Design and Analysis of Axial Turbine Power Extraction from a Small-Scale Rotating Detonation Rocket Combustor

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The Rotating Detonation Turbine Generator (RDTG) project, in conjunction with Braun's Engineering Factory for Advanced Supersonic Technologies (BEFAST Lab) at North Carolina State University, aims to present an experimental set-up to prove the feasibility of power generation using an axial turbine generator in the exhaust of a rotating detonation engine (RDE). This is accomplished through the design and experimental validation of a small turbine blisk capable of extracting power from BEFAST Lab's RDE exhaust. RDE technology offers thermodynamic advantages over conventional deflagration-based systems. However, unsteady, high temperature, supersonic exhaust presents challenges for conventional turbines. The small-scale turbine rotor-stator assembly is designed with consideration of detonation induced shock waves. Blade geometry design is conducted using Advanced Design Technology and Aerodynamic Solutions software. Turbomachinery CFD simulations are used to compares parameters to 0D models. Structural and dynamic simulations for the assembly were conducted using MATLAB and Simscape. Furthermore, finite element methods are used to assess material stresses during operation. The proposed experimental validation involves controlled short-duration RDE firings; a target electrical power output of 3 kW serves as the primary performance benchmark, while secondary objectives encompass efficiency maximization, thermal stability, and mechanical longevity. Instrumentation, including a high-frequency pressure transducer, pressure taps, thermocouples, and a torque sensor, allows real-time data acquisition during testing. This study represents a proof of concept for compact and efficient energy extraction systems capable of operating under RDE combustion conditions, and will act as the first step in BEFAST Lab's platform for developing RDE-driven axial turbines.

I. Introduction

Developing clean, more efficient energy technology is a major focus of current research in all fields. Advances in manufacturing technology allow new forms of combustion technology as potential solutions. Several types of engines fulfill this requirement; in particular, those using pressure-gain combustion methods. Recently, rotating detonation engines, which use a detonation (supersonic flame front) rather than a deflagration to complete combustion, have been gathering traction for generating propulsion as rocket engines. Beyond propulsion, this technology has the potential to be implemented within the combustion engine in a power generation system. These combustors, called rotating detonation combustors (RDCs), represent an opportunity to achieve greater thermodynamic efficiency goals in power generation over their counterparts [3]. However, these systems face significant challenges due to the fluctuating exhaust produced by RDCs, which induce low supersonic flows and large flow angle fluctuations (i.e. unsteady flows) [2]. These unsteady inflows severely impact the performance of downstream conventional turbines. Examples include increased pressure losses, unstable operation, and shock wave formation, which ultimately lead to reduced power output[3]. In addition, the high heat generated during detonation makes putting anything downstream for power

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generation a design challenge [1]. There is a need for turbine designs optimized to handle these challenges, as well as the high heat flux levels found within RDCs.

The RDTG project is advised and funded by Dr. James Braun, assistant professor at North Carolina State University researching supersonic propulsion methods through BEFAST lab. With their support, our team will work to optimize turbine systems for RDC applications, utilizing their small-scale RDE to test our setup. The RDE used in this project has been estimated to produce exhaust temperatures estimated to be 2500 K, moving at supersonic speeds with chamber pressures ranging between 2 and 8 bar in the presence of the detonation wave.

This paper proposes the design and testing of a small-scale turbine generator to test the potential of converting the kinetic and thermal energy of the exhaust into rotational energy to be harvested by a starter generator. The advancements made in this project will pave the way for future research and industrial applications involving RDCs. The benefits of this work include finding cost effective solutions to improving the thermodynamic efficiency of power generation and propulsion systems such as power plants and aircraft engines. Additionally, more efficient engines reduces the environmental impact while helping to meet the growing global power demand. The ultimate goal of this project is to create a system that will act as a platform for testing a wide range of different technologies to address the critical challenges with turbine power extraction from RDC exhaust.

II. Design Overview

The Rotating Detonation Turbine Generator design was created by Liquid Rocketry Lab - Advanced Projects. The design attempts to address the challenges inherent in RDC technology while optimizing for power generation efficiency. The system features an axial turbine engineered with considerations for the supersonic, unsteady flow conditions produced by RDCs. This is achieved through inverse blade design of the stator and rotor sections to manage shock interactions and flow conditioning within the expected flow conditions. The turbine connects to a shaft assembly supported by angular contact bearings selected to withstand high rotational speeds and thrusting loads. Balancing is a critical aspect for any high-speed rotating system – special consideration was made to ensure each rotating component falls within a balancing standard of G 2.5. The system employs a high-performance brushless DC motor that functions as both a starter for pre-spinning the turbine and a generator for power production. Our design incorporates air sealing mechanisms to isolate the bearings from combustion products and heat. The entire assembly is housed in a stainless steel containment structure designed for repeatable experimentation without corroding. Special design considerations and materials were chosen for high-risk components including total pressure probes and bladed geometries. Designed with the methodology of modularity, sections of the cowling shown in Figure 2 highlight this.

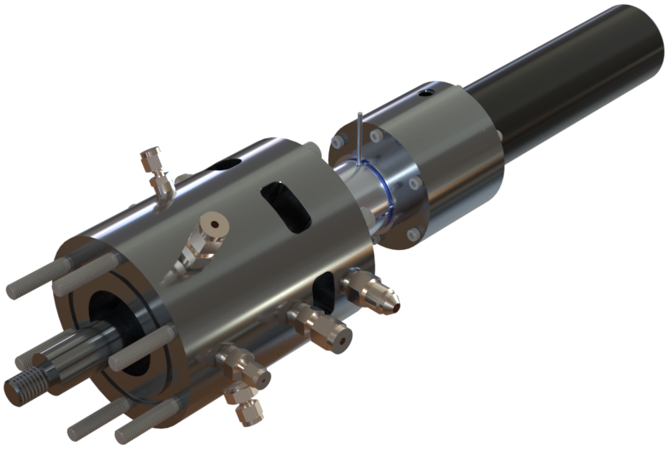


Fig. 1 Turbine Generator Housing

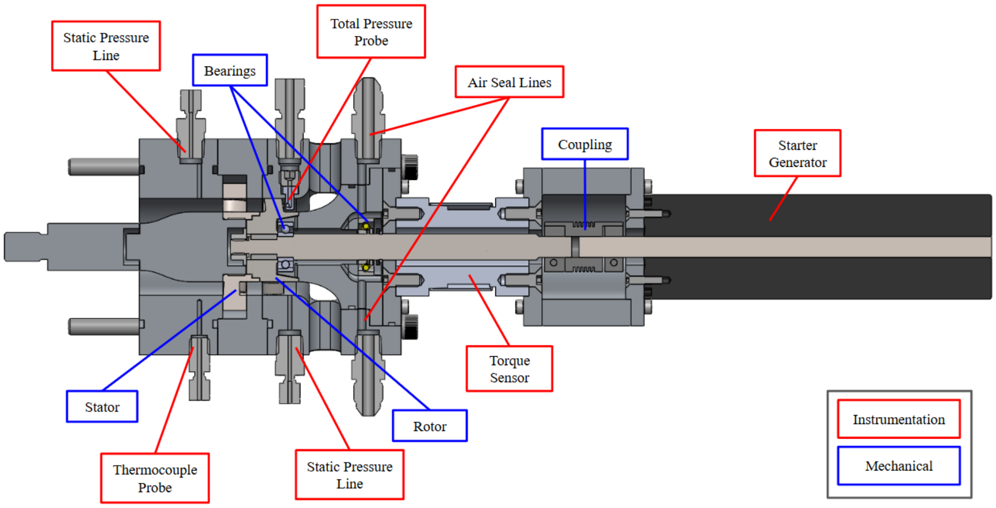


Fig. 2 Cross Section of Turbine Generator

A. Subsystem Design Components

1. Starter Generator

The electrical system of the RDTG, shown in Figure 3, is designed to support both power generation and data acquisition, ensuring precise monitoring and control during testing. A 7 kW 60,000 RPM brushless DC motor was selected for its suitability to the requirements of the system's starter and generator modes. At the start of a test, the device pre-spins the turbine to operational speeds before the initiation of detonation where mechanical energy is converted into electrical power. The starter generator is seamlessly driven by an open-source COTS VESC (Vedder Electronic Speed Controller) which includes configurable parameters within the firmware, allowing for optimization of motor efficiency, regenerative braking, and current limits, ensuring safe and stable operation under extreme conditions. A robust power distribution system manages the flow, measurement, and dissipation of excess electrical energy. Finally, the system is capable of simultaneously reporting live data, recording data, and uploading in real-time for further analysis/processing on the NI DAQ/LabVIEW. This setup allows for detailed performance characterization and accurate tracking of generated electrical power, system efficiency, and transient behavior during detonation events.

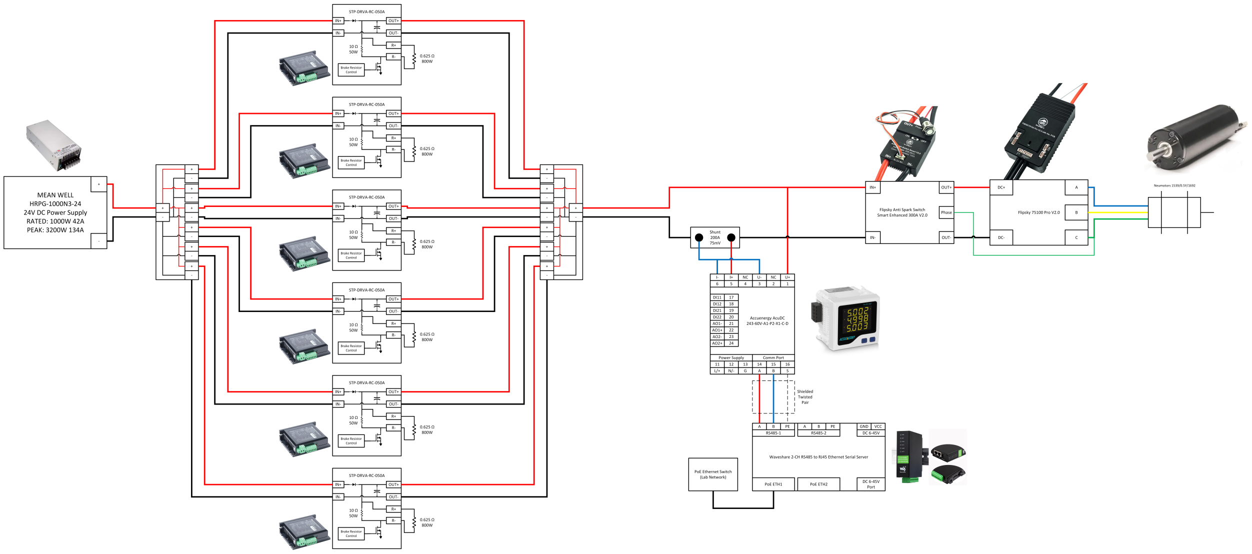


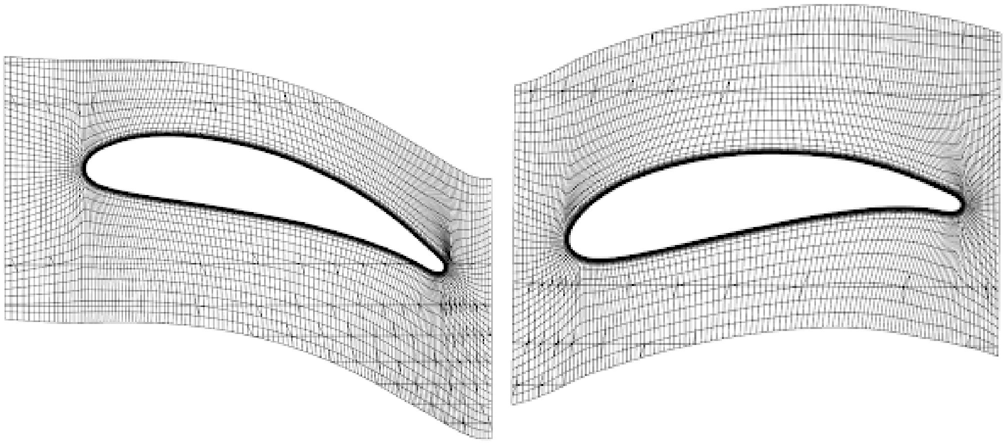
Fig. 3 Starter Generator System Diagram

2. Turbine

The turbine contains a single stage design to extract power from the exhaust flow. To start, a 0D isentropic turbine model was developed to determine downstream parameters and turning angles to reach 3 kilowatts of power. The model was based on Euler's Turbomachinery equation shown in Eq. 1, where isentropic flow was assumed for the analysis. The velocity values, C_{u1} and C_{u2}, are the tangential velocities at the inlet and outlet of the rotor. The 0D model provided a baseline for target parameter to then be refined in the sizing code.

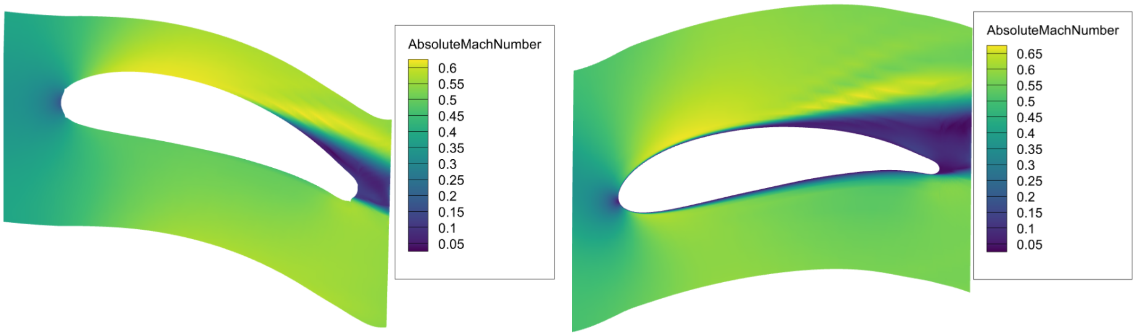
$$P = \dot{m}U(C_{u2} - C_{u1}) \tag{1}$$

Following the 0D model, stator and rotor geometries were generated through TURBOdesign by Advanced Design Technologies. The 1-D sizing and mean-line analysis code contains an inverse design approach that uses inlet aerodynamic conditions and a meridional profile to generate the blades for the rotor and stator. A stator and rotor blade count of 15 was set for the solver.



(a) Stator Mesh **(b) Rotor Mesh**

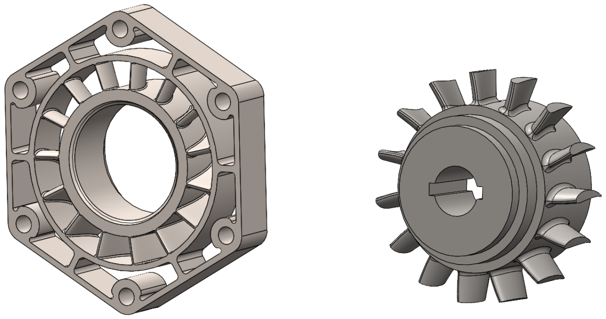
Fig. 4 Fluid Volume Mesh for CFD



(a) Version 1 Stator **(b) Version 1 Rotor**

Fig. 5 Mach Number Contours for Version 1 of Stator (a) and Rotor (b)

The generated blade profiles were extracted from the software. ADSCFD, a GPU-optimized computational fluid dynamics code by AeroDynamic Solutions, was used to compare with the 0D analysis. Code WAND, an automated OHH-type meshing program, was used to generate the fluid volumes shown in Figures 4a and 4b. Following mesh generation, Code LEO, a density-based CFD code, was run in conjunction with Code WAND. Contours were generated based on the CFD solution with Tecplot. Once the blade design and CFD validation was completed, CAD models of the stator and rotor were developed to be manufactured and then integrated.



(a) Stator **(b) Rotor**

Fig. 6 Custom Designed Inconel 718 and 316L Stainless Steel Stator (a) and 303 Stainless Steel Rotor (b)

3. Static Mechanical

The static components of the design are responsible for rigidly fixing each component of the assembly such as the stator, rotor, shaft, and motor, while also properly guiding exhaust through turbine components and out to the atmosphere. The components are listed from upstream to downstream and can be seen in Figure 2 above. It should be noted that each component is machined from 303 Stainless Steel stock ordered from McMaster-Carr.

To begin with, the pre-stator shroud gives space for the center-body to route the exhaust to the stator and rotor, while also containing instrumentation to measure flow parameters exiting the RDE. The stator shroud itself holds the stator to precision and is bolted to the turbine shroud with 18-8 SS Socket Head Screws. The turbine shroud is responsible for holding the deflector in place and venting the exhaust to the atmosphere through six 12 by 23.50 mm holes. Each shroud is further responsible for containing shrapnel in the case of failure and are all attached to the RDE via 1/4-28 Steel Alloy Socket Head Screws. The deflector piece rigidly supports the bearings, radially deflects the RDE exhaust, and houses the shaft assembly and air sealing system. The air sealing system serves to protect the bearings from hot exhaust by running air from a 200 psi compressor through the clearance between the turbine and deflector. This system is designed specifically to route the air around the bearings to avoid lubrication stripping.

The final components downstream feature an ATO-DYJN-104 micro reaction torque sensor and custom motor mount, containing holes to route excess high pressure air out from inside the assembly. A flange containing six more 18-8 SS Socket Head Screws hold the deflector and turbine shroud. The torque sensor attaches to the flange with four 18-8 SS Hex Drive Flat Head Screws, which are used downstream to attach the sensor to the motor mount. The motor mount is held together with two flanges each containing six 18-8 SS Socket Head Screws. Finally, the downstream motor mount flange is attached to the motor with four 18-8 SS Hex Drive Flat Head Screws.

4. Rotor Mechanical

The rotating components within our design are comprised of a shaft with a tight tolerance, high-precision angular contact bearings, and a balanced miniature bellows coupling. These components were iterated and confirmed for feasibility by analyzing static behavior through MATLAB code solving Euler-Bernoulli beam equations and dynamic behavior through MATLAB Simscape Driveline Tools. The shaft was machined from a 10 mm diameter 420 Stainless Steel shaft blank, featuring a straightness tolerance of 0.03 mm per 300 mm, and diameter reductions upstream and downstream to interface with the rotor and coupling. At the very tip of the shaft, a M6 thread is used to secure a serrated flange nut to constraint the rotor axially in one direction with respect to the shaft. The shaft also features a small 0.2 mm gap in order to support the bearing pre-load mechanism.

The bearings used are two super precision angular contact bearings from Lily Bearings: 719/8 CE/P4A (8 mm bore) and 71900 CE/P4A (10 mm bore). Both bearings have RPM ratings over 150,000 RPM, radial load ratings above 1.7 kN, and temperature ratings of 383 Kelvin. The bearings are pre-loaded using a rotor clip and a wave disc spring, pre-loading the bearings at around 2% of their load capacity (11 lbs).

The coupling used is an R+W miniature bellows coupling, with a length of 30 mm, two 8 mm bore diameters on either side, and a 19 mm outer diameter. The maximum displacement values range from 0.15 mm laterally, 1.5 degrees angularly, and 0.5 mm axially.

5. Instrumentation and Data Acquisition

An extensive sensor system is needed to maintain safety while collecting the data needed to calculate performance parameters. The rotational velocity of the system is tracked by RPM sensors on the motor controller and power meter. The surface temperatures of the motor and outer surface of the rotor housing are also tracked. The power produced by the generator is calculated by measuring the torque and rotational velocity, as well as the voltage and current. In addition to these instruments, the total pressure, static pressure, and temperature are measured throughout the turbine-generator system, allowing for the estimation of expansion ratio, adiabatic efficiency, and turbine efficiency. An NI chassis and internal LabVIEW program is used to record data in real-time.

A total of four K type thermocouples are used to estimate flow-temperature measurements; due to the very high temperatures in the chamber, the thermocouples are placed in blind holes terminating 2 mm from the inner wall (the fourth thermocouple, used to refine the thermal coefficient of the wall, is placed in a blind hole terminating 5 mm from the inner wall.) Static pressure measurements are obtained from air lines placed in the side of the wall. In order to withstand the high temperatures, the total pressure probes are constructed of tungsten; the data points before and after the turbine allow for the calculation of expansion ratio. Most pressure measurements are taken by a Scanivalve DSA5000, while the static pressure measurement P.1 is taken by a high frequency pressure transducer.

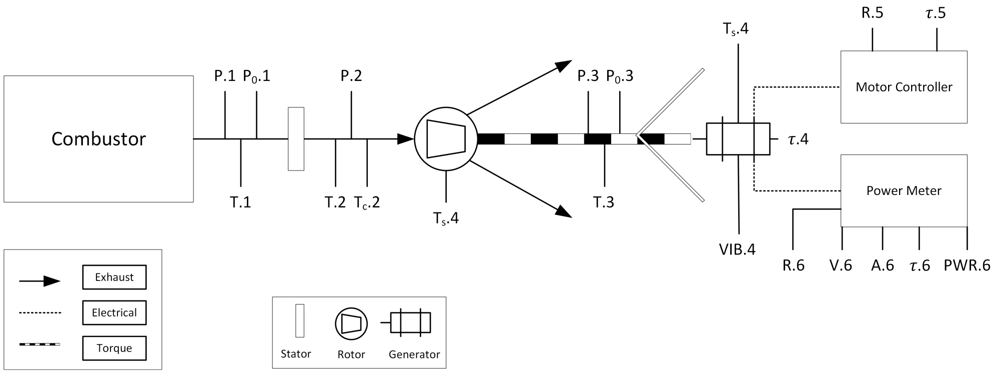


Fig. 7 System P&ID Diagram

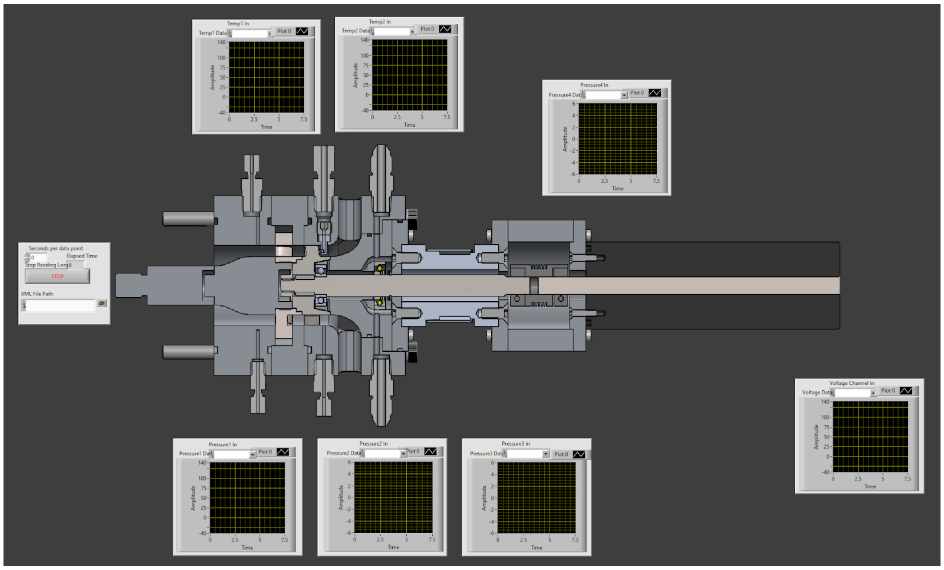


Fig. 8 Labview User Interface

B. Concept of Operations

A critical component of the RDTG project is creating a foundation for further research. The senior design project is limited to the academic year, but the work will be expanded upon in the future. Within NC State, each system will be designed, tested, and iterated on throughout the project. With the goal to create a platform for expansion, design will continue as components are fabricated, including potential cooling systems for both RDC and turbine sections. The work will be published for other institutions to build upon. The ultimate goal is to create an industry-viable product for energy, transportation, and defense sectors.

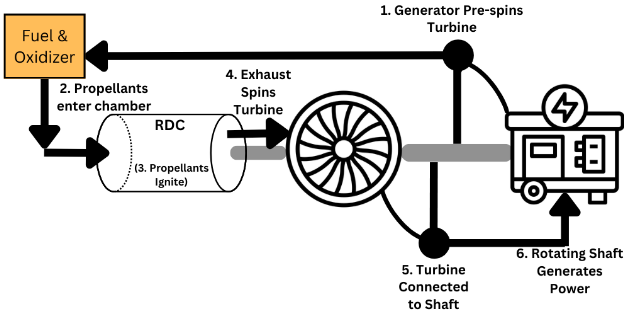


Fig. 9 Systems Concept of Operations

Specifically, the project aims to generate energy using RDC exhaust to spin a supersonic turbine as shown in Figure 9. The operational sequence begins by powering the motor to pre-spin the turbine blade to an estimated steady-state RPM, ensuring accurate data collection during the short operation time. Once this RPM is reached, power to the motor is cut, methane fuel and oxygen oxidizer are added to the RDC, and propellants are detonated in the chamber. The experiment will not exceed 5 seconds, eliminating the need for extensive cooling. Supersonic exhaust from the detonations propels the pre-spun turbine blades. RPM measurements, mechanical power, and electrical power generated are compared against theoretical values to evaluate performance and efficiency. The data acquisition system collects high and low frequency pressure measurements and temperature readings via thermocouples for the LabVIEW system. Torque and RPM sensors track turbine and generator rotational speed and power output. Voltmeters and ammeters monitor electrical performance. High-speed cameras capture exhaust fluctuations caused by detonation waves, allowing analysis of the detonation process and its impact on blade stability and efficiency.

C. Functional Block Diagram

The functional block diagram illustrates the key components and systems involved in the operation of the RDTG. At its core, the system includes the RDC provided by BEFAST, feeding the turbine and instrumentation housing. The RDTG instrumentation collects necessary data, such as pressure measurements from transducers and temperature readings via thermocouples, feeding this information to the data acquisition system. The goal is to incorporate both static and total pressure measurements through pressure lines and total pressure probes. However, this may become a future goal as time permits. The detonation chamber produces exhaust gases that drive the turbine blades. The turbine converts the kinetic energy from the exhaust into mechanical energy, rotating the shaft, which is connected to a generator. The mechanical systems, including the bearings and shaft, are designed to create smooth and safe power generation. Torque and RPM sensors track the turbine and generator's rotational speed and power output.

Data acquisition is collected and fed to a LabVIEW VI, which processes inputs from these sensors and cameras, allowing for real-time analysis. The Command Center oversees system control and data analysis, while very short test times paired with pre-spinning ensure safe and efficient operation.

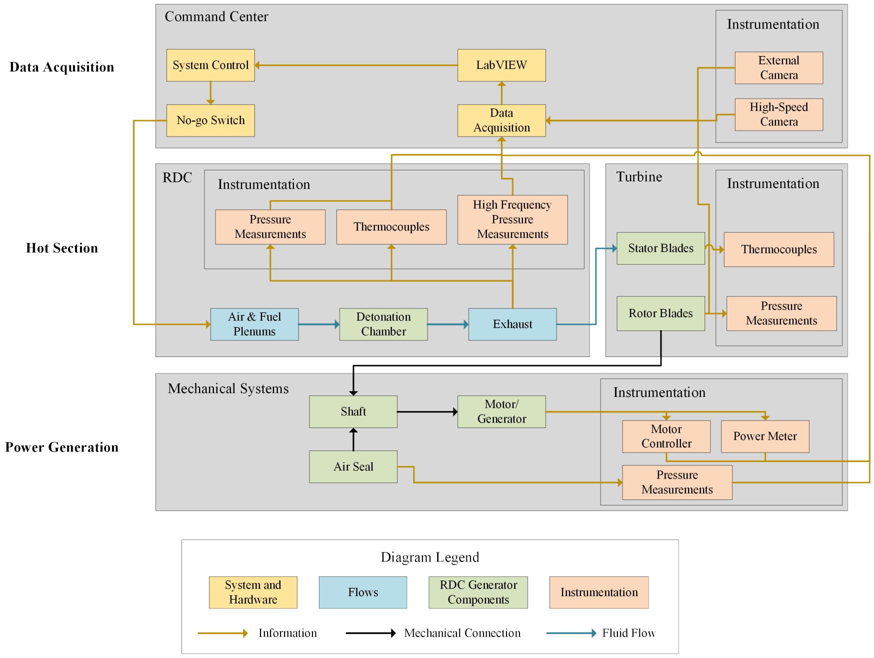


Fig. 10 Functional Block Diagram

III. Prototype

A. Manufacturing

A majority of the manufacturing was completed by the RDTG team with a few components outsourced due to lack of appropriate equipment and complex design requirements. For example, the stator was additively manufactured by a third party out of two different materials: Inconel 718 and 316L stainless steel. The rotor blades will be outsourced to CAMAL at North Carolina State University. Both of these items will be post-processed by our team to ensure they fit within our system.

In regards to the rest of the components, 303 stainless steel was ordered and machined using both manual lathes and computer numerical control (CNC) mills provided by the NCSU machine shops and ShopSpace Makerspace. Utilizing a variety of tools and tool-holding equipment provided by SCHUNK and BEFAST Research Lab, each component is precisely manufactured and audited by built-in digital readout systems, test indicators, micrometers, and digital calipers. Each member received proper machine training either from ShopSpace or the NCSU machine shop professionals. The electrical components were wired and mounted by the RDTG team as well.

(a) Post Lathe Operation **(b) Cutting 303 Stainless Stock**

Fig. 11 Example of Machining Performed by the Team

B. Validation, Verification, and Testing

The first set of simulations completed featured a transient analysis of the stator and rotor. Using Rocket Propulsion Analysis (RPA) software, ambient blade temperature and film coefficient were estimated on the stator and rotor. Then, a transient ANSYS FEA simulation was run to determine testing limits on our design and where our design could stand to be improved to reduce stresses.

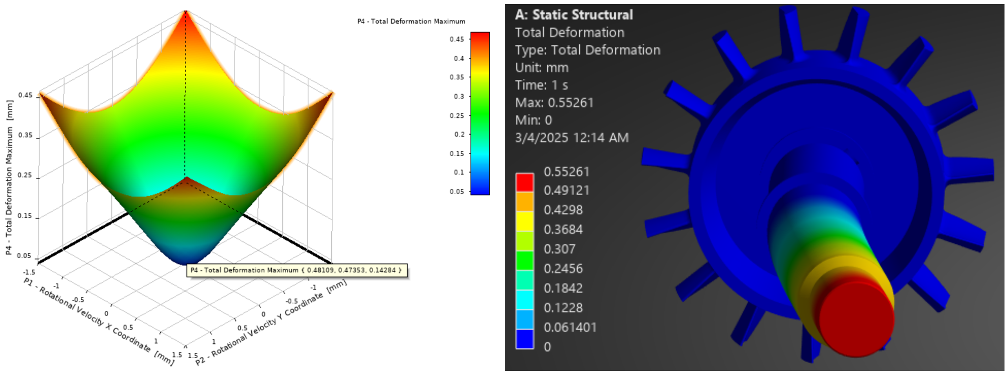
The next set of the simulations includes a modal analysis on the shaft assembly. The first critical natural frequencies were found to be around 1265 Hz, with mode shapes corresponding to deflection at the coupling end, assuming that the end is allowed to freely deflect within the limits of the coupling. The rest of the natural frequencies were assumed to be large enough to be negligible compared to the first pair. A design of experiments was conducted with 50 samples created by Latin-Hypercube sampling to determine how balanced the shaft needs to be to remain within the coupling limits. The results are shown in Figure 12 below, concluding that a radial distance of 0.65 mm away from the COM plane results in deformation beyond the coupling's allowable limit. Utilizing a G rating of 2.5 (typical for turbomachinery), Equations 2 & 3 yield the allowable mass imbalance [4].

$$U_{per} = 1000 * \frac{G * m}{\Omega} \tag{2}$$

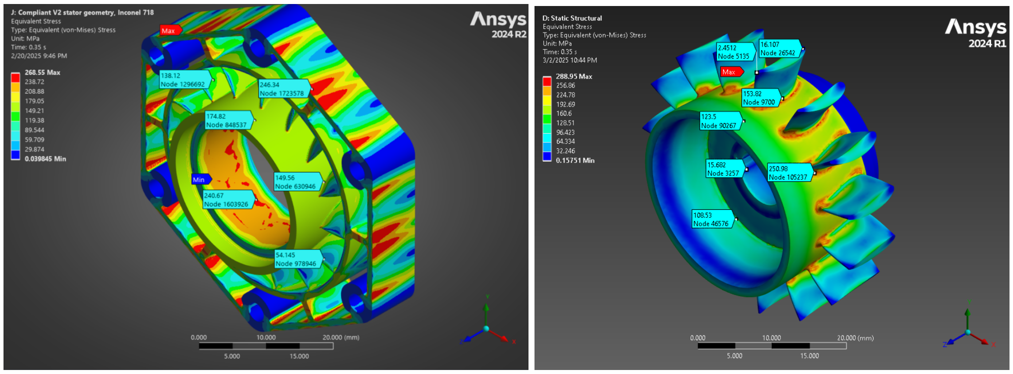
Where U_{per} is the permissible residual imbalance (in g*mm), G is the balance quality grade (in mm/s), m is the rotor mass (in kg), and Ω is the angular velocity (in rad/s). To determine the mass imbalance per mm to stay within a G 2.5 rating, Eqn. 3 is used.

$$m_{imb} = \frac{U_{per}}{L * r_{max}} \tag{3}$$

Where m_{imb} is the mass imbalance per shaft length (in g/mm), L is the shaft length (in mm), r_{max} is the maximum allowable distance from COM (in mm). As a result, the mass imbalance must be less than 1.2 mg per mm to remain within the G 2.5 rating.



(a) Deformation Surface Response **(b) Shaft Deformation Relating to Mode Shape**



(c) Stator Transient FEA **(d) Rotor Transient FEA**

Fig. 12 FEA and CFD Simulations

IV. Conclusion

In this document, the RDTG concept was presented, a novel system designed to harness detonation engines for axial turbine-based energy extraction. Our approach addresses challenges posed by RDC's inherent characteristics while creating a platform for testing future systems. The RDTG integrates multiple subsystems to generate electrical power from an RDC's exhaust. Through trade studies and feasibility analyses, the team developed a design balancing performance, safety, cost, and manufacturability. The axial turbine configuration, featuring optimized rotor and stator sections, is designed to survive the supersonic exhaust while extracting power. Computational analysis predicts performance across operational conditions, with simulations indicating the design should withstand the extreme thermal and mechanical stresses caused by the RDC's exhaust for the test duration. The shaft and bearing assembly incorporates pre-lubricated angular contact bearings to handle both radial and axial loads at speeds up to 30,000 RPM. The air sealing system isolates sensitive components from combustion products and heat. Our brushless DC motor/generator provides dual functionality for pre-spinning the turbine and converting rotational energy to electrical power. Risk assessment and mitigation strategies have been incorporated throughout the design. Our test plan will progress from component-level verification to system testing, ensuring each subsystem meets requirements before integration. The design is projected to satisfy all project objectives, with achievable higher goals depending on test results once the BEFAST RDC is complete. Manufacturing and assembly plans are close to completion. This work establishes a foundation for future research in pressure gain combustion power generation. The modular design allows for future iterations incorporating advanced cooling strategies, optimized aerodynamics, and alternative power extraction geometries. Data collected during testing will contribute to understanding interactions between detonation-based combustion and turbomachinery, providing insight into new solutions with improved efficiency. The RDTG system represents an approach to harnessing rotating detonation technology for power generation applications. This design has potential to enable more efficient energy systems for sustainable power solutions.

Appendix

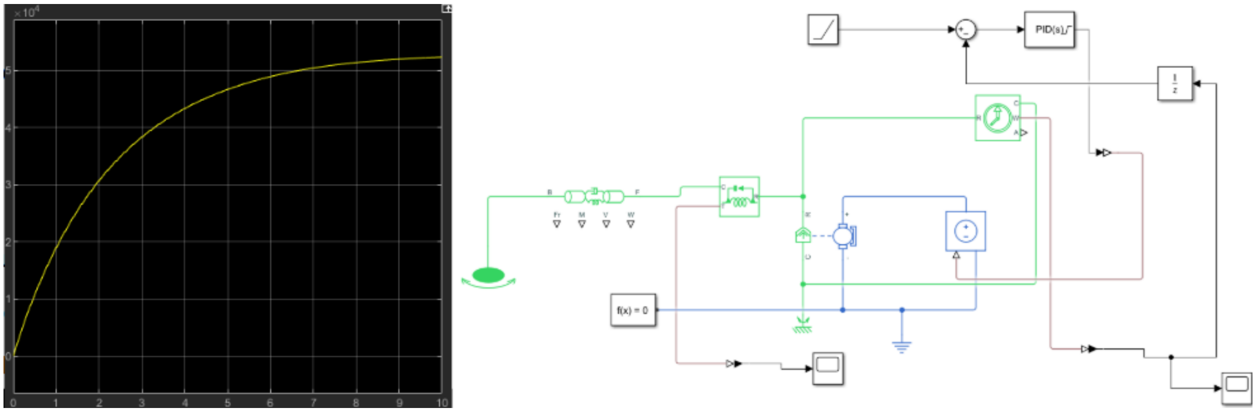


Fig. 13 System Dynamic Behavior: RPM vs. Time

Acknowledgments

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Lastly, the team wants to extend our thanks to Dr. James Braun and the members of his lab, BE-FAST Labs, at North Carolina State University. Without their support and expertise, this project would not be possible. Thank you, Dr. Braun. And to all the members of the senior design team who have dedicated their time to its success.

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