On the Presence of Inhomogeneous Co-Rotating Detonation Waves in a Rotating Detonation Combustor

Alexander Feleo and Mirko Gamba
University of Michigan
Ann Arbor, MI, U.S.A.

1 Introduction

Detonation combustion is attractive over the typical deflagration combustion as a means to increase the thermal efficiency of a combined thermodynamic cycle. The increase in static pressure across the detonation wave front prior to the chemical reactions reduces the entropy generation for the same amount of heat release. Thus, more work or thrust can be extracted for the same amount of fuel input, thereby significantly reducing fuel consumption. Much of the current research on detonation-based devices is focused on rotating detonation engines/combustors (RDEs/RDCs). The standard RDC geometry is a cylindrical annulus where the bulk fluid motion is axial while the detonation wave propagates continuously and periodically in the circumferential direction. The geometry, while simple, is designed to promote these circumferential waves and the resulting flow-field can be quite complex. In particular, multiple waves can coexist simultaneously in the system which will be the focus of this work.

Multiple detonation waves can arise depending on the geometric configuration and the operating condition tested, with the number, direction, and speed of the wave(s) depending on the specific operating conditions [1–3]. These waves can either be co-rotating or counter-rotating, and their propagation can be stable in that the same operation can occur for prolonged periods [2, 3]. The addition of an exit constriction on the annulus generally leads to an increase in the number of detonation wave(s) (i.e., multiplicity), which is theorized to be due to the reflection of the downstream propagating oblique wave reflections off the nozzle [4]. Likewise, changing the combustor length while having an exit constriction leads to a change in the multiplicity [5]. The co-rotating waves must maintain nearly identical speeds, otherwise, a modal transition will occur where one wave is overtaken by another and is consumed [6]. At this point, the physical mechanism that dictates the number of detonation waves is unknown, although several explanations have been put forth as documented by Anand and Gutmark [3]. In addition to the primary detonation wave(s), finite-strength waves traveling at slower speeds than the detonation wave(s), referred to as secondary waves, have been also been observed [7, 8]. Secondary waves travel counter to the detonation wave and a non-linear interaction occurs when they intersect the detonation wave, leading to a momentary change in detonation structure that results in an increase in pressure and likely reduced heat release rate. Although they are typically weaker and near acoustic speeds, chemical reactions support their propagation similar to the primary detonation wave(s) [7]. Thus, they appear to be the weak limit of counter-propagating detonation wave(s) and are differentiated due to their lower pressure rise. The overarching goal of this work is to demonstrate that detonation waves can co-rotate

Correspondence to: afeleo@umich.edu

simultaneously at the same speed, but with different pressure increases and that this operation is independent of the presence of secondary waves. Additionally, it is found that the lower-pressure detonation wave causes a loss in performance compared to the case where the two waves are identical.

2 Experimental Setup

A simplified representation of the tested RDC is shown in Figure 1. A description of the injection and outlet geometry can be found in previous work [5,9]. The nozzle exit area is 50% of that of the detonation channel. A variety of H_2/air operating conditions are tested in this work. The air mass flux, as defined by the inlet throat ($\dot{m}''_{\mathrm{a}} = \dot{m}_{\mathrm{a}}/A_{3.1}$), ranged from 190 to 650 $\mathrm{kg\ s^{-1}\ m^{-2}}$. Meanwhile, the equivalence ratio (ϕ) ranged from 0.6 to 1.2. Sustained rotating detonative operation was achieved for all tests [5].

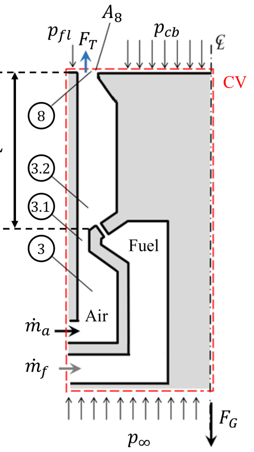


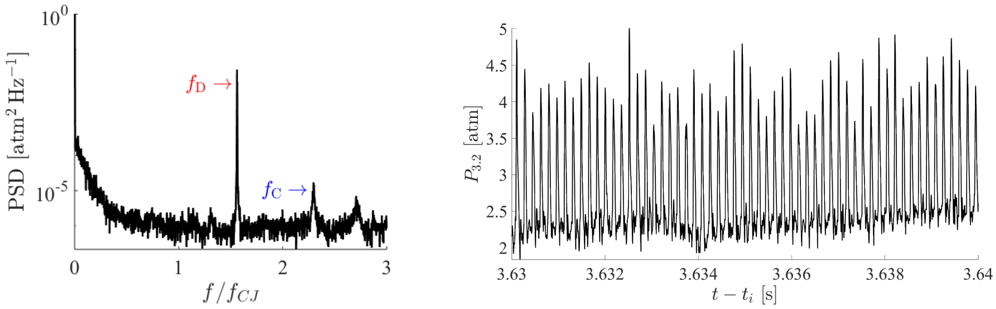
Figure 1: Schematic diagram of RDC geometry along with definition of geometric stations.

Pressure measurements and video are used in conjunction to characterize operational modes and wave dynamics of the system [7]. Water-cooled, high-speed pressure transducers, Kulite EWCTV-312-500A, were flush-mounted along the outer wall of the RDC to take measurements within the detonation channel with a sampling frequency of 500 kHz. A Phantom TMX 5010 recorded the video of the entire annulus, with a resolution of 768×640, an exposure time of 10 μs, and a frame rate of 60,000. The unfiltered light was collected with a 105 mm f/2.8 macro lens. To study the H_2/air combustion, radiative emission from electronically excited OH (OH*) is collected from the channel, filtered using a 320 nm filter, and measured using a photomultiplier tube (PMT, Hamamatsu R3788). The OH* is assumed to be a marker of heat release regions [9].

3 Types of Co-Rotating Detonation Waves

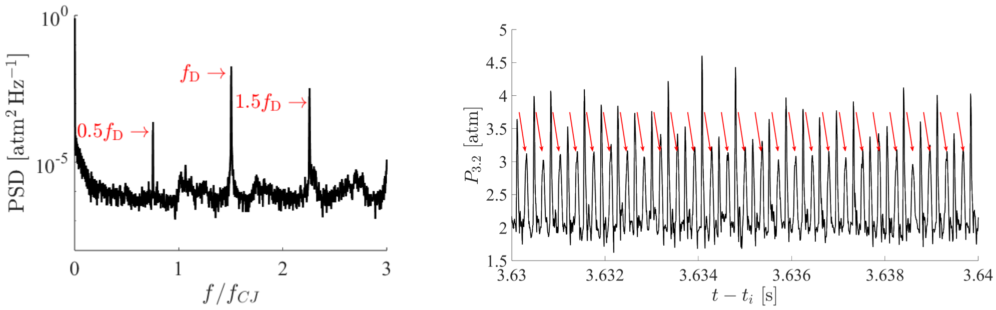
Typically, when multiple co-rotating detonation waves are observed experimentally, the waves are homogeneous in that the speeds and pressure rise across the waves are effectively identical. Here we will refer to this as indistinguishable co-rotating detonation waves (ICRD). In regards to the high-speed pressure spectrum, this results in a peak at the product of the wave multiplicity and the frequency of the individual waves. An example of this is shown in Figure 2(a), which is for $\dot{m}''_{\mathrm{a}} = 514\ \ \mathrm{kg\ s^{-1}\ m^{-2}}$ and $\phi = 0.6$. Two co-rotating waves are observed propagating at $0.78 f_{\mathrm{CJ}}$ resulting in a combined frequency of $f_{\mathrm{D}} = 1.56 f_{\mathrm{CJ}}$. The quantity f_{CJ} indicates the rotational frequency of an ideal detonation wave at the nominal equivalence ratio. Meanwhile, there is a very weak secondary wave system at $2.29 f_{\mathrm{CJ}}$, labeled as f_{C}. The secondary wave system is determined to be weak from the low spectral strength and the lack of spectral peaks caused by the non-linear interactions between the primary detonation waves and the secondary waves. To demonstrate that the operation is ICRD, the associated time series of the channel pressure ($P_{3.2}$) is shown in Figure 2(b) during steady operation. Time is relative to ignition (t_{i}). The low magnitude of the pressure rises is consistent with the RDC literature and the deficit from the ideal CJ conditions as caused by flowfield non-idealities is well-documented [3, 10]. Additionally, the physical pressure sensor may attenuate the magnitude pressure rise across the shock, although this has yet to be demonstrated. Nevertheless, the key feature in Figure 2(b) is that overall the pressure rise is effectively constant with no discernible pattern to the variations between subsequent waves.

Co-rotating, multi-wave operation can also result in instances where the detonation wave(s) are distinguishable from one another, although this is typically not reported. Consider the spectrum in Figure 3(a), which is for $\dot{m}''_{\mathrm{a}} = 451\ \ \mathrm{kg\ s^{-1}\ m^{-2}}$ and $\phi = 0.6$. The strongest observable peak, $1.50 f_{\mathrm{CJ}}$, suggests



(a) (b)

Figure 2: a) The spectrum of an ICRD operation. b) The time variations in channel pressure of an ICRD operation. Both figures for $\dot{m}''_a = 514 \text{ kg s}^{-1} \text{ m}^{-2}$ and $\phi = 0.6$.



(a) (b)

Figure 3: a) The spectrum of a DCRD operation with peaks at $0.5 f_D$ and $1.5 f_D$. b) The time variations in channel pressure of an DCRD operation. Both figures for $\dot{m}''_a = 451 \text{ kg s}^{-1} \text{ m}^{-2}$ and $\phi = 0.6$.

that two co-rotating detonation waves exist in the RDC, similar to ICRD. However, additional spectral peaks at $0.75 f_{CJ}$ and $2.25 f_{CJ}$ exist, which were not present in the DCRD case. These peaks are exactly 0.5 and 1.5 multiples of the primary frequency. Either there is a single wave at $0.75 f_{CJ}$ with a harmonic at $1.50 f_{CJ}$ and the harmonic a has greater spectral strength than the fundamental frequency, or there are two co-rotating detonation waves traveling at $0.75 f_{CJ}$. The aft high-speed video confirmed the existence of two co-rotating waves; however, the frequencies at $0.75 f_{CJ}$ and $2.25 f_{CJ}$ remain unaddressed.

The corresponding high-speed pressure trace is shown in Figure 3(b). A general trend is evident where a detonation wave whose peak pressure is about 3.5 atm is followed by a weaker detonation wave whose peak pressure is about 3 atm. Typically, every second detonation wave appears weaker than the preceding detonation wave which is highlighted with red arrows. The variability in the larger pressure spike is stochastic and lowers the spectral strength in Figure 3(a), but does not create additional spectral peaks. It is possible that this phenomenon is a result of a secondary wave system that non-linearly interacts with the detonation waves, thereby causing the larger pressure spike [7]. For this to be possible given Figure 3(a), the secondary wave(s) would have to be the same speed as the primary detonation wave(s) and interact precisely at the sensor location. If the speeds were different, the secondary waves would result in an additional frequency peak in the spectrum along with the non-linear interaction frequencies. Figure 3(a) does not exhibit either of these features. The aft video is also analyzed [7] to confirm that secondary waves were not present. Thus, secondary waves cannot be responsible for the additional spectral peaks.

The spectrum must then be caused by two detonation waves that are continuously traveling at the same speed, but with different individual pressure ratios, making the waves inhomogeneous or distinguishable co-rotating detonations (DCRD). In the simplified one-dimensional ZND structure, there is a unique relationship between wave speed and pressure ratio for a given global mixture. However, once loss mechanisms such as parasitic deflagration or mixture leakage are considered [10], the relationship between pressure ratio and wave speed is no longer unique. Continually propagating detonation waves in RDCs likely exist due to a balancing of the complex physics on multiple scales. There is both chemistry and shock dynamics locally at the wavefront while there is dissipation and feedback to the air and fuel injectors that ultimately create a suitable flowfield in front of the detonation. It is therefore possible that the two detonation wavefronts experience a different combination of these multi-scale phenomena such that they achieve the same wave speed albeit with different strengths in terms of pressure.

To further examine the observed behavior and the DCRD operation, phase averaging is applied to both the high-speed pressure and OH*-chemiluminescence measurements over the period of one of the individual detonation waves ($\overline{\tau}$) as shown in Figure 4(a) in black and red, respectively. The detonation waves are moving from left to right. There is an azimuthal separation between the measurements of $\pi/4$, so a phase shift correction of $t/\overline{\tau} = 0.25$ is applied to the OH* signal. Dashed blue lines mark the peaks. While the peaks are not exactly $0.5\overline{\tau}$ (or π radians) apart, the start of the pressure increases does occur $0.5\overline{\tau}$ after the strong wave. The strong wave exhibited a sharper wavefront in terms of both pressure and OH*, while the weak wave is broader with a significantly lower magnitude. This suggests a thicker wave with less coupling between the heat release and the shock wave. The strong wave's pressure rise is not as sharp as ideal detonations, but this could be caused by the phase-averaging procedure due to variability in wavespeed, physical sensor limitations, etc. The weak wave cannot be a wave reflection or purely acoustic due to the associated heat release associated. The pressure and OH* measurements are taken at different radial locations, being near the outer body and inner body respectively. Nevertheless, the strong wave is stronger in both pressure and OH* emission, indicating that the discrepancy between the waves cannot be attributed to the waves at different radial locations.

4 Performance Discussion

The thermodynamic benefit of detonation-based combustors hinges upon the static pressure rise across the wavefront prior to chemical reactions. This results in less entropy generation than the constant pressure deflagration. Typically, multi-wave operation of RDCs is thought to be beneficial for performance since the shorter time between detonation wave passages reduces the chance of auto-ignition within the fresh reactant mixture thereby mitigating deflagrative losses, which produces more entropy. Parasitic deflagration has been previously observed and modeled to be especially detrimental to the pressure rise across a detonation wave [9, 10]. Focusing on the OH* (red) signal in Figure 4(a), the measurable signal leading up to (to the right of) the weaker peak is both larger in magnitude and longer in time than the signal prior to the stronger peak. This implies that there is an increase in parasitic deflagration prior to the second detonation wave, correlating with a weaker wave. By integrating the phase-averaged signal between 0 and $0.5\overline{\tau}$ along with between $0.5\overline{\tau}$ and $\overline{\tau}$, it is found that the total OH* signal, which we assume is a measure of the total heat release, observed between the two waves is nearly identical. Since the second wave has an overall lower pressure and is closer to deflagration, a loss of potential gain occurs as the entropy production of the second wave is greater than if all the heat was released in the first wave. Thus, DCRD operation is theorized to result in worse performance than ICRD.

The direct impact of DCRD operation cannot be measured since ICRD operation cannot be purposely induced for the same geometry and operating conditions, necessitating modeling. Chacon [11] demonstrated that the impact of secondary combustion on thrust production can be evaluated using the reduced-order model from Shepard and Kasahara [12]. The same approach is applied here. Three cases are considered for the purpose of demonstration. Case 1 is an equivalent ICRD operation where both waves

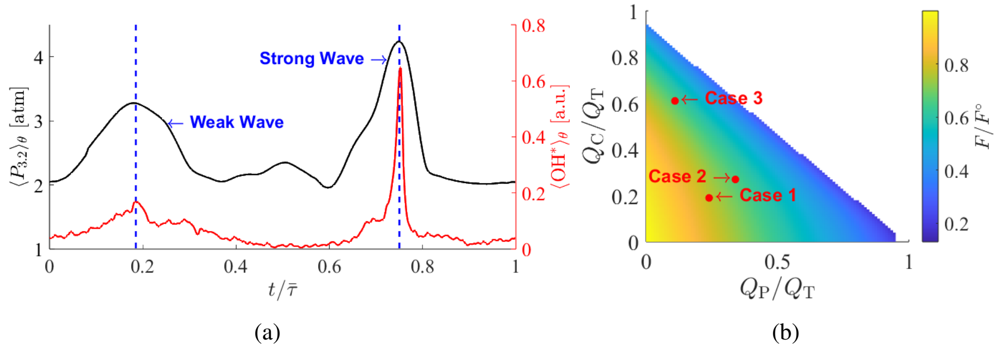


Figure 4: a) Phase-averaged profiles of channel pressure (black) and OH* chemiluminescence (red). Waves move from left to right. b) Visualization of thrust decrement from secondary combustion.

have identical OH* profiles as the strong wave in Figure 4(a). Case 2 includes the weaker wave while assigning the region of $0.18\bar{\tau}$ to $0.22\bar{\tau}$ to the detonation. Case 3 considers the weaker wave to be deflagration of leaked reactants. The breakdown in the heat release [9] in parasitic deflagration (Q_{P}), detonation (Q_{D}), and deflagration of leaked reactants (Q_{C}) relative to the total heat release (Q_{T}) is summarized in Table 1. The change in thrust (F) relative to the ideal (F°) is also reported and is visualized in Figure 4(b). From this analysis, having the weaker wave (whether in Case 2 or 3) results results in a significant performance decrement when compared to an equivalent ICRD operation (Case 1). Specifically, the thrust in Cases 2 and 3 are reduced by 14% and 37% respectively relative to Case 1.

In a previous work, it was demonstrated that the performance of a RDC as measured by both thrust was insensitive to the changes in the detonation wave(s) induced by changes in combustor length [5]. Importantly, the existence of the DCRD in certain lengths did not cause a significant change in thrust when compared to other lengths. However, these other combustor lengths had other changes to the detonation wave(s) such as a lower number of waves, slower detonation waves, etc. leading to other losses. It is theorized that the balance of various loss mechanisms in the different configurations resulted in the insensitivity in performance, thereby DCRD is still detrimental overall in comparison to ICRD.

5 Conclusion

Inhomogeneous (distinguishable) co-rotating detonation waves were observed in a H_2/air operated RDC with an exit constriction. A second detonation wave propagated in the same direction and at the same speed as the first detonation wave, although the pressure rise across the individual waves was different. This behavior was not caused by counter-propagating secondary acoustic waves. The second wave had a distinct chemiluminescence presence in the aft video and channel OH* measurement, indicating heat release is associated with the second wave. Using phase-averaging, the second wave is observed to have broader and weaker pressure and chemiluminescence profiles. By equating the measured OH* chemiluminescence to heat release, a comparable amount of heat release occurs in the second wave compared to

Table 1: Breakdown of heat release in different combustion events and their impact on thrust production.

Case	$Q_{\mathrm{P}}/Q_{\mathrm{T}}$	$Q_{\mathrm{D}}/Q_{\mathrm{T}}$	$Q_{\mathrm{C}}/Q_{\mathrm{T}}$	F/F°
1	0.24	0.56	0.19	0.79
2	0.34	0.39	0.27	0.68
3	0.11	0.27	0.61	0.50

the stronger first wave. Since this heat release occurs at a lower pressure than the first detonation, more entropy is produced,; thereby being a detriment to the overall RDC performance. Through reduced-order modeling, a significant decrement in theoretical thrust production is demonstrated.

References

[1] F. A. Bykovskii, S. A. Zhdan, and E. F. Vedernikov, "Continuous spin detonations," *Journal of Propulsion and Power*, vol. 22, no. 6, pp. 1204–1216, 2006. [Online]. Available: http://dx.doi.org/10.2514/1.17656

[2] B. A. Rankin, D. R. Richardson, A. W. Caswell, A. G. Naples, J. L. Hoke, and F. R. Schauer, "Chemiluminescence imaging of an optically accessible non-premixed rotating detonation engine," *Combustion and Flame*, vol. 176, pp. 12–22, 2017. [Online]. Available: https://doi.org/10.1016/j.combustflame.2016.09.020

[3] V. Anand and E. Gutmark, "Rotating detonation combustors and their similarities to rocket instabilities," *Progress in Energy and Combustion Science*, vol. 73, pp. 182–234, 2019.

[4] G. Ge, L. Deng, H. Ma, X. Liu, L. Jin, and C. Zhou, "Effect of blockage ratio on the existence of multiple waves in rotating detonation engine," *Acta Astronautica*, vol. 164, pp. 230–240, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0094576519311907

[5] A. Feleo, J. Shepard, and M. Gamba, "Experimental study of the invariance of pressure gain with respect to the dynamics of multiple competing waves in a rotating detonation combustor," in *AIAA Scitech 2023 Forum*, January 2023.

[6] J. W. Bennewitz, B. R. Bigler, J. J. Pilgram, and W. A. Hargus Jr, "Modal transitions in rotating detonation rocket engines," *International Journal of Energetic Materials and Chemical Propulsion*, vol. 18, no. 2, 2019.

[7] F. Chacon, A. D. Feleo, and M. Gamba, "Secondary waves dynamics and their impact on detonation structure in rotating detonation combustors," *Shock Waves*, vol. 31, no. 7, pp. 675–702, Oct. 2021. [Online]. Available: https://doi.org/10.1007/s00193-021-01034-6

[8] M. Bohon, R. Bluemner, C. Paschereit, and E. Gutmark, "High-speed imaging of wave modes in an RDC," *Experimental Thermal and Fluid Science*, vol. 102, pp. 28–37, Apr. 2019. [Online]. Available: https://doi.org/10.1016/j.expthermflusci.2018.10.031

[9] A. Feleo, F. Chacon, and M. Gamba, "Effects of heat release distribution on detonation properties in a H2/air rotating detonation combustor from OH* chemiluminesence," in *AIAA Propulsion and Energy 2019 Forum*. Paper No. AIAA-2019-4045, 2019. [Online]. Available: https://doi.org/10.2514/6.2019-4045

[10] F. Chacon and M. Gamba, "Study of parasitic combustion in an optically accessible continuous wave rotating detonation engine," in *AIAA Scitech 2019 Forum*. San Diego, CA: American Institute of Aeronautics and Astronautics Inc, AIAA, 2019. [Online]. Available: https://arc.aiaa.org/doi/abs/10.2514/6.2019-0473

[11] F. Chacon, "Non-ideal phenomena in rotating detonation combustors," Ph.D. dissertation, University of Michigan, 2020.

[12] J. E. Shepherd and J. Kasahara, "Analytical models for the thrust of a rotating detonation engine," 2017.