University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Project Definition Document (PDD)

Subsonic-Supersonic Nozzle

Approvals

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I. Problem or Need

Project Definition: Design a nozzle that can accelerate subsonic flow to supersonic flow. Validate the design by reproducing a testing environment similar to the JetCat stock exhaust flow. The nozzle shall not decrease engine thrust-to-weight ratio and shall have the ability to be constructed using additive manufacturing processes.

Figure 1: Nozzle will be designed to this JetCat P90-RXi Engine

There are a few fields of interest that this project can provide enhancements to. In industries of fast moving small aircraft [7], there is an emerging need for Remotely Piloted Aircraft (RPA's), and a successful nozzle design that is accessible could be what provides RPA's with supersonic capabilities. Additionally, the field of additive manufacturing is on a large rise [8], and engineers have started to truly explore the capabilities that 3D printing could provide to areas of study like aerodynamics and propulsion.

Currently, there are several problems in the engine industry that are motivation for this work. Engines that produce supersonic thrust are not very easily attainable commercially, largely due to costs in manufacturing supersonic engines. Creating a nozzle that accelerates subsonic flow to supersonic flow provides a cost efficient solution to this problem. This is worth noting because current supersonic engines are very large compared to those that are subsonic and attaching a nozzle would be more space and weight efficient than entirely replacing a subsonic engine with a supersonic engine.

The limitations of materials that are used for additive manufacturing are not well known at this point, so finding materials that can be 3D printed and also withstand extreme temperature conditions would provide benefits in the future for upgradable and accessible nozzles that are used to achieve supersonic capabilities.

II. Previous Work

The use of nozzles to accelerate flow from subsonic to supersonic has been widely studied in fluid dynamics. It has been proven that a converging-diverging nozzle (CD or de Laval nozzle) can be used to accelerate flow from a subsonic intake, through a sonic throat, and out as supersonic exhaust. NASA's ramjets and rockets usually employ this design, as well as most major supersonic engine manufacturers currently. A study was also done at the University of Cincinnati that analyzed the flow structure of supersonic jets from conical C-D models [6]. The paper published by this group gives important insight for possible CFD modeling techniques, and ways to make experimental measurements without testing the nozzle in an engine (such as particle image velocimetry).

Past senior projects at CU Boulder could also provide useful insight into this project. The goal of DANTE in 2009 was to demonstrate an afterburner that would increase the thrust by 50%, and not degrade the engine thrust-to-weight ratio. The AMT AT-450 nozzle was modified with an afterburner and variable area nozzle. The goal of REAPER in 2015 was to use heat recuperation to increase turbine performance. This team produced considerable data, and understanding of the JetCat ECU in relation to operation of the P90-RXi engine. They also created a control board to bypass the stock engine shut-off feature that prevents any changes from the original manufactured engine state. This control board has not shown successful integration with the JetCat engine, which has motivated the choice to design an engine analog.

The subsonic to supersonic nozzle problem that shall be analyzed by this project exists separate of the previous design problems. The supersonic nozzle problem pays no mind to afterburner performance or biofuel burning; the problem is one of flow control and acceleration according to a handful of boundary conditions.

III. Specific Objectives

The specified requirement from the AFRL stated that the designed nozzle shall not decrease the thrust to weight ratio (T/W). This requirement became our Level 1 success parameter for the performance of our nozzle, which led to increasing the T/W ratio as the Level 2 success for the performance of the nozzle. This would be done by either increasing the thrust or decreasing the added weight of the designed nozzle.

The project will accomplish the goals as outlined below. The Objective Matrix is viewed in chronological order from left to right, with three distinct levels of success corresponding to each heading. Absolute minimum levels of success are those found in the Level 1 designation; absolute maximum levels of success correspond with the Level 3 designation. There also exist To Be Determined (TBD) values because knowledge and experience in these areas are unknown and still need to be researched.

	Model/Simulation	**Design/Manufacturing**	**Testing**
Level 1	• Model stock engine exhaust with given parameters (T, P, $\dot{m}$, V) • Model air in nozzle changing from subsonic flow to supersonic flow • No decrease of T/W	• Manufacture convergent-divergent nozzle that fits and can attach to JetCat engine • Material survives the testing environment for at least 30 seconds	• Replicate an engine analog that simulates exhaust velocity and temperature, within (TBD %) of stock engine conditions
Level 2	• Increase in thrust of (TBD %)	• Nozzle built using additive manufacturing, where material survives testing environment for at least TBD time	• Engine analog shall model exhaust pressure within (TBD %) of stock engine conditions
Level 3	• Verification that modelled nozzle and manufactured nozzle have output performance within (% TBD) of one another	• Nozzle built using additive manufacturing that can be reused TBD times and not fail in the testing environment	• Nozzle integrated and tested with the JetCat engine

Table 1: Objective Matrix for levels of success

IV. Functional Requirements

The following functional block diagrams, figures 2 and 3, separate our two available options for testing a nozzle that will be designed to accelerate flow from subsonic to supersonic speeds. The provided equipment, engine, fuel system, and control system will output an exhaust at TBD exit conditions. These flow conditions will be measured prior to developing the nozzle. Once the nozzle is developed, the nozzle will be attached to the engine so that the flow can be directed through it. The flow exiting the nozzle will then be measured to verify that the flow has turned supersonic. In the event of inevitable engine failure, an analog test engine will be used as shown in figure 3. How this system will work and what the mechanical make-up will be is still vague because of the many available options for testing. It is known that a pressure tank and heat source will be required to replicate the engine exhaust conditions.

The larger bold boxes outlining the systems differentiate between pre-existing equipment and what needs to be manufactured, procured, or purchased.

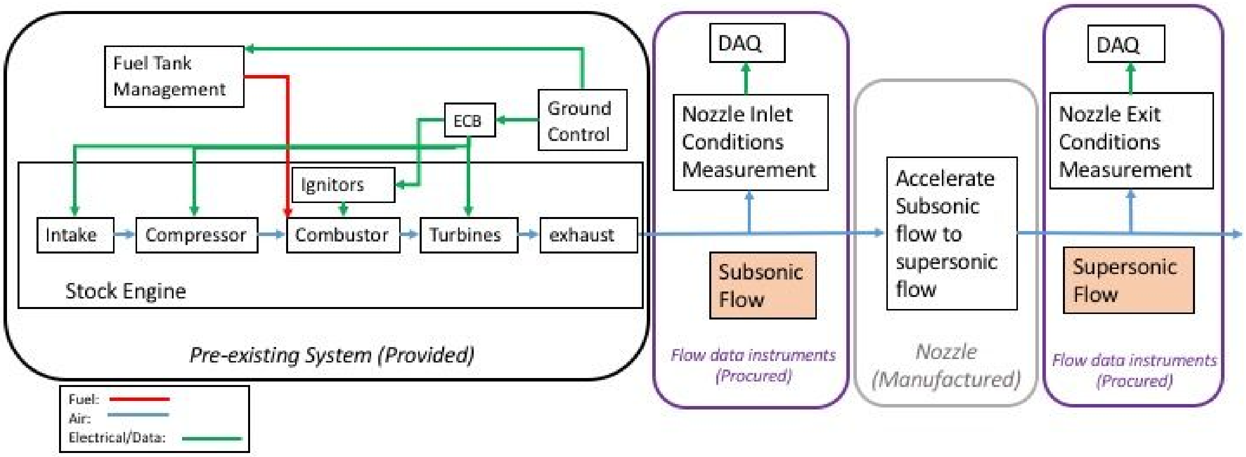

Figure 2: Functional Block Diagram with Engine Incorporated

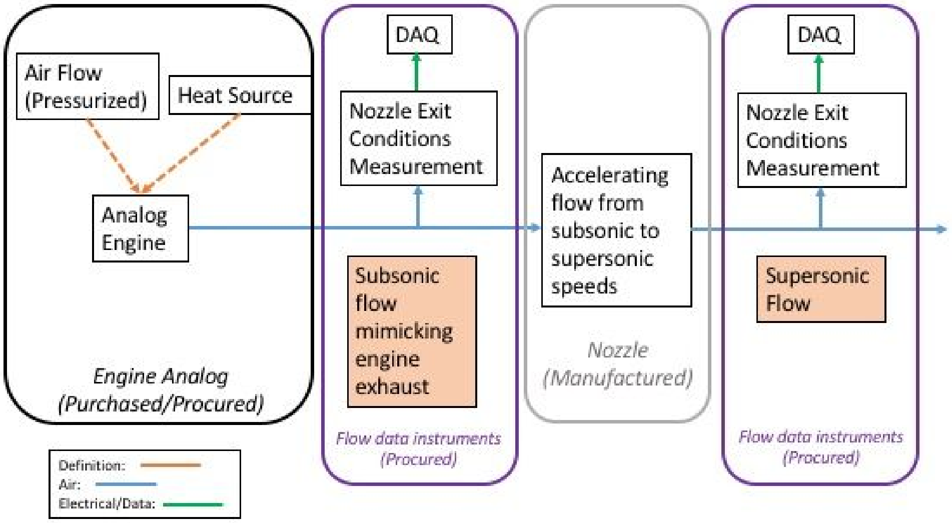

Figure 3: Functional Block Diagram with Analog Engine

The Concept of Operations (CONOPS) is shown in Figure 4. The engine will start up in nominal conditions and then will be throttled up to maximum throttle. There it will achieve maximum thrust, at which point the exhaust gas will directed through the converging/diverging nozzle which will accelerate the exit thrust from subsonic to supersonic speeds. Due to the engine's temperamental nature, an analogous test bed will be created to test and verify the nozzle design and performance. The addition of a nozzle capable of supersonic speeds will allow small subsonic engines to gain the ability to reach supersonic speeds without an entire redesign of the engine. This expands the reach that, in this case, the engine can perform at without losing much of its thrust to weight ratio.

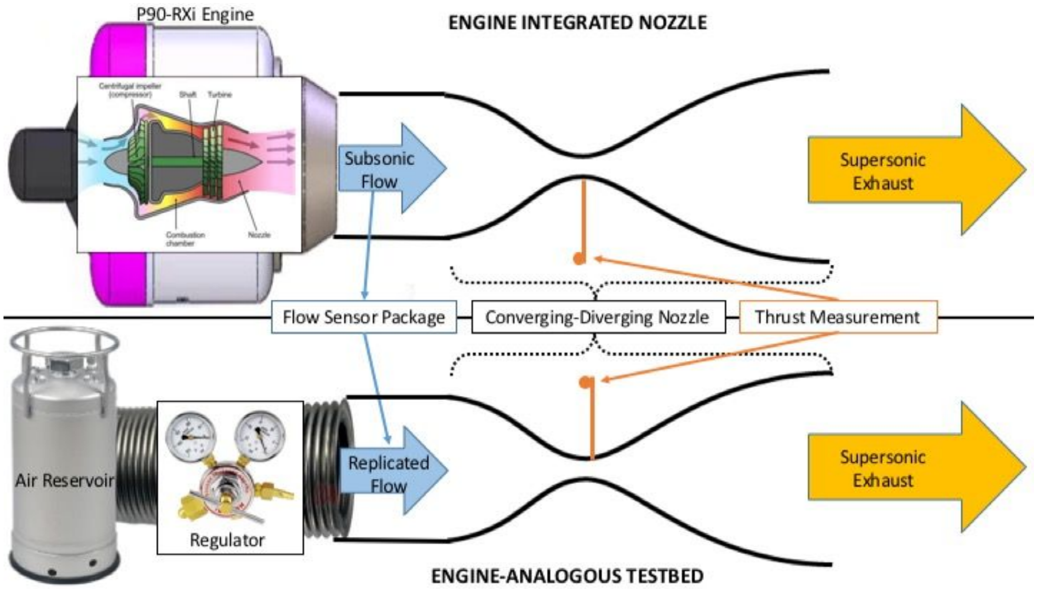

Figure 4: Concept of Operations

V. Critical Project Elements

1. P90-RXi Engine
    1.1. The engine is known to be very temperamental and off-nominal conditions cause the ECU to shut down the engine. With these limitations in mind, it's expected that testing with the engine might not be possible. As such, the exhaust flow conditions will need to be accurately determined so that an alternate testbed can be used.
2. Simulation
    2.1. A Computational Fluid Dynamics (CFD) model will be used to simulate the exhaust flow conditions entering the nozzle to be designed. Difficulties with this include modeling supersonic flow and setting up boundary conditions properly.
3. Exhaust Nozzle
    3.1. Additive manufacturing processes might introduce unnecessary imperfections to the nozzle design which would otherwise affect nozzle performance. Attention must be paid to selecting an additive manufacturing process that produces as few flaws in the nozzle surface as possible; additionally, the nozzle might need to be finished by hand to eliminate turbulence-causing imperfections.
    3.2. Selecting a nozzle design that will interface onto the stock engine without excessive modification or adding excessive weight to the engine structure may be difficult.
4. Testing
    4.1. A testbed, or beds, will need to be developed to mimic the JetCat's nominal exhaust flow and to test the performance of the nozzle. Due to the high temperature of the exhaust it may be necessary to conduct a separate thermal test to observe thermal response characteristics.

VI. Team Skills and Interests

Team Member	**Skills and Interests**	**CPE**
Alex	propulsion, aerodynamics, engine testing, experience with engines, Matlab, C, Fluent, and AutoDesk Inventor	engine, simulation, nozzle, testing, ECU
Andrew Q.	propulsion, aerodynamics, embedded sys, microcontrollers, Matlab, AutoDesk Inventor	engine, nozzle, testing, ECU
Andrew S.	aerodynamics, fluid dynamics, experimental testing	nozzle, testing
Corrina	manufacturing, engine testing, experience with experimental work, fluid dynamics	engine, nozzle, testing
Grant	engine testing, microcontrollers, experience with Matlab and Ansys simulations	engine, simulation, testing, ECU
Jack	manufacturing, design, CAD modeling, experience with SolidWorks fluid flow simulations	simulation, nozzle
Jared	aerodynamics, microavionics, embedded sys, experience with Matlab, C, Fluent, Simulink, debugging/profiling	simulation, nozzle, ECU
Nate	aerodynamics, manufacturing, testing, experience with Matlab and SolidWorks	engine, simulation, nozzle, testing
Tucker	aerodynamics, experience with propulsions, Matlab	simulation, nozzle

VII. Resources

CPE	**Resources/Source**
P90-RXi Engine	Matt Rhode - previous experience with engine operation and configuration REAPER Team - hands-on experience with engine Bobby Hodgekinson - experience with JetCat P90 RXi engine alterations Trudy Shwartz - experience with embedded systems
Simulation	John Farnsworth - extensive aerodynamic research Farnsworth's Wind Tunnel - Facility to test and simulate aerodynamic properties John Evans - CFD and aerodynamic knowledge Fluent - CFD Software STAR-CCM+ - CFD Software (Dr. Argrow's License)
Exhaust Nozzle	Brian Argrow - high-speed aerodynamics James Nabity - industry propulsion experience 3D Printing - Companies that have the ability to manufacture nozzle out of specified material
Testing	Matt Rhode - experience with engine testing Boulder Airport - Facility and space to test engine performance

VIII. References

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