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Development of an Automatic-Calibrating Small-Scale Thrust Stand for Rotating Detonation Rocket Engines

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The Rotating Detonation Engine has been seen as the next step for rocket propulsion applications with the advent of the Rotating Detonation Rocket Engine, an engine configuration developed by the Air Force Research Laboratory. In an effort to flight-test this engine and provide a dataset to train detonation-based simulation, the Rotating Detonation Rocket Engine has been tested in a collaborative effort including the University of Central Florida. For this testing, a thrust stand was developed to obtain the key thrust and impulse data necessary for advancing the engine to flight readiness. This thrust stand utilized the small-scale of the Rotating Detonation Rocket Engine to motivate an axial-loading measurement approach and the integration of an automatic-calibration subassembly, altogether which allows for incredibly accurate thrust measurements from an engine. Results using this thrust stand for two similar engine configurations are shown to validate the operation of the thrust stand.

I. Introduction

The Rotating Detonation Engine (RDE) is a combustion technology rapidly gaining momentum for propulsion and power generation. For its relatively simple operation, lending to its mechanical simplicity, the RDE has significant potential to combine and replace current compressor and combustor stages in gas turbine engines [1]. The RDE operates under the constant-volume combustion cycle, often also referred to as pressure-gain combustion, utilizing the pressure rise, high temperature, and short burning time scale of a shock-flame coupled detonation wave. The RDE consists of a cylindrical annulus channel confined by an inner and outer body, in which a detonation wave(s) is initiated and can propagate so long as it is supplied with fuel and oxidizer. Propellant mixture is supplied from one end of the channel by micro-nozzle injectors and open on the other end to exhaust the hot products that supply thrust or energy for power generation.

The RDE was first conceived in 1958 by Voitsekhovskii [2] after shock-flame coupling studies in Europe in the 1940s [3]. The United States closely followed in the development of the RDE in the 1960s with their observations of detonation phenomena as transverse combustion instabilities in rocket motors [4–6], eventually lending to detonation-based engines for propulsion. The development and investigations into the RDE fell out of research with the advancement of the conventional Brayton Cycle gas turbine engine, only recently resurging. Given its original

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discovery and application to rocket propulsion in the United States, contemporary research has continued to align with the use of the RDE in rocket propulsion.

Comprehensive investigations into the RDE for rocket application have been led by the Air Force Research Laboratory (AFRL) in a directive to produce and flight-test a Rotating Detonation Rocket Engine (RDRE) by 2025. Hence, the development of the 3-inch diameter Distribution-A RDRE, produced by AFRL [7], depicted in Figure 1. In a collaborative effort across numerous universities and research facilities, this RDRE configuration was distributed and tested for operational metrics in chamber dynamics, detonation wave characteristics, and thrust production. Not only would this testing facilitate the design iteration of the RDRE for its flight-test readiness, but the data from this testing would be disseminated as experimental boundary conditions to the RDE modeling community through a series of Modeling Validation for Propulsion (MVP) workshops, led by the simulation team at AFRL [8].

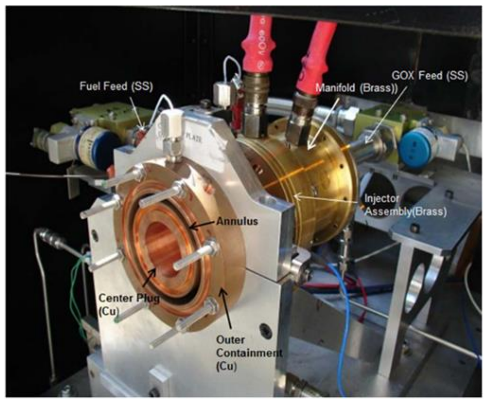

Fig. 1 AFRL Distribution-A Rotating Detonation Rocket Engine, at Edwards Air Force Base [9].

The University of Central Florida (UCF) was one of the universities to work with AFRL in the Distribution-A RDRE testing, having developed a similar architecture to the AFRL Distribution-A, and thus had specifically designed a small-scale thrust stand to gather thrust and impulse data in this collaborative effort. The UCF thrust stand design was unique for its size, its means of measuring thrust, and its capability for an automated self-calibration procedure for its load cell. This design was quite different than the conventional strain gauge sled design usually employed for RDE testing [10,11] and engine-mounted applications [12,13], amidst other more unique kinematic-based traversing sled designs [14]. The purpose of this paper is to explain the design process and motivations for the UCF thrust stand, along with demonstrating its capabilities through experimental data.

II. Experimental Methods

Design Motivations

The thrust stand was designed with numerous objectives in mind, largely motivated by the testing of a small-scale 3-inch RDE. With a smaller engine configuration, the ability to discern thrust directly from the engine could be possible by placing a load cell in line, axially with the engine. This would result in more accurate thrust measurements for the engine than compared to a sled design that needs to account for a moment arm acting on the strain gauge. Also, as a result of the smaller engine configuration, the thrust stand could be maneuvered into different orientations, which would be valuable for different fuel injection schemes such as liquid droplet detonations that heavily depend on droplet suspension time in the annulus.

Thrust stands, which utilize load cells or strain gauges, as with all mechanical systems, very quickly fall out of calibration from mechanical fatigue and hardware deformation. For this reason, the accuracy of thrust measurements reduces dramatically over test campaigns without regular calibration. The current, accepted procedures for thrust stand calibration fall into two main categories: the dead weight method [15] and the pendulum impact technique [16], with the cited references providing experimental setups utilizing the respective calibration methods. The dead weight method is the most common method, simply placing known masses on the load cell or strain gauge and developing a calibration curve to map output load cell voltage to force. This method can be incredibly difficult to perform in-situ, often requiring the equipment to be removed from the stand and loaded on a dedicated surface or stand. Not only is this a timely process but can discount some effects on the load cell or strain gauge that arise from the structure and setup of the thrust stand. The second calibration procedure is the pendulum impact technique, which sees a swinging mass that impacts the thrust stand in a way to produce a load, which is matched with a theoretical impact. This technique is not widely used and still requires some adjustment to the thrust stand system in order to run the calibration.

Thus, to facilitate rapid and repeatable calibration, a procedure involving piston loading a secondary load cell was developed. This scheme was modeled after a thrust stand design used at Physical Sciences Inc. for their small-scale RDE testing, a design which also used piston loading as a calibration technique. Essentially, a piston could be actuated with air, providing a force that would be attached to a secondary load cell to determine the output force of the piston. The secondary load cell, or calibration load cell, would then be attached to the RDE via some structural mechanism which would translate the piston load to the primary load cell that directly measures the thrust from the engine, thereby simulating a load from the RDE which could be verified both by the calibration load cell and theoretically from the pressurization of the piston and shaft area.

Experimental Thrust Stand

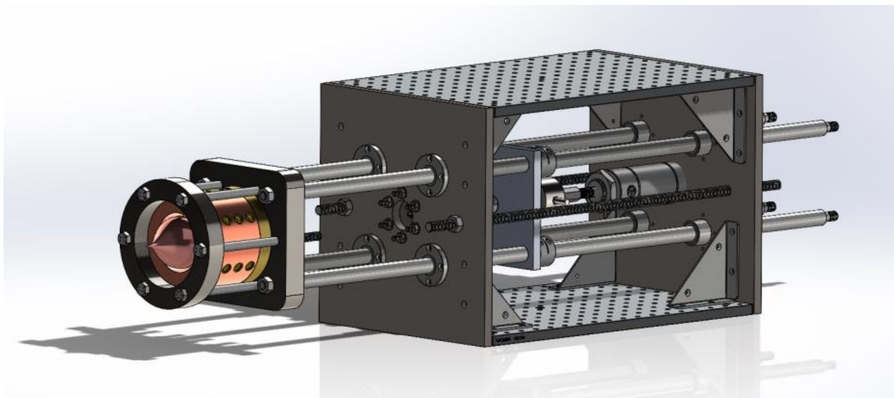

Fig. 2 CAD model of UCF thrust stand design, also showing the mounted Distribution-A RDRE.

Given the design motivations detailed, the UCF thrust stand was developed, pictured in Figure 2. The entirety of the stand, including the mounted engine, falls within the dimensions of 36-in by 12-in by 12-in, making for a relatively small footprint when compared to the engine size, which can be seen at the left of Figure 2. The thrust stand consists of four linear shafts floating along linear ball bearings, one end of the shafts connected to a mounting assembly. While the engine is mounted in place, the plenum is connected to the primary load cell, or data load cell, that is mounted on the backside of the first vertical plate. This subassembly is considered the main thrust section for which the engine thrust is directly measured and output, depicted as the red boxed section in Figure 3. The linear shafts continue to the rear of the stand, but not before holding a floating plate, which connects the linear shafts to the automatic-calibration subassembly (in blue in Figure 3), which include the piston and calibration load cell. A more detailed description of the calibration procedure will be given later.

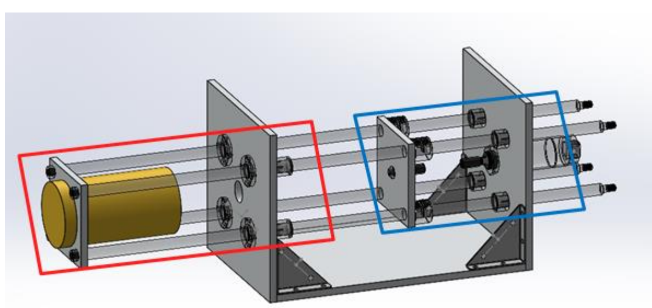

Fig. 3 CAD model of UCF thrust stand design, showing the main thrust section (red) and the automatic-calibration section (blue).

The structural components of the thrust stand are made from 316L stainless steel vertical plates, end-threaded linear shafts, and anodized aluminum base and top plates. Together, with steel corner brackets, the structural assembly is incredibly rigid at all orientations, and capable of supporting its weight under mounting from either the top or bottom plates. An additional pair of steel threaded rods provide support to the stainless-steel vertical plates and a sturdy mounting location should the thrust stand be oriented in the vertical direction. The linear shafts were iterated for their length and thickness in order to accommodate larger RDEs with potentially longer plenums, whilst also being thick enough to reduce bending of the shafts at the linear bearing interfaces, on the order of <0.001-in to ensure that the engine remains mounted in-line with the thrust stand. Combined with a similarly 0.001-in machine tolerance for the placement of the linear shafts and linear bearings, the structure provides a smooth, frictionless traversal system for the engine, and thus a more accurate thrust measurement from the thrust stand.

Not pictured in the CAD model is the associated electronics accompanying both load cells, being discrete mV/V signal amplifiers, low-pass signal conditioners, and a separate 24-V power supply dedicated to the powering of the load cells and paired electronics. For the combination of load cells and the Data Acquisition (DAQ) unit, both the data and calibration load cells will be able to sample at a minimum of 1000-Hz, for what has been currently tested with this thrust stand.

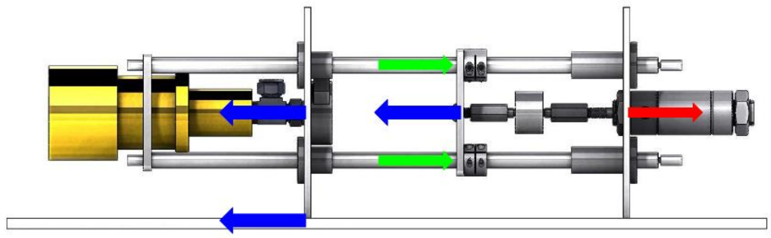

Fig. 4 Showing the UCF thrust stand design with the propagating loads as arrows, being the applied force from the piston (red), the transport forces along the shaft (green), and the reaction forces to the structure and to the data load cell (blue).

As mentioned briefly, the automatic-calibration subassembly consists of a reverse-motion piston that when pressurized with a gas, retracts, and applies a load through the calibration load cell and bolt that are attached to the piston shaft. The calibration load cell measures the applied load, and the bolt pulls on a plate that distributes the piston load to all four linear shafts, which in turn pull on the mounted engine, thereby producing a simulated load on the main data load cell attached behind the engine. Thus, a load can be simulated on the data load cell in-situ and from a variable, controllable source, altogether shown in Figure 4.

An advantage to the piston loading calibration is that the calibration procedure can be automated, such that the pressurization and therefore the applied load can be ramped up and ramped down at intervals through a series of solenoid actuators and vents. A detailed set of calibration points can be successively attained, thereby providing a more detailed or specific calibration from voltage output to force input, shown in Figure 5. By automating the process of pressurizing the piston, a calibration can be achieved for the data load cell before every test fire with no hardware modifications, costing less than a minute of time before each engine test fire.

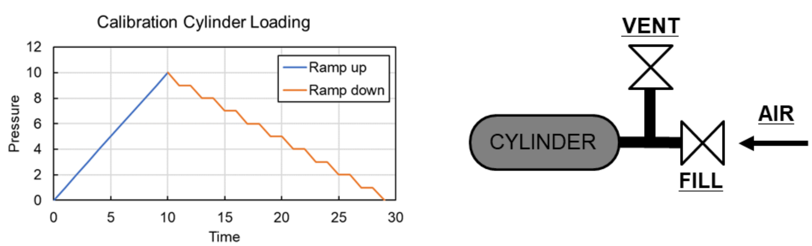

Fig. 5 Calibration procedure example, showing the pressure to the piston, which applies a force to the load cells, and the procedure of ramping up and down the pressure to encompass a loading regime.

The thrust stand was developed for use of testing the UCF 3-in RDRE developed by CREARE, based on the AFRL Distribution-A 3-in diameter RDRE; however, the thrust stand was designed to be modular in the engines that could be mounted. As a result, two major test campaigns will be explained, with its results presented here, both in order to validate the thrust measurements from this stand and to demonstrate the viability of this thrust stand in an experimental campaign.

III. Results

Nozzle Swirl Attenuation Tests

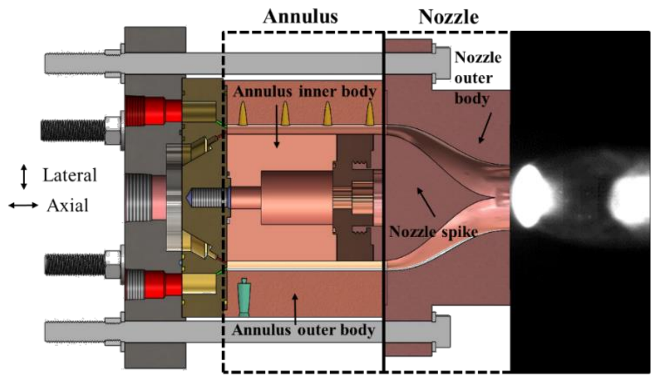

Fig. 6 CREARE 3-in RDRE configuration, with nozzle attachment, showing the nozzle outer body and nozzle interior spike.

This 3-inch RDRE configuration, shown in Figure 6, was developed between UCF and CREARE prior to the primary Distribution-A MVP efforts. This configuration was used to test a number of key RDE topics, such as gaseous hydrogen and oxygen detonations in the RDE [17] and exhaust swirl attenuation by a 5th-order polynomial converging spike nozzle [18,19]. For the purpose of this paper, the latter topic was further investigated. Previous research, cited above, utilized numerical frequency and PIV methodology from side-end and back-end imaging to determine the effect of the nozzle on the swirl of the exhaust. However, this current research used the thrust measured from the thrust stand as a metric for exhaust attenuation, such that higher thrust is indicative of lateral swirl being forced into the axial direction. The nozzle was tested under three configurations: (1) Baseline with no nozzle, (2) Nozzle with no interior spike, and (3) Nozzle with interior spike. The nozzle was tested for the RDRE operating at semi-nominal flow conditions for the hardware, being 0.53 lbm/s total mass flow rate at 1.11 fuel-air equivalence ratio of gaseous methane and oxygen.

As mentioned in the previous section, the thrust stand was calibrated using the piston calibration assembly. The data load cell did not need to be removed during this calibration procedure, which involved pressurizing the piston for a range of pressures and thus applied loads to the stand. Up to five cycles of pressurizing and measuring loads were possible in one minute, allowing for a rapid data set of 100,000s of voltage-load points over the full range of the data load cell. Figure 7 shows such a calibration that was rapidly achieved in under a minute before a set of 12 hot-fire tests, also showing the post-test set calibration. Not only are the similar pre- and post-test calibrations proving the longevity of the system architecture over numerous test fires, but these calibrations were taken with no modifications to the system. It is entirely possible for the calibration procedure to be fully automated into a test campaign, calibrating the thrust stand before each hot-fire test, which is the intended use of this type of automatic calibration setup.

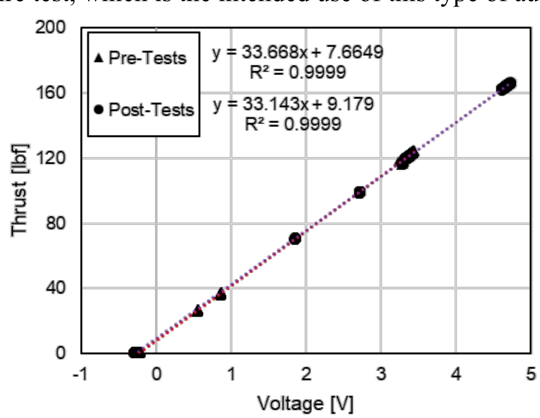

Fig. 7 Pre- and Post-test thrust stand calibrations over a range of loads applied to the data load cell.

The three nozzle configurations were tested for repeatability and precision over the same flow condition. The baseline, no nozzle configuration performed as expected, generating some thrust from the natural lateral relief of the detonation waves. Also as expected, with the addition of the outer nozzle, with no interior spike, the thrust increased by approximately 20-lbf now that the annular combustion chamber was converged down to a single throat. With the addition of the interior spike, there was a slight 5-lbf increase in thrust. The potential explanation for this is that the spike fills up a large recirculatory region that would be present at the inner body, thus reducing pressure loss and flow quality.

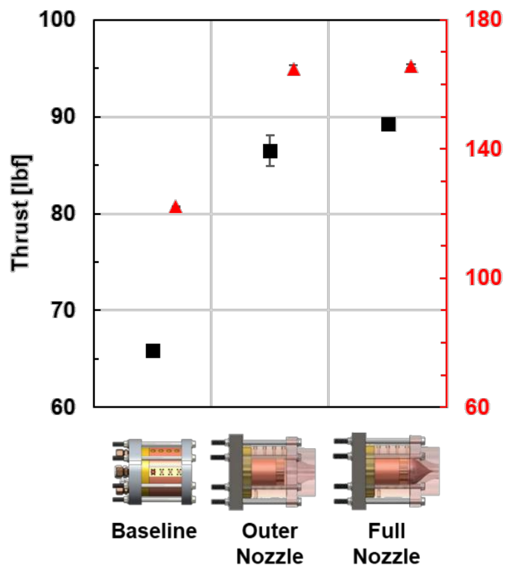

Fig. 8 Thrust and specific impulse results from the three nozzle configurations.

With regards to the attenuation of the lateral swirl from the nozzle, it is still unclear. There seems to be a slight increase in performance with the nozzle and interior spike utilized; however, visual access into the flow is difficult with the nature of this type of nozzle. Some evidence of the swirling flow coming from the RDRE can be seen in the exhaust of the nozzle but is very difficult to confidently realize. What can be said is that the flow quality of the exhaust seems to have steadied out spatially and temporally with the addition of the nozzle, proving that the chaotic, swirling flow of an RDE can be choked down to a singular throat with relatively uniform flow.

IV. Conclusion

The RDE started as an idea stemming from rocket motor combustion instabilities and continued to grow in the rocket engine propulsion sector. As calls to push the RDE for rocket application increased, in a technology coined as the RDRE, efforts have been made experimentally on the behalf of preparation for flight demonstration and as conditions for the modeling community. Being a propulsion-based technology, the thrust of the RDRE is a key metric to the experimental testing. Therefore, a thrust stand was developed at the University of Central Florida, motivated by systems at AFRL and at Physical Sciences Inc. This thrust stand utilized the small-scale of the RDRE as motivation for an axial-loading measurement configuration and an automatic-calibration subassembly, which together could produce high-fidelity thrust measurements, validated, and further applied to key RDE operation research.

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