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

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1 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], 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 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 [5]. 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 [6].

The University of Central Florida (UCF) was one of the universities to work with AFRL in the Distribution-A RDRE testing, and thus had specifically designed a small-scale thrust test stand (TTS) to gather thrust and impulse data in this collaborative effort. The UCF TTS 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 [7] and engine-mounted applications [8], amidst other more unique kinematic-based traversing sled designs [9]. The purpose of this paper is to explain the design process and motivations for the UCF TTS, along with demonstrating its capabilities in small-scale engine facilities.

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2 Methods

The TTS 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 TTS 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.

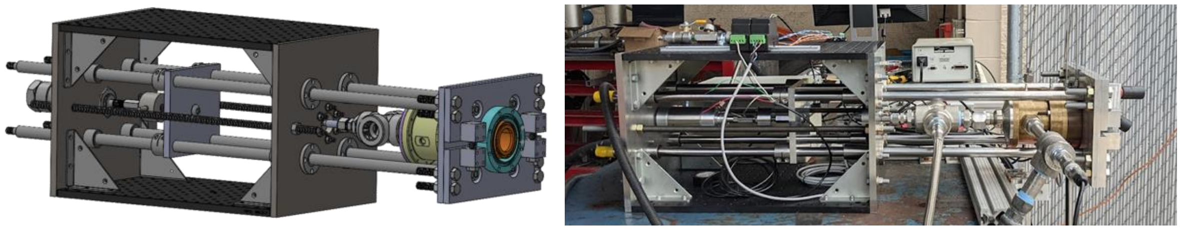

Figure 1: CAD model of the Thrust Test Stand (TTS) with Distribution-A 3-inch RDRE from AFRL (left). Image of TTS before hot-fire operation, including peripheral electronics (right).

Thrust stands, which utilize load cells or strain gauges, very quickly fall out of calibration from mechanical fatigue and hardware deformation. For this reason, the accuracy of thrust measurements reduce dramatically over test campaigns without regular calibration. The current, accepted procedures for TTS calibration fall into two main categories: the dead weight method [10] and the pendulum impact technique [11], with the cited references providing experimental setups utilizing the respective calibration methods. However, all of these methods involve a lengthy and cumbersome setup and testing process. Thus, to facilitate rapid and repeatable calibration, a procedure involving piston loading a secondary load cell was developed.

This scheme was modeled after a TTS 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 a floating structure 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.

Figure 2: Image of TTS hot-fire operation, showing exhaust plume.

Given the design motivations detailed, the UCF TTS was developed and tesetd, shown 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 TTS consists of four linear shafts floating along linear ball bearings, one end of the shafts connected to a mounting assembly, which in the configuration above consists of a clamping mechanism for mounting the AFRL Distribution-A RDRE to the stand. 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. Linear shafts continue to the rear of the stand, holding a floating plate, which connects the data load cell to the automatic-calibration subassembly which includes the piston and calibration load cell.

The structural components of the TTS 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 TTS 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 (30-µm) to ensure that the engine remains mounted in-line with the TTS. Combined with a similarly 0.001-in (30-µm) 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 TTS.

The associated electronics accompanying both load cells includes 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, which is the sampling rate currently being tested.

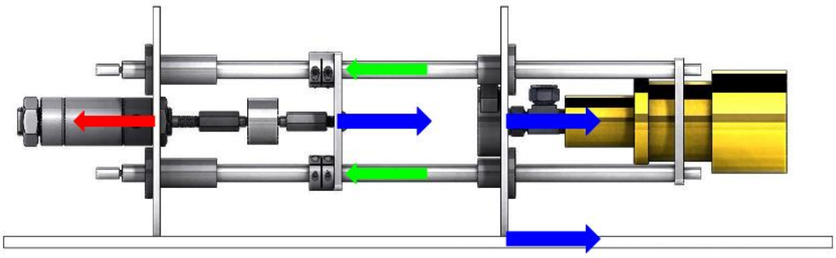

Figure 3: Loading diagram of the UCF TTS with the propagating loads as arrows: the applied force from the piston (red), the transport forces along the shaft (green), and the reaction forces to the structure and to the data load cell (blue).

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 3.

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 4. 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.

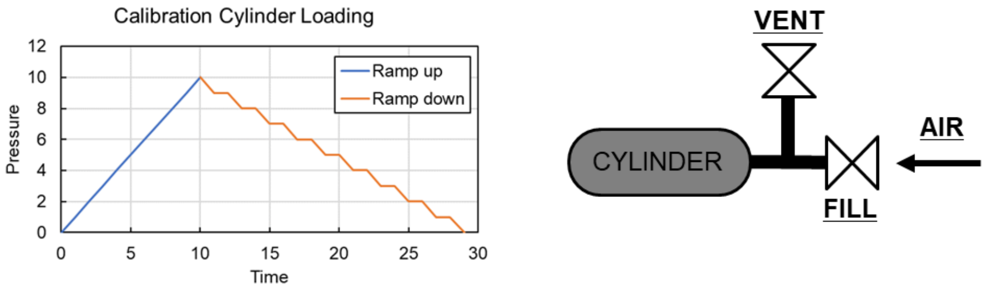

Figure 4: Calibration procedure example, showing the pressure to the piston, which applies a force to the load cells, and the procedure of ramping up and down the pressure to encompass a loading regime.

3 Results

The TTS was developed for use of testing the AFRL Distribution-A 3-in diameter RDRE; however, the TTS was designed to be modular in the engines that could be mounted. Another 3-inch RDRE configuration, shown in Figure 5, was developed between AFRL and UCF 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 [12] and exhaust swirl attenuation by a 5th-order polynomial converging spike nozzle [13], [14]. Previous research for the latter 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. Current research uses the thrust measured from the TTS as a metric for exhaust attenuation, such that higher thrust is indicative of lateral swirl being forced into the axial direction, shown in Figure 5 with a sample of this thrust data. Given that this hardware is still being used for other research efforts, only a small piece of this data can be shown at this time.

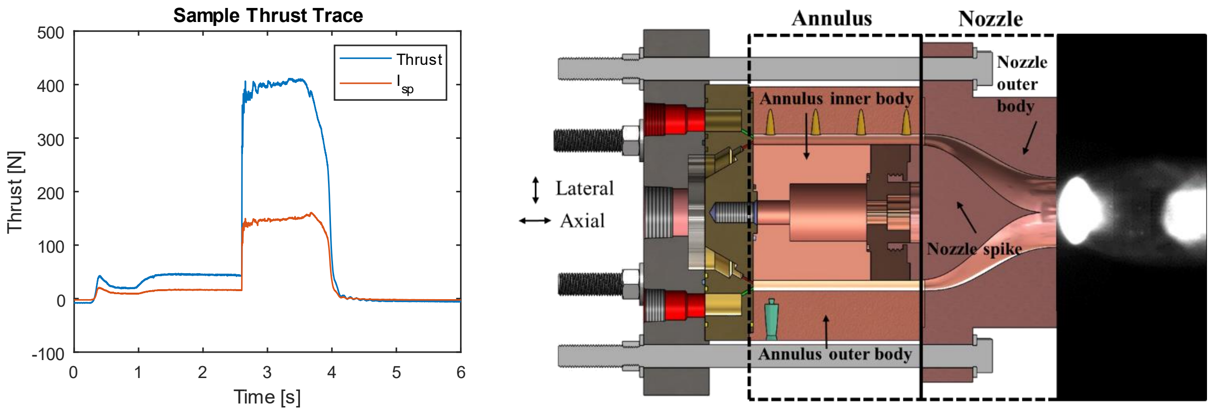

Figure 5: CREARE 3-in RDRE configuration (right), with nozzle attachment, showing the nozzle outer body and nozzle interior spike; Sample thrust measurements (left).

Onto the AFRL Distribution-A 3-in diameter RDRE, the RDRE configuration tested was a part of the MVP workshop initiative, and thus is connected to a dataset of identical testing at collaborative universities and research laboratories with this same RDRE hardware. Thus, the thrust measurements in this testing can be directly compared to measurements taken at Purdue University and AFRL Edwards Air Force Base, both as a form of validation and to further compliment the data to be disseminated to the modeling community, for the purpose of the MVP efforts.

All components of the RDRE TTS were fabricated using third-party machining services and assembled at UCF. The TTS was interfaced with a robust support structure capable of transferring the primary RDRE thrust load to the ground, resulting in a static-test fire configuration. Loading occurs in two modes:

calibration and hot-fire. For all hot-fire test campaigns, the RDRE is integrated with the TTS and a calibration procedure is performed on the TTS to prepare the system for hot-fire.

Regarding the calibration procedure, it is performed on the TTS at the beginning, middle, and end of every day for each test campaign and is summarized as follows: Load-cell calibration is performed first at the start of every testing-day to verify both data and calibration load cells function nominally as expected. Any unknown electrical or mechanical issues that may have affected the loading mechanism of the TTS between the previous test campaign and the calibration step are captured, diagnosed, and mitigated at this point. For the calibration, the piston is pressurized to approximately 50-psi (345-kPa) which correlates to approximately 110-lbf (500-N) directed onto the calibration load cell. At this time, the load from both the calibration load cell and the data load cell are recorded, during which the piston is slowly vented to a lower pressure. Figure 6 shows the piston chamber pressure and the calibration load cell reading during the venting process, along with the linear curve fit of the load data. With the corresponding calibration load cell data, the data load cell readings are adjusted to match, thus calibrating the data load cell. This is repeated for up to 10 times, to ensure consistent calibration fits. After calibration is complete and the loading mechanism is verified to function as required, the TTS is configured for hot-fire loading. The calibration load cell is mechanically uncoupled from the RDRE thrust by the removal of a coupling nut, which fastens the calibration load cell to the thrust plate. The data load cell remains in-line with the RDRE thrust, and the system is configured for hot-fire.

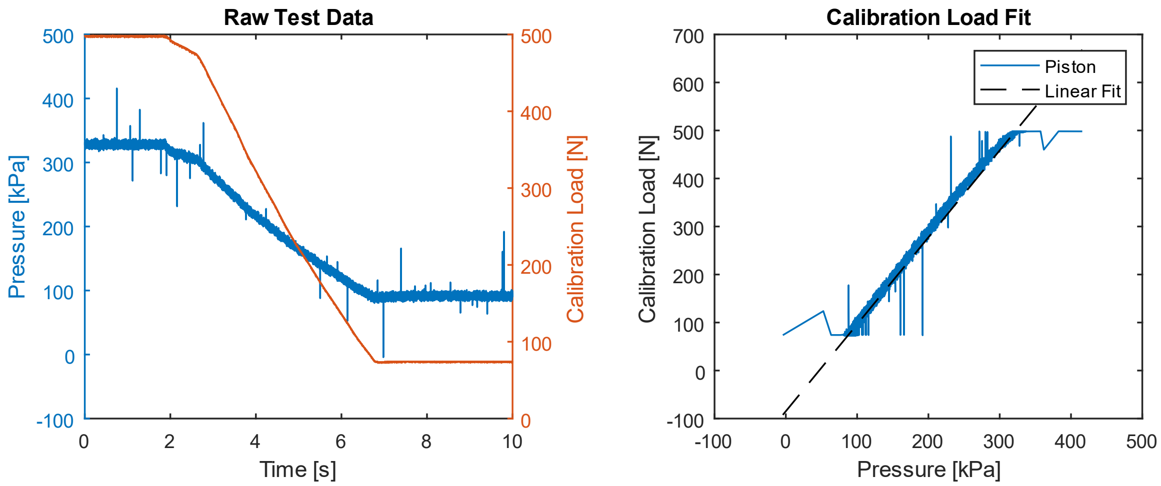

Figure 6: Piston pressure versus calibration load (left). Calibration loads are then fitted (right), with the linear fit becoming the correction for the data load cell readings.

Thus far, 55 hot-fire campaigns have been performed using the TTS, all of which successfully measured thrust data of the fired RDRE. These thrust results have been compared to sled-design systems at AFRL and Purdue University, which differences between loads by less than 5%.

4 Conclusion

As calls to push the RDRE for rocket application have increased, efforts have been made experimentally to bring the RDRE to flight readiness. Being a propulsion-based technology, the thrust of the RDRE is a key metric to the experimental testing. Therefore, a TTS was developed at the University of Central Florida, motivated by systems at AFRL and at Physical Sciences Inc. This TTS 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 RDRE operation research.

Acknowledgements

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