Unmanned Aerial Vehicle (UAV) Propulsion Research: Conceptual Studies of “Ultra-Compact Shaft-Less Jet Engines” for Next Generation UAVs

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UNMANNED AERIAL VEHICLE (UAV) PROPULSION RESEARCH:
Conceptual Studies of “Ultra-Compact Shaft-Less Jet Engines” for Next Generation UAVs

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2 Project Summary

Unmanned Aerial Vehicles (UAVs) are becoming more commonly used in today’s global environment, ranging anywhere from military applications to entertainment for enthusiasts and hobbyists. Current generation UAV’s mainstream propulsive devices are based on three principles: a scaled (or “downsized”) turbine (or “jet”) engine, an electric driven fan blade, and a gas powered rotating fan blade. With the complexity of scaled jet engines, regular maintenance needs to be scheduled. For a typical small-scale jet engine, the maintenance is required every 24 hours of flight. With the added maintenance costs and complexity of rotating machinery (turbines/shafts) within scaled jet engines, UAV designers are driven away from using jet engines as propulsive devices, leaving a large void in current production of these devices. Our research team strongly believes that, by combining an electric motor driven fan and a simplified alternative design for the compression and combustion processes, it can possibly develop an energy efficient, reliable, and cost effective next generation small-scale jet engine for UAVs. A basic conceptual study of a small-scale “turbine-less” jet engine was first introduced by CAL State LA researchers recently. Our design concept is “Ultra-Compact Shaft-Less Jet Engine.” The basic idea of our design concept was originally formulated on the work of CAL State LA, however, our research team is planning to innovate the concept through simulation based design optimization, detailed component analysis, and experimental verifications in aerodynamics and combustion. A comprehensive study, utilizing Computational Fluid Dynamics (CFD) based advanced computer-simulation analysis methodology and experimental investigations (wind tunnel test for aerodynamics and static jet engine test for combustion), is hereby proposed. The proposed project will greatly contribute to the current research efforts of developing the next generation UAV propulsion system.
3 Data and Results

3.1 Design Considerations

Previously attempted by CAL State LA researchers, the proposal of a “shaft-less” jet engine was invented through the combination of an Electric Ducted Fan and a combustion section. The idea is to eliminate the need for an output shaft and work associated with the use of a turbine, and essentially their losses throughout the energy transfers. The researcher’s design seemed to lack the necessary components or ingenuity to allow for a continuous flame. Observed in the provided video, their attempt failed in the complete combustion of propane in their combustion chamber. In fact, critical components of their design seemed to lack generalized ideas in the field of propulsion. Through the iterative design process, Embry-Riddle hopes to improve on the work that CAL State LA researchers have done in their attempt to obtain a smaller, more efficient propulsive package for small scale UAV applications.

3.2 Design Revs and Iterative Design Process

Through the design process, an iterative approach was taken. Through the use of ANSYS-Fluent 15.0 and SC/TETRA, a complete engine model was analyzed. First using Quasi-2D analysis, the engine was optimized for flow transition and compression throughout the engine. Using a basic unit length for a thickness, flow optimization was performed through the inlet as well as the combustion chamber. While the models were being optimized for flow, a three dimensional half plane model was used in order to gain 3D effects from fluid motion through the combustion chamber as well as off of the flame holders.

Once adequate data was achieved from the non-combustion models, ANSYS-Fluent 15.0 was used for a non-premixed foreign species model. Again, this was first performed in Quasi-2D analysis, and slowly switched to 3D half Plane analysis.

With the shaft-less jet engine, various typical engine components are neglected or ignored for our analysis. For example, stations 1, 2, and 3 on a typical jet engine are separate entities. However, these are all the same station for the shaft-less jet engine. There is a station 4 as well as a station 8 to the engine.

3.3 Fan/Inlet Design

An Electric Ducted Fan (EDF) was used for the main device used to move air through the shaft-less jet engine. Because this engine model lacks a turbine disk, work needs to be done through the use of an electric motor. The electric motor is then translated into power through the use of a carbon fiber fan blade. The fan used on the EDF is an eleven-blade design, allowing for optimal mass airflow throughout the entirety of the engine. According to specifications from the manufacturer, predicted thrust from the fan unit alone is expected to be 7 kgf to 9.6 kgf of thrust at sea level conditions and using sufficient power supplies. For the maximum performance and validation from the shaft-less jet engine, 2 4800mAh LiPo batteries with 7 cells each will be used to take advantage of the carbon fiber fan blade’s efficiency and power.

Inlet design was considered to help optimize inlet flow and inlet area into the engine. For pure experimental data, a manufactured inlet for the EDF engine will be purchased and fitted onto the engine. Leading into optimization of the engine and airflow in the coming semesters, inlet design can be seen as an area of interest for the Advanced Computer...
Simulation Lab. Optimizing and manufacturing an inlet for a desired flight regime will ultimately lead to a cleaner and leaner burn, leading to increased performance from the engine.

### 3.4 Combustion Chamber and Compression Cycle

The combustion chamber will have to contain the highest temperatures and most pressure of the shaft-less jet engine. The chamber itself will be made of ceramic coated 304 Stainless Steel in order to stand the high temperatures and will be mounted flush with the nozzle and EDF.

The compression cycle strictly consists of the mass flow through the EDF slowing down and increasing pressure once the flow reaches the combustion chamber. Therefore the compression expected is 1.5 to 2 compressor pressure ratio as received by CFD results.

### 3.5 Flame Holder

The flame holder is a critical part of the shaft-less jet engine. This component plays two roles in the functionality of the engine. First, the flame holder acts as a turbulence generator in the wake of the engine. Generating a turbulence wake in the laminar air helps prorogate flame growth and strength. In order to maintain a continuous flame, there needs to be turbulence in the region where the fuel and air will mix. The second role of the flame holder is to allow fuel to enter the closed system. Holes are located on the upper surface of the flame holder, creating turbulent fuel to air mixture. Propane will combust anywhere from 2 % to 9.2% of a fuel to air ratio, meaning anything below and above this value will not combust.

### 3.6 Ignition System

The means of igniting the fuel to air ratio will be through the implementation of a spark plug just aft of the flame holders. The idea and logic behind the ignition cycle will be to use the spark plug in order to get an initial light from the fuel. If for any reason there is an adverse condition through the engine, a continuous spark will be used in order to gain ultimate engine burn and efficiency. Under normal operating conditions, the spark plug will be used only in the ignition cycle of the engine. Therefore it will only need to be used for the beginning start up sequence and then turned off for continuous burn. The flame holder design is such that the flame will continue to hold the flame throughout operation. Through research and MATLAB simulations, this level is seen at roughly 5.2% for ignition conditions. Efficiency of the burner itself in the MATLAB was used at 85 percent which is a conservative number.

### 3.7 Nozzle

Nozzle design was considered through the design of the engine. The exit diameter of the flow was set to around 40mm diameter and then analyzed using Computational Fluid Dynamics. Efficiencies on the nozzle in the MATLAB engine code was used at 95 percent, which is a conservative number for nozzle design.

### 3.8 Computational Fluid Dynamics (CFD) Results

Extensive iteration and design was completed through the use of Computational Fluid Dynamics. ANSYS 15.0 as well as SC/TETRA was used in order to optimize airflow and compression ratios. Two methods of CFD were used for the complete analysis of the engine. Combustion and non-combustion were both modeled using specific software. SC/TETRA was mainly used for the optimization of airflow through the engine. Designing the combustion chamber and inlet parameters are key elements in overall engine performance. Through the iterative process, the most recent results are as follows. The internal pressures seen in the critical regions on the engine (the combustion chamber) are on average 17,500 Pa due to inlet conditions alone. Density within the combustion chamber is seen at 1.3054 kg/m^3, above the standard 1.0017 kg/m^3 seen on an average day in Prescott.

The other aspect of Computational Fluid Dynamics was to analyze the complete combustion of C3H8 propane in the combustion section of the engine. With the use of ANSYS-Fluent 15, a non-premixed foreign species analysis was
used to help simulate combustion conditions within the engine. As before, all analysis were done at the standard conditions of Prescott, Arizona. With a fuel/air ration set at 2.7%, at combustion, the combustion chamber will see around 940,000 Pa, or around 11 times that of atmospheric pressures. The highest pressures are seen on the walls of the bottleneck of the nozzle, at around 1,100,000 Pa. Throughout the combustion process, the walls of the combustion chamber will see roughly 1500K, or around 2250 degrees Fahrenheit. This temperature is below that of the operating temperatures of the 304L Stainless Steel that is being used. At a fuel to air ratio of 2.7%, the CFD data suggests that the engine will see a complete burn of the propane being injected, meaning that there is little CO leaving the nozzle.

3.9 MATLAB Engine Simulation Design

The engine cycle for the simulated in MATLAB using a four stage process: inlet, compressor, burner, nozzle. The code was ran through with varying compressor pressure ratios in order to see what the engine is capable of and what will actually be expected. Above shows the relationship between compressor pressure ratio and exit velocity, nozzle exit radius, and gross thrust. The Electric Ducted Fan will cause the pressure to be between 1.5-2 for a compressor pressure ratio which yields a gross thrust from18.75 to 46.8 kgf and it is seen that if the EDF can achieve a higher compressor pressure ratio the amount of thrust gained would dramatically increase. For the ideal case the thrust between the two compressor pressure ratios would be from 29 to 58.25 kgf since conservative efficiencies were used. The radius of the nozzle yielded between 0.02675 and 0.026 m while our chosen nozzle currently has a radius of 0.02794 m for a radius which allows a factor of safety to prevent backup. The expected exit velocity shall be between 108 and 267 m/s which is a big range however given the relationship it makes sense.

3.10 Support Material
Contours of Relative Total Pressure (pascal)

File: Shape_Group1_488.fld
Cycle: 488
Time: 0.000000
4 Purchasing and Parts

The purchasing of parts was done through Ginger MacGowan in the Undergraduate Research Institute located within the library (Room 119). Six weeks was given to the ordering and purchasing of all the parts needed for the shaft-less jet engine. During that time, part numbers were assigned to each individual part in order to ease the assembly and design process of the engine. Below lists the part numbers and description of each part needed. Below is also the numbering system used for the shaft-less jet engine.

X-XXXX
Black = Engine Number
Green = Rev Number
Red = Specific Part Number

<table>
<thead>
<tr>
<th>P/N</th>
<th>Part Description</th>
<th>Manufacturer</th>
<th>Special Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-0101</td>
<td>Carbon Fiber Fan Casing and 11 Blade Fan</td>
<td>Jet Turbines RC</td>
<td>Purchased from France with the addition of the HET Typhoon Motor</td>
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<tr>
<td>1-0102</td>
<td>Engine Motor</td>
<td>HET Typhoon 800-73-590</td>
<td>Purchased from Jet Turbines RC and installed with Fan Case</td>
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<tr>
<td>1-0103</td>
<td>Engine Motor Protective Housing</td>
<td>Embry Riddle Aeronautical University</td>
<td>3D Printed in Library 119</td>
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<tr>
<td>1-0104</td>
<td>Engine Mounts</td>
<td>Embry Riddle Aeronautical University</td>
<td>3D Printed in Library 119</td>
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<tr>
<td>1-0105</td>
<td>Fan Case Mounted Wiring Brackets</td>
<td>Embry Riddle Aeronautical University</td>
<td>3D Printed in Library 119</td>
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<tr>
<td>1-0106</td>
<td>Fan Case Mounted EEC Controller Bracket</td>
<td>Embry Riddle Aeronautical University</td>
<td>3D Printed in Library 119</td>
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<td>1-0107</td>
<td>EEC Controller</td>
<td>Phoenix Edge 80HV, 50V 80-Amp ESC (CSE010010500)</td>
<td>Ordered from Horizon Hobby</td>
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<td>1-0108</td>
<td>Mounting Flange</td>
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<td>3D Printed in Library 119</td>
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<td>1-0109</td>
<td>Mounting Flange Hardware</td>
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<td>1-0110</td>
<td>Combustion Chamber with a Ceramic High</td>
<td>Ryan Bishop is Manufacturing the combustion chamber from .065” 304L</td>
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<td>Item</td>
<td>Part Description</td>
<td>Notes</td>
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<td>1-0111</td>
<td>Flame Holder</td>
<td>Manufactured by Ryan Bishop, Cerakote done by APC in Phoenix</td>
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<td>1-0112</td>
<td>Engine Inlet</td>
<td>Embry Riddle Aeronautical University (3D Printed in Library 119)</td>
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<td>1-0113</td>
<td>Engine Batteries</td>
<td>SpyderBatteries 12S 5300mAh 30C (Progressive RC)</td>
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<td>1-0114</td>
<td>Remote Control for the Engine</td>
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<tr>
<td>1-0115</td>
<td>Fuel Flow Meter</td>
<td>AALBORG (GFM Mass Flow Meter From AALBORG)</td>
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<td>3D Printing Element</td>
<td>MakerBot PLA Black filament for MakerBot Replicator 2, LARGE ROLL</td>
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<td>Inlet Compression Layer</td>
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<td>1-0118</td>
<td>Spark Plug</td>
<td>Small Stroke Sparkplug used</td>
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</table>
5 Fabrication

Due to the technical difficulty required for fabrication of a varying geometry nozzle, the design was forced to be modified for the final product. All standard dimensions have remained the same within the combustion chamber, flame holder, and nozzle exit diameter, but the convergence had been simplified.

Combustion Chamber entrance / Flame holder

Fan exit

Completed Design
6 Testing and Evaluation

For the purposes of static testing, a test rig to house the engine needed to be developed as well. Below the stand can be seen – included within the setup is first a switch connected to the Li-Po battery supply, then connected to the ESC, which are routed directly to the power supply connectors on the fan. Additional connections run from the ESC to the receiver for throttle control as well as for the ESC cooling fan. An additional small Li-Po was needed in order to power the receiver in order to connect to the RC transmitter for throttle input.

For data measurements, a Pitot Static tube was connected to two separate manometers in order to obtain static and total temperatures as measured against atmospheric pressure. These were combined with a thermocouple connected to a computer via a DAQ with data received and transcribed in LabView. Samples were taken both within the combustion chamber and at the nozzle exit three times at each throttle setting, in order to compare total properties at each station, obtain a proper nozzle efficiency, and compare the performance variation over the life of a battery cycle.

Front of test stand
Rear of test stand

Connection to Manometers
Our experimental results proved to vary from the CFD results received. Perhaps the biggest contributor in the discrepancies could be attributed to the differences between the simulated and final design products. As the CFD modeled designs were produced in order to optimize compression ratios and combustion, limitations to that our projected results were quite likely due to the modifications in construction. This testing proves that further CFD analysis will need to be taken utilizing a comparable engine model to the developed product in order to more accurately verify results. Once this model has been computationally analyzed, further design iterations can be conducted for development of a second model.

The pressure data measurements taken within the combustion chamber were deemed unreliable due to the amount of turbulent flow directly aft of the fan. However, temperature data was able to be collected, and this allowed us to calculate a proper nozzle efficiency of 97.87%. Using this efficiency combined with temperature/pressure relationships allowed us to predict what the potential chamber properties were to be used in further CFD testing. As expected, drops in performance directly related to battery voltage consumption could be observed, however they were minimal as to not drastically affect overall performance.

Pressure distributions as observed at the nozzle exit – local atmospheric pressure is 83.73 kPa
Temperature curves as observed at the nozzle exit – local atmospheric temperature is 298.7 K

After analysis, despite our values of maximum thrust being slightly higher or matching that specified by the manufacturer of 10.39-9.52 kgf, this was below the projected values obtained from CFD and Matlab coding. This proved to be similar for our maximum velocity and density values of 67.14-64.34 m/s and 0.97913-0.97779 kg/m^3, respectively. Final computations provided a total compression ratio of only 1.0668.

Unfortunately, we were unable to proceed with combustion testing of the engine. During a third trial of data collection at the nozzle exit running throttle at 90% for 30 seconds and 100% for 30 seconds with a 3 minute cooling window in-between (minimum 15% throttle for continuous airflow over the motor), the brushless motor gave out 50 seconds into the third run. This was attributed to the ESC failing to limit a larger than needed current being supplied by the Li-Po batteries of approximately 175 Amps to the brushless motors limit of 127.8 Amps as specified by the manufacturer. Future testing will be aided by utilizing an ESC Programmable Control Unit to more effectively regulate the current and voltage running from the Li-Po’s to the motor, as well as assuring more proper specification compatibility between the two prior to purchase.
7 Conclusion

With the necessity of some crucial design change from the computational iteration process to the experimental testing, our final product still proved to yield performance numbers beneficial both in cost and efficiency to comparable scaled down jet engines. Future pursuit of this project would allow for further improving computer models, and by harnessing the potential of 3D printing the combustion chamber and nozzle would allow us to experimentally test the appropriate gains witnessed via simulations.
8 CATIA Drawings