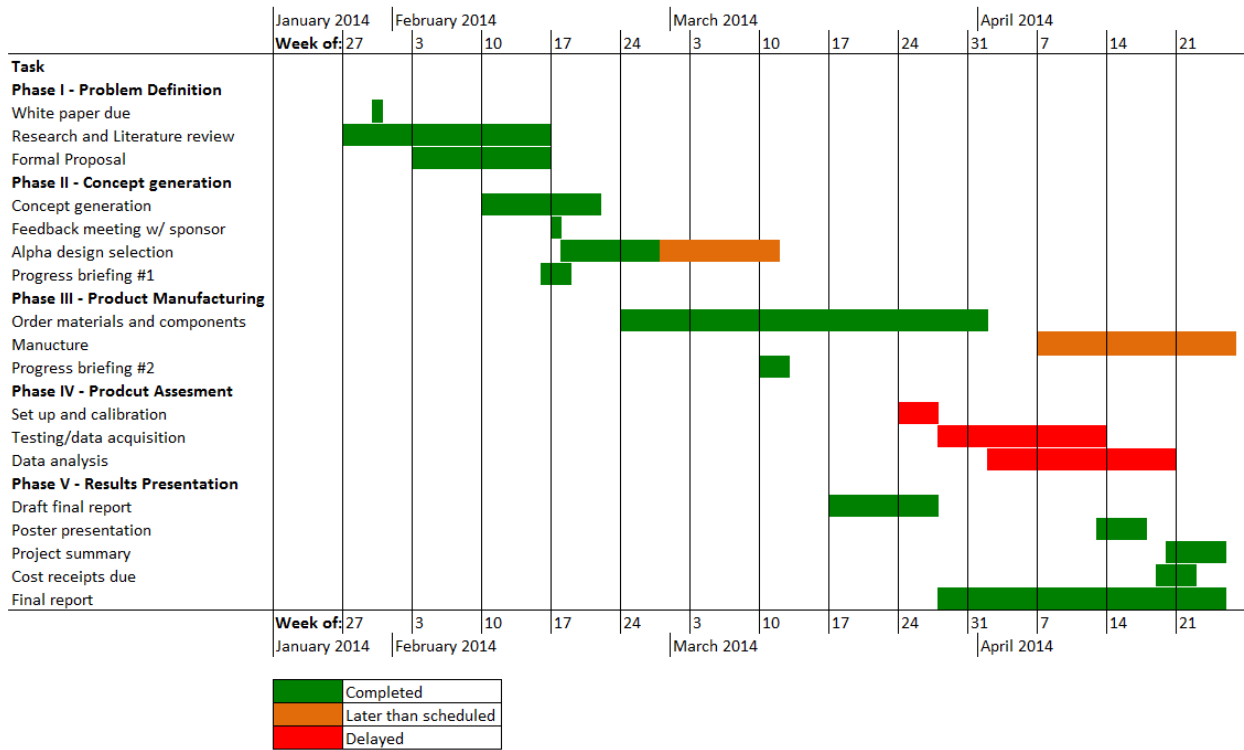
Figure E1: Project schedule as a Gantt Chart

Appendix F – List of manufactured parts

Part Name	Part no.	Material
Exhaust 1 piece front	125	Stainless Steel sheet
Exhaust inner	128	Stainless Steel sheet
Overlap plate	129	Stainless Steel sheet
Exhaust outer	130	Stainless Steel sheet
Exhaust cone	132	Stainless Steel sheet
Exhaust stack rear	133	Stainless Steel sheet
Exhaust stack top/bottom	134	Stainless Steel sheet
Mounting Lug	137	Stainless Steel sheet
Collar	142	AISI 4340 steel
Clamp ring	143	Stainless steel
Gasket	144	
Shaft Tunnel	145	45D X 45 mm Al 6082 circular bar
Turbine Shaft	146	15D x 100 mm AISI 4340 steel circular bar
Manifold	148	
Gearbox Case	155	83D x 40 mm AL 6082 circular bar
Bearing support spigot	156	15D x 100 mm AISI 4340 steel circular bar
Gearbox Front	157	83D x 9 mm AL 6082 circular bar
Prop-shaft housing	158	65D X 35 mm Al 6082 circular bar
Cowl	159	Aluminium alloy
Prop Driver	160	steel
Prop-shaft	163	15D x 100 mm AISI 4340 steel circular bar
Oil Thrower	168	15D x 100 mm AISI 4340 steel circular bar

Table F1: List of manufactured parts

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