# Effect of Secondary Waves on Rotating Detonation Combustor Properties

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## 1 Introduction

Rotating Detonation Combustors (RDC) are a type of combustor that use detonation waves to consume reactants instead of deflagration waves as in traditional gas turbine engines. An RDC is composed of an annular channel with a width that is small compared to the diameter of the device. Fresh reactants are continuously fed into the device in the axial direction by an injection system. A detonation wave travels within the channel in the azimuthal direction consuming the fresh reactants along the entrance to the channel. The use of detonation over deflagration causes a pressure rise during combustion, an effect that is termed pressure gain combustion. This pressure gain allows for additional work to be extracted by turbomachinery, thus increasing the cycle thermal efficiency.

The flow field of a RDC is highly unsteady and complex, comprising of both supersonic and subsonic flows as well as combustion. Previous work by Bykovskii et al. hypothesized the possible entrainment of products into the fill region of the next detonation cycle [1]. This entrainment process was considered to be one of the key reasons responsible for differences between ideal calculations and measured detonation properties. Additional work at the Air Force Research Lab by Rankin et al. [2] used OH chemiluminescence images in order to investigate the flow field of an optically accessible round RDC. In that study they observed the variation in detonation height and wave number under varying geometric properties and their associated effects on the detonation, including the operation of the device with counter propagating detonation waves. Secondary wave systems have been observed by a number of experimental groups for a variety of injection schemes and operating conditions [2–4]. Previous work has shown it is possible to extract detonation wave speed information from x-t diagrams using image analysis techniques such as the Hough transform [5]. Numerical studies by Sato et al. [6] have recently shown non-uniformities in detonation propagation and structure in a typical RDC configuration. These non-ideal detonation structures are of keen interest for their impact on detonation properties and the resulting flow field.

This work will discuss some of the potential impacts of secondary waves, defined below, that are observed during operation of an RDC on detonation properties. Although secondary waves are observed over a range of operating conditions and geometries [4, 7], here we will focus on a single experimental condition for a specific injector configuration that has been observed to operate with and without a secondary wave system. Currently the mechanism controlling the existence or strength of secondary waves is not known. However, their impact on detonation wave properties can readily be identified and quantified. The objective of this work is to highlight and discuss some of these effects on a well-studied condition of operation, leaving the necessary general treatment to future work.

## 2 Secondary Waves

There are many examples in the literature where the operation of an RDC was reported to include additional phenomena that have wave-like characteristics (e.g., propagate with well-defined properties). Therefore, the concept of secondary waves has been used in the literature to refer to potentially different phenomena including multiple detonation wave systems [2, 5], plenum/combustor dynamics coupling [8], and combustion instabilities for marginally stable operations [4, 8, 9]. Here we restrict the term *secondary wave* to any disturbance that results in a pressure or combustion signature that propagates with characteristic properties, e.g. speed, amplitude, etc, separate from the main detonation wave(s). These waves can be identified in high-speed wall static pressure measurements as well as in high-speed chemiluminescence measurements (e.g. video, emission point measurements) [7, 10]. In principle these waves may be azimuthal or longitudinal, with more than one wave system potentially being present simultaneously. Using a data analysis technique we have developed and termed circuit wave analysis [7], we have identified two azimuthal wave systems that have appeared in three drastically different injector designs over a wide range of operation conditions. The two wave systems are: (a) a fast wave counter-propagating to the main detonation wave and moving at nearly the speed of the main detonation wave; and (b) a slow wave-pair, spaced 180$^{o}$ apart, traveling counter to the main detonation wave at a speed approximately equal to the speed of sound of post-detonation gases. Figure 1 shows the types of waves that are present in our RDC using an axial air inlet over a range of operation conditions that resulted in detonation behavior. In this study we specifically focus on the slow counter wave-pair. The source of this wave pair has not conclusively been determined as of yet. However, additional experiments we have conducted recently suggest that the counter propagating wave pair can be eliminated by an appropriate design of the RDC flow path in spite of the fact that these modified designs do not significantly alter the overall acoustic modes of the device. In addition, the presence of the counter wave-pair has been found to vary with operation condition and injection scheme for the same detonation channel geometry with similar azimuthal acoustic modes. These additional experiments and observations currently lead us to believe that the counter wave-pair to be discussed here is not solely the direct result of chamber acoustics supported by the unsteady heat release, but is supported by additional

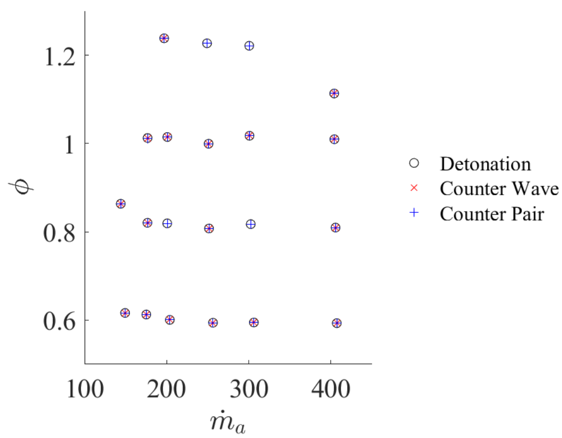



Figure 1: Operational condition map showing cases that resulted in detonation wave operation. In addition the presence of secondary waves during operation at those conditions are also noted.

critical phenomena. Full development of this concept is left to future work.

## 3 Discussion

The work presented here was conducted on the Michigan Rotating Detonation Engine (MRDE), an experimental test bed for injector testing, wave dynamics testing, and general operability testing. In this work we will focus on a single air/fuel handling configuration based on an axial air inlet design. Additional information and testing can be found in previous studies [11, 12]. Here we consider a single operational condition that has demonstrated operation with and without secondary waves. The nominal operation condition of interest was $90\ \mathrm{kg\ s^{-1}\ m^{-2}}$ air mass flux with an equivalence ratio of 0.6, with hydrogen as the sole fuel. At this operation condition the RDC has been observed to transition between having or not having secondary waves. A waterfall spectrum constructed from high-speed pressure measurements from one run that has exhibited this transitory behavior is shown in figure 2. In this run, the total run time was 4 seconds and was initiated at 6 seconds where operation with the presence of the secondary wave was readily established. Then, the device transitioned to operation without the secondary wave at approximately 8 seconds and lasted until the end of the run (at the 10 seconds mark). Prior to the transition at the 8 seconds mark the operation of the device is characterized primarily by two spectral tones. The first tone is at approximately $0.8 f_{CJ}$, which has been confirmed to be associated with the main detonation wave from both high-speed pressure measurements and chemiluminescence video. The second tone of interest is the frequency at approximately $1.1 f_{CJ}$, which corresponds to counter wave-pair described in the previous section. After the 8 second mark the tone at $1.1 f_{CJ}$ associated with the secondary wave is greatly suppressed if not entirely absent. The cause of this transition in device behavior is not known. Once this occurs there is a noticeable increase in the speed of the main detonation wave by approximately 3% of the ideal Chapman-Jouguet speed (evaluated at the global equivalence ratio of this operating condition). The increase in propagation speed is hypothesized to be due to a reduction in partial combustion of the fill region prior to the passage of the detonation wave as we have explained in our previous work [13]. Zero-dimensional modeling of the effects of parasitic combustion on detonation wave properties has shown that increasing the amount of parasitic combustion results in a reduction of the detonation speed. In addition, secondary waves have been observed to increase the level of parasitic combustion [13].

In addition the presence of a secondary wave system has a drastic effect on the observed temporal evolution of the pressure trace measured in the detonation channel. Figure 3 shows representative portions of high-speed pressure traces taken during the run used to construct the the waterfall spectrum shown in figure 2. Specifically, figure 3(a) is a portion of the pressure trace prior to the transition at the 8 second mark when the secondary wave is present, while figure 3(b) is taken from the same run after the transition at the 8 second mark where the secondary wave is not present. Both signals have a minimum pressure near 1 atm and pressure peaks in the range of approximately 2 to 3 atm with approximately the same period. However, the portion of run with the secondary wave shows a much greater cycle-to-cycle variability of the pressure history over the cycle, which results in a greater variability in peak pressure over the cycle when compared to the portion without the secondary wave. Using statistical methods outlined in one of our previous work [12], we can compare some metrics quantifying the cycle-to-cycle variability of the pressure traces, such as peak and base pressures. The results are summarized in the table 1.

Table 1 summarizes the mean and standard deviation values of the base and peak pressure with and without the secondary wave. This shows that operation when the secondary wave is present results in a modest rise in peak pressure (approximately 9%) at approximately equal base pressure. However, operation with

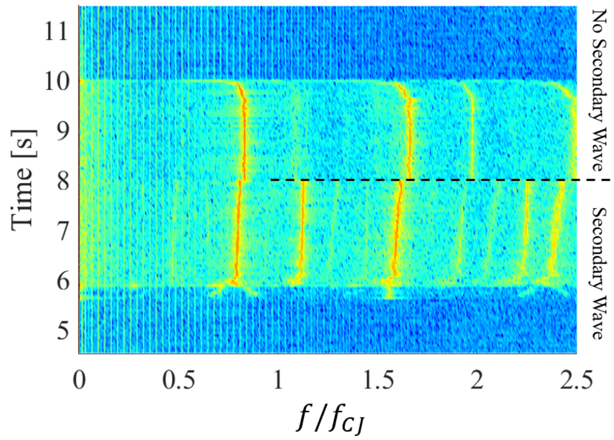



Figure 2: Waterfall spectrum constructed from high-speed pressure measurements. Halfway through the run the secondary wave system ceases to exist, correlating with an increase in detonation wave speed. Frequencies have been normalized by the ideal frequency that would be expected from a single Chapman-Jouguet detonation wave propagating into a uniform mixture at the global equivalence ratio.

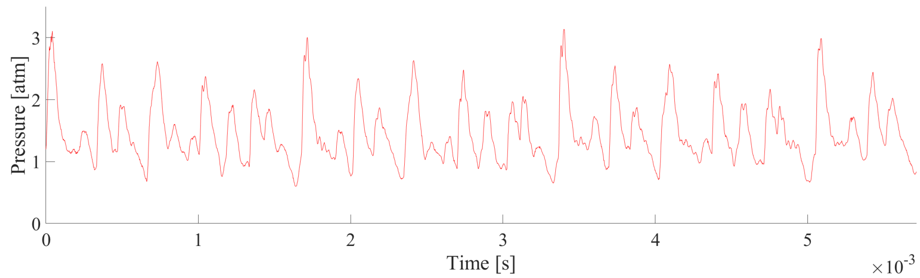
Table 1: Comparison between mean and standard deviation of base and peak pressure for a single operation condition with and without secondary waves (SW).

| Statistic [atm] | SW | No SW |
|---|---|---|
| Peak Pressure mean | 2.45 | 2.20 |
| Peak Pressure std | 0.38 | 0.19 |
| Base Pressure mean | 0.77 | 0.84 |
| Base Pressure std | 0.18 | 0.15 |

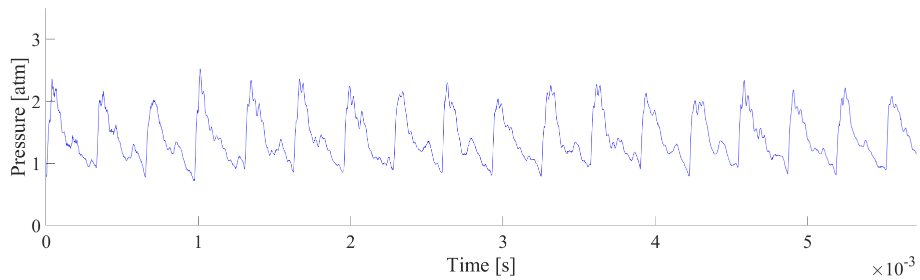
the secondary wave present doubles the standard deviation of peak pressure, suggesting the presence of the secondary wave induces a much greater variability of the pressure variation in the cycle. This is consistent with the more irregular pressure trace shown in figure 3(a). The increase in peak pressure and cycle-to-cycle variability of the pressure variation are currently hypothesized to be due to a non-linear interaction between the main detonation wave and the counter propagating wave pair. This coupling likely results from two separate but important interactions. First is the impact of the secondary wave on parasitic combustion, causing the detonation wave to propagate into a fill region with spatially and temporally non-uniform distribution of composition and temperature. The second interaction arises when the detonation wave physically collides with one of the counter propagating wave pair, resulting in a reinforcement (constructive interference) of the strength of the detonation wave, resulting in a localized increase in chemical reaction and pressure. Both of these interactions may result in greater cycle-to-cycle variability in detonation properties, which may ultimately impact the average performance of the RDC.

## 4 Conclusion

Secondary wave systems have been observed to significantly impact the properties of detonation waves traveling in the annulus of rotating detonation combustors. These impacts are the manifestations of two dif-




(a)




(b)

Figure 3: Examples of time variation of pressure measured during the same experimental run where the operation mode switches from (a) having to (b) not having a secondary wave.

ferent interactions that the secondary wave has with the detonation wave. The first is an indirect interaction associated with an increase in parasitic combustion as a result of the presence of the secondary wave. This type of interaction has been observed in previous experiments and is hypothesized to result in a reduction in detonation wave speed as seen when the secondary wave is present. The second interaction results from a non-linear interaction between the secondary wave and the detonation wave when they collide and interact, causing a transitory strengthening of the detonation wave, which results in a transitory higher peak pressure and localized heat release. This second interaction is then responsible for a greater cycle-to-cycle variation of peak pressure and possibly overall behavior of the RDC. Greater understanding of these interactions, as well as the controlling mechanisms for the presence of secondary waves, will likely play a crucial role in determining the potential thermodynamic performance of these devices as well as their integration into energy conversion systems.

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