Study of Rotating Detonation Combustor Dynamics During Changes in Operating Mode

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1 Introduction

The rotating detonation engine/combustor (RDE/RDC) has been extensively studied in recent years due to its relative simplicity, compactness, and the potential for efficiency and performance improvements when compared to conventional deflagration-based combustors. A variety of configurations have demonstrated successful operation and many performance metrics have been developed to characterize their function and feasibility [1]. Conventional RDC performance analysis typically focuses upon directly measurable quantities such as observed wave speed, pressure rise associated with the wave(s) within the channel, or produced thrust and overall end-to-end pressure gain of the device. Although laboratory testing of these devices is typically limited to short durations of a few seconds, these short sequences can include thousands of cycles across which the mode of operation can significantly vary.

The "mode of operation" of an RDC is a simplified description of the reaction occurring within the combustor. This can include rotational operation with a discrete number of waves that propagate in one or both directions. This mode of operation is that typically associated with an RDC and is the source of the acronym "RDC." However, RDCs can also exhibit off-nominal characteristics in which rotational operation is not observed and deflagrative combustion and/or a longitudinal pulsing mode is present. The points at which the characteristics of operation change, either through changing between rotational, longitudinal, and deflagrative modes, or in which the number of waves or wave direction changes while remaining within a rotational mode are commonly referred to as mode/modal changes [2, 3].

Although an operating RDC can reach a quasi-steady condition in which one or more reaction fronts continually propagate with properties and modes that have little variability from cycle-to-cycle, the processes that sustain the operation of the device are inherently unsteady. The continually propagating wave(s) or wave system(s) may exhibit quasi-steady characteristics but ignition events, operating mode changes, variations in inlet conditions, or other unknown factors can cause the dynamics of the wave system(s) to change in a variety of ways. For example, RDC ignition and initiation has been previously studied by Fotia *et al.* [4] and Ma *et al.* [5], though these studies did not focus on inter-cycle and individual cycle-to-cycle variations outside of the initial ignition and stabilization periods.

Anand *et al.* [6] investigated wave multiplicity by analyzing the conditions under which the number of co-rotating waves within an RDC changed. Their focus was on identifying the conditions that establish the number of waves for particular conditions of operation, rather than investigating the characteristics, conditions, and mechanisms that are responsible for the switching between different directions of

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rotation or number of waves (e.g., switching between 2 and 3 co-rotating waves) during operation at nominally constant inlet conditions. This present study differs from many of the previous studies in that it focuses on wave directionality and number changes during operation after the initial ignition transient and while inlet conditions are nominally held constant.

Thus, the goal of this work is to investigate how changes in operation occur during quasi-steady periods and determine if any quantifiable differences can be attributed to these changes through the analysis of high-speed pressure and chemiluminescence emission measurements of the wave system within an RDC obtained through high-speed video taken aft-looking-forward normal to the exhaust plane. The Circuit Wave Analysis (CWA) methodology [7] developed previously is leveraged to perform targeted analysis during periods in which the mode of operation changes. This research will specifically focus on the consequences of rapid wave directionality changes.

The CWA method produces measures of wave characteristics such as wave direction, velocity, and relative strength (based on the emission intensity) averaged over a small number of cycles (seven cycles for the present study). Thus, it is used to identify the time periods of interest and characterize wave properties before and after mode changes. These periods of interest are then further analyzed using space-time ($x - t$) diagrams generated from the high-speed videos overlaid upon high-speed pressure traces to quantify changes in operation. Although the timescale of mode change can vastly vary from (essentially) instantaneous to hundreds of cycles, in this study we specifically focus on operation mode changes that occur on timescales that are on the order of a single rotational cycle. These changes are on a sufficiently fast timescale that they can be assumed to be due to internal RDC dynamics associated with the wave system(s) rather then events associated with external influences.

2 Experimental Setup

The annular RDC configuration utilized for all tests in this study was that of an axial air inlet with rear-facing angled fuel injection similar to that previously outlined by Shepard *et al.* [8]. The facility arrangement and control system were unchanged from what previously presented. This configuration consists of a variable area axial air inlet with 120 discrete fuel injectors issuing into a 105 mm long channel (measured from the fuel injector holes to the exhaust plane). All experiments were conducted with ambient temperature air and hydrogen mixtures. Data presented in this work were from tests conducted at an air inlet area corresponding to an approximate area ratio (AR = $A_{\text{exhaust}}/A_{\text{inlet}}$) of 5. The channel configuration is such that the inner wall is smoothly contoured from the minimum area throat of the inlet to the constant area portion of the channel at which the channel inner diameter is 121.4 mm and outer diameter is 152 mm, with a resultant 15.2 mm channel width. A convergent nozzle was installed at the channel exhaust with an approximately 47% area restriction relative to the maximum cross-sectional channel area. A basic schematic of the RDC flowpath with sensor locations is shown in Figure 1.

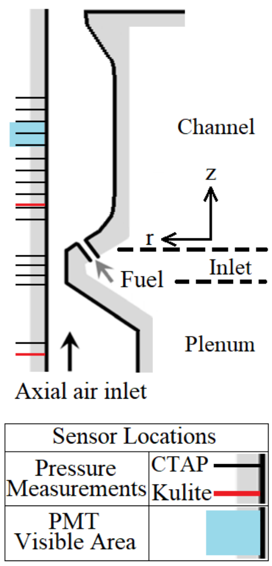

Figure 1: Simplified schematic view of RDC flowpath used in this study.

Initiation was accomplished through two means. A hydrogen-air afterburner was continuously operated throughout the entirety of the fuel-on portion for each test, acting as both a mode of initiation through flashback and as a safety feature to prevent flow of unburnt fuel through the facility exhaust system. Additionally, a hydrogen-oxygen pre-detonator was fired at 7 Hz for the first half-second following the fuel-on command.

In addition to low-speed (200 Hz sample rate) Capillary Tube Averaged Pressure (CTAP) measurements at various axial locations, high-speed (500 kHz sample rate) Kulite pressure transducers were installed 15 mm downstream of the fuel injectors within the detonation channel and within the air feed plenum. A photo-multiplier tube (PMT) was installed with a 320 ± 10 nm optical filter to observe OH* chemiluminescence emission within the channel. The PMT measurements were taken at a 90^o azimuthal offset from the high-speed pressure transducers and at an axial location 20 mm downstream. The combustor annulus was imaged aft-looking-forward through a fused quartz window installed in the facility exhaust duct with a Phantom TMX camera mounted 2 m from the RDC exhaust plane. A viewable area of 512 x 512 pixels captured the entirety of the RDC channel, and video was collected at 50k-80k frames per second during the entirety of the fuel-on portion of each test. Observations based upon analysis of the chemiluminescence emission associated with the detonation wave(s) captured on the high-speed videos in combination with pressure time-histories from the high-speed pressure transducers (in both the channel and air plenum) are the focus of this work.

3 Conditions and Modes of Operation

A variety of operating modes have been identified in this RDC configuration in our prior studies [8]. These modes include (1) a purely deflagrative mode, (2) a longitudinal pulsing mode, (3) rotational modes in which one or more continuously propagating and possibly competing waves are present, and (4) hybrid modes in which multiple of the other modes are observed to compete and repeatedly alternate (over different timescales) throughout the course of one test sequence. This work is focused on the rotational mode of operation and changes that occur within individual test cases conducted at constant inlet conditions. Because changes between pulsing and rotational modes were observed to occur on timescales significantly longer than that of a typical rotational cycle, presently it is difficult to determine if these hybrid modes are induced by dynamics of small-scale process associated with the detonation or if they are due to large-scale ones, such as detonation quenching/re-initiation supported by the continuously operated afterburner, or macroscopic disruption of the inlet or exhaust flow as a consequence of the detonation wave dynamics. As such, the focus of this work is on mode changing that occurs on sufficiently short timescales (on the order of one cycle/rotation) and that are assumed to be due to local dynamics associated with small-scale processes of the detonation.

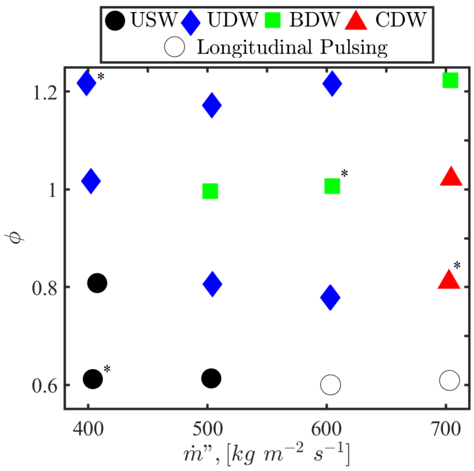

Figure 2: Summary of operating conditions considered and identified modes of operation. Examples used in later analysis identified.

Data from a subset of tests encompassing sweeps in inlet air mass flux and equivalence ratio is analyzed for this study, with the conditions summarized in Figure 2. These sweeps include tests that exhibit the previously outlined longitudinal pulsing mode (2) and multiple sub-modes of rotational operation (3). The four distinct sub-modes of rotational operation observed are defined as follows: (A) uni-directional single-wave operation (USW), (B) steady operation with a uni-directional dominant wave and weak counter-rotating wave (UDW), (C) bi-directional operation in which the dominant wave and weak counter-rotating wave alternate directionality for significant and distinct time periods (BDW), and (D) chaotic operation in which the dominant wave direction is constantly alternating and does not persist in one direction for significant time periods (CDW).

4 Results

Utilizing the optical chemiluminescence observed in the high-speed videos taken for all test cases, $x - t$ diagrams are generated. These $x - t$ diagrams are used to characterize the wave(s) within the channel and determine their position and relative strength based upon local signal intensity. These diagrams are generated by segmenting the viewable area of the RDC exhaust into $N_{\mathrm{B}} = 101$ azimuthal bins and determining the average signal intensity within these bins for each frame. An example diagram is shown in Figure 3 in which steady single wave operation can be observed, this case was conducted at an inlet air mass flux of $400\ \mathrm{kg\ m^{-2}\ s^{-1}}$ and equivalence ratio of $\phi = 0.6$. The CWA methodology uses these $x - t$ diagrams to determine the characteristics of the wave(s) within the RDC. For details, see Chacon *et al.* [7].

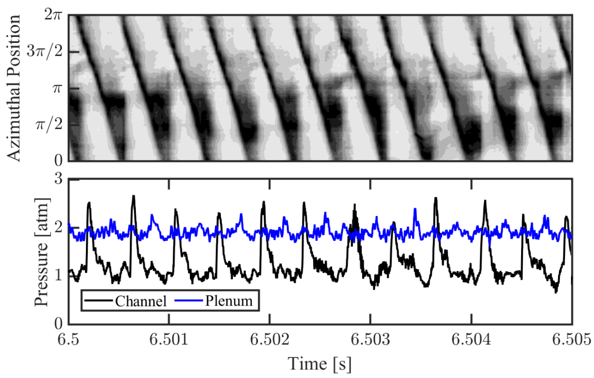

Figure 3: Example (top) $x - t$ diagram and (bottom) pressure time-history illustrating steady single-wave operation. Test condition $\dot{m}'' = 400\ \mathrm{kg\ m^{-2}\ s^{-1}}$, $\phi = 0.6$.

CWA results from four cases exhibiting the previously outlined modes of operation are shown in Figure 4, with key features identified. In these plots the markers represent observed waves, with $\log(S)$ representing the relative strength of the wave(s) defined by the observed emission intensity and v/D_{CJ} representing the wave speed relative to an ideal Chapman-Jouguet detonation evaluated at the global equivalence ratio. The sign of v/D_{CJ} indicates the directionality. The USW case shows a single wave with limited indications of any counter-rotating waves. The UDW case clearly shows a continually present weak counter-rotating wave, with the dominant wave continuing in the same direction throughout the course of the test. The BDW case again shows the presence of a (weaker) counter-rotating wave, but the direction of the dominant wave is seen to change multiple times for discrete periods throughout the course of the test. The CDW case is characterized by a pair of counter-rotating waves of relatively similar intensity that do not indicate discrete time periods in which the wave propagating in either of the direction is significantly and consistently identified as stronger. It is also worth noting that as suggested by the spreading of the measured rotational speed v/D_{CJ}, change in operation from USW to UDW, BDW and CDW can result in an increase in cycle-to-cycle variation of the wave speed.

The BDW and CDW cases are unique in that there are clear deviations in the mode of operation with no identifiable causes or leading indicators that would explain the mode changes. Run conditions were held constant throughout, and no changes in system level behavior were observed that would explain the cause of or result from the switch in dominant wave directionality. This can be observed in Figure 5. These represent phase averages of the pressure and PMT data (top) and the probability density functions (PDFs) of measurable quantities (bottom) obtained during various points throughout each test case of Figures 2 & 4. The measurable quantities were referenced to ideal CJ conditions for wave speed and channel pressure rise, and to a constant 2 atm for observed pressure rise within the plenum. This constant does not have a physical meaning but was chosen to place all distributions on the same scale. For the USW & UDW cases operation was segmented into three discrete 0.5 second periods to generate the curves and statistics shown, with little variation observed throughout the course of each test. For the BDW case the time periods of (+/-) dominant wave directionality correspond to the discrete periods identified in Figure 4. For the CDW case the $x - t$ diagrams and CWA results were used to identify four short-duration windows (in each direction) in which greater than five consecutive cycles of constant dominant wave directionality could be identified which were then used to generate the phase average

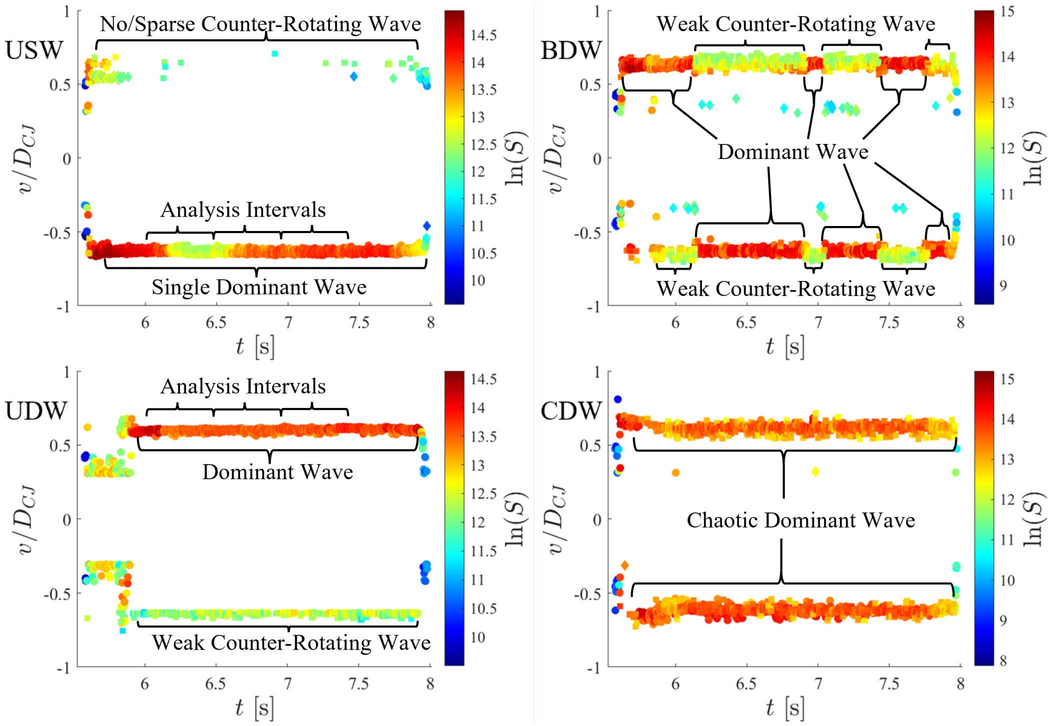

Figure 4: Time-history of wave properties evaluated with CWA demonstrating the four modes of rotational operation identified in the study, starred cases of Figure 2: (top, left) USW; (bottom, left) UDW; (top, right) BDW; and (bottom, right) CDW.

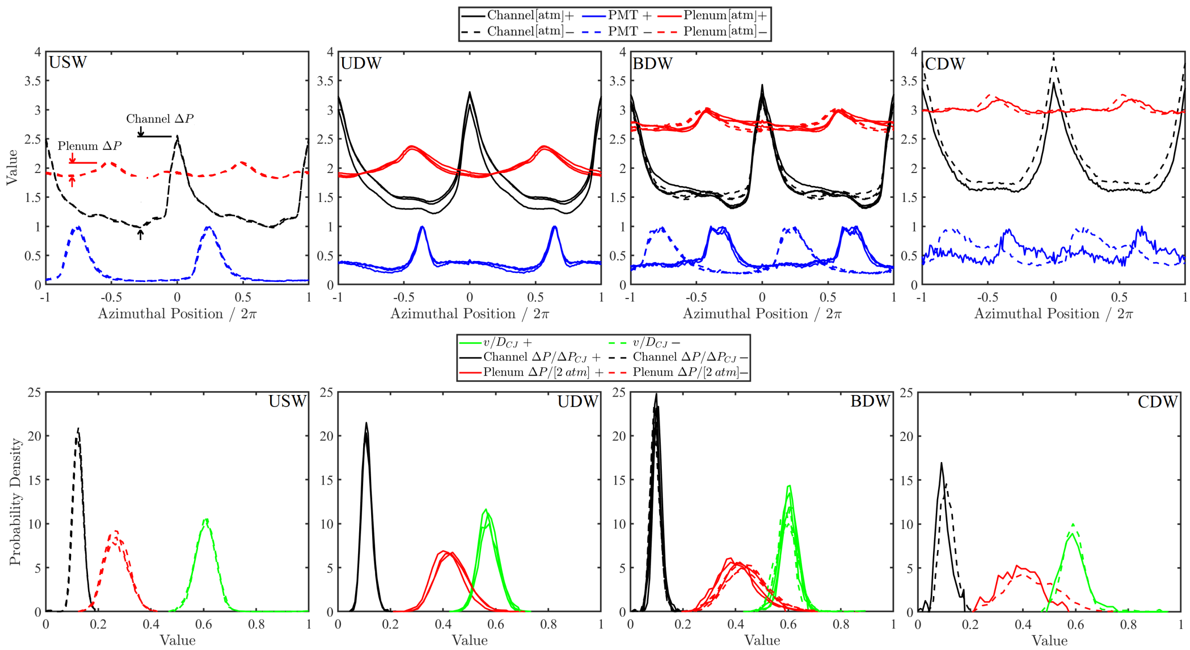

Figure 5: Phase-average pressure and PMT profiles (Top) and PDFs of measurable quantities (Bottom) during identified modes of operation. Cases of Figures 2 & 4 from left-to-right: USW, UDW, BDW, CDW. Solid (dash) lines indicate wave rotating in the clock-wise (counter-clock-wise) direction.

profiles and statistics. As these periods only result in a total of 51 (+) and 266 (-) cycles for analysis the probability densities are considerably less smooth than the other operating modes in which statistics were based only larger sample sizes.

All examples indicate minimal deviations in the average pressure and PMT profiles and in the wave speed and pressure rise observed in both the channel and plenum throughout the course of each individual test, and the BDW and CDW modes similarly indicate minimal deviations in these quantities when the dominant wave changes direction. The BDW example shows minimal differences despite the multiple directional changes, while the CDW case also shows minimal differences in the brief periods in the dominant wave maintains constant directionality for 5 cycles.

5 Conclusions

Within a subset of data obtained within a previously studied RDC configuration four modes of rotational operation have been identified and described. They include two modes in which the dominant wave continually propagates in one direction, representing cases with (UDW) and without a consistent counter-rotating wave (USW). The other two modes include counter-rotating waves, with directional changes of the dominant wave occurring on discrete (BDW) and continuous (CDW) intervals.

Analysis of the bi-directional dominant wave and chaotic dominant wave modes of operation indicate that the characteristics associated with the dominant wave do not show significant variation with changes in direction. No cause for the changes in direction has been identified, but this analysis also indicates that there is no measurable impact on the characteristics of the dominant wave that results from directionality changes. This observation seems to hold irrespective of the number of directional / relative strength changes that occur throughout the course of a single continuous test. Further work is ongoing to attempt to determine possible causes for this behavior.

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