Enhancing Rotating Detonation Stability Through Constructive Wave Interference

Jennifer Bishop

Faculty Advisors: Dr. Matt Quinlan and Dr. Christopher Foley

UCCS Department of Mechanical
and Aerospace Engineering

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1 Abstract

Rotating detonation engines (RDEs) are a next-generation propulsion technology that offer greater efficiency than conventional engines. Their adoption is limited by operational challenges, however. Unlike traditional combustion systems, RDEs sustain combustion through continuously propagating detonation waves in an annular chamber. A major issue is destructive interference, which occurs when detonation waves collide and disrupt operation [1].

This study presents a two-branch linear detonation facility model to examine detonation wave propagation and interaction. In this system, a detonation wave travels through an upper and a lower branch. Although the detonation wave velocity is constant, the shorter path length in the upper branch causes it to reach the recombination junction earlier. This early arrival allows the detonation to also propagate upstream into the lower branch, where it collides with the incoming lower wavefront, resulting in destructive interference, i.e., the two detonations become two shock waves and may weaken as they propagate. As the shockwave in the lower channel propagates eventually to the combustor section of our facility, it may not be strong enough to become a detonation wave as it encounters fresh reactants. To mitigate this wave weakening, a third branch is introduced as a passive delay mechanism near the lower branch. This branch admits a detonation wave from the upper wave, which is than reflected and rejoins the lower branch shock wave—and with the correct timing, in a synchronized manner to strengthen the shockwave before entering the combustor. The resulting constructive interference stabilizes the second detonation as it passes through the combustor.

In this work, a mathematical model is developed to determine the optimal third branch length and timing for shock strengthening. In the model, we assume that the time it takes for the detonation from the upper branch to travel down, reflect, and return to the recombination junction is equal to the time required for the detonation/shock in the lower branch to arrive at the junction. We have expressed the time as a function of velocity and distance, enabling a relationship between wave dynamics and geometric parameters.

The resulting equation is used to calculate the third branch length that promotes a stable second detonation in the combustor (by ensuring the trailing shockwave is strong enough). In future work, this approach will be validated using both MATLAB and PeleC simulations. MATLAB will model wave timing in the simplified system but more realistic conditions, while PeleC will simulate high-fidelity detonation behavior. Together, these tools will assess the effectiveness of the proposed geometry in sustaining stable combustion. By optimizing wave interactions, this research advances the ability to elucidate the fundamental processes

that control propellant injection and mixing, leading to higher-efficiency RDEs, reinforcing their potential for aerospace propulsion and high-performance engine systems.

2 Introduction

Improving wave dynamics in RDEs could significantly advance propulsion technologies for space exploration, hypersonic flight, and other high-performance aerospace applications. These systems must be compact, powerful, and thermodynamically efficient while operating reliably under extreme conditions.

RDEs are pressure-gain combustors that sustain supersonic combustion within an annular combustion chamber, where a detonation wave continuously consumes the axially injected fuel-oxidizer mixtures [2]. As the wave propagates circumferentially, it compresses the unburned mixture through a leading shock, initiating rapid chemical reactions in a high-pressure, high-temperature region. These reactions produce combustion products that expand downstream through oblique shocks and expansion waves, facilitating axial thrust generation [3]. The primary flow structures observed in an operating RDE are illustrated in Fig. 1. Part (A) depicts a three-dimensional CFD simulation of a rotating detonation engine, while part (B) highlights key flow features, including the detonation front and oblique shock [2].

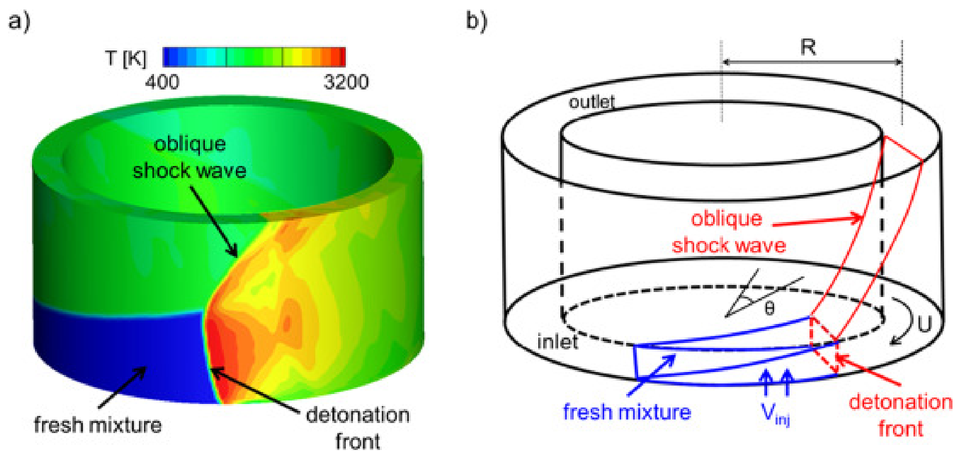

Figure 1: (A) CFD simulation showing detonation wave propagation in an RDE. (B) Annotated schematic of key flow structures, including the rotating detonation front and oblique shock system [2].

There are two types of combustion waves: deflagrations and detonations. A deflagration is a subsonic wave sustained by a chemical reaction and typically propagates through thermal/radical diffusion. This form of combustion is used in conventional aircraft turbines and gas-powered engines. On the other hand, a detonation is a supersonic combustion wave sustained by a extremely fast chemical reaction that results in a higher pressure, temperature, and density than would be found in the more conventional deflagration combustion based systems. In a detonation process, combustion is initiated almost instantaneously by a shock wave that compresses and heats the reactants, leading to a rapid energy release, causing a discontinuous jump in flow properties. As a result, detonation enables faster heat release, reduced entropy generation, and has approximately 5% higher thermodynamic efficiency compared to deflagration combustion systems [3].

RDEs are pressure-gain combustion (PGC) in which an unsteady periodic detonation causes a net increase in stagnation pressure because the gas expansion occurs in a constrained environment [4]. Unlike conventional constant-pressure combustion systems, PGC allows the combustion process to contribute positively to the stagnation pressure rise across the engine. This increase in pressure improves the thermodynamic cycle efficiency by allowing more of the input energy to be converted into useful work during expansion through a turbine or nozzle [5].

Detonation wave behavior in RDEs is often described using Chapman-Jouget (CJ) theory, which provides a simplified model of detonation based on ideal gas dynamics and conservation laws. The CJ model assumes the chemical reaction occurs instantaneously behind a leading shock, reducing the detonation front to a single discontinuity. The wave propagates at a velocity such that the flow of combustion products becomes sonic relative to the wavefront (i.e., in the wave-fixed coordinate frame) behind the reaction zone. This sonic condition, known as the upper CJ point, ensures that downstream disturbances cannot travel upstream. CJ theory allows analytical prediction of post-detonation conditions but neglects finite-rate chemistry and internal structure, motivating the use of more detailed models like the Zel'dovich-von Neumann-Döring (ZND) formulation [6].

The ZND model is a three-zone model that includes the shock, an induction zone, and a rapid chemical reaction zone. This model assumes that the shock is a discontinuity (while in reality, it may be a few mean free paths in width but very thin still) and that the reaction rate is zero ahead of the shock and finite behind it. Transport effects are neglected. Behind the shock, the compressed gas reaches a region of elevated pressure and temperature, commonly referred to as the von Neumann spike, before significant chemical reactions occur. By resolving the internal structure of the wave, the ZND model supports analysis of induction delays, reaction zone thickness, and wave instabilities, all of which are relevant to RDE performance [6].

RDEs are sensitive to a variety of flow instabilities that can hinder detonation wave propagation and reduce performance. Prior studies have identified mechanisms such as inlet-induced backflow and chamber boundary reflections as major contributors to unsteady behavior. For example, pressure waves reflected from an exhaust throat can travel upstream and disrupt the fuel-filling process, introducing fluctuations in detonation timing and wave stability [7]. These disruptions may block or even reverse injector flow, requiring recovery time before a steady flow is reestablished. During this recovery period, poor mixing and inconsistent reactant distribution can impair detonation timing, stability, and performance.

A critical factor in mitigating these unsteady behaviors is the precise control of detonation timing, as phase mismatches between successive detonations can exacerbate flow disturbances and inhibit sustained operation. In addition to the well-documented instabilities above, a potential source of disruption arises from wave-wave interactions, where multiple detonation fronts within the chamber (e.g., counter-rotating) collide and interfere. These collisions may cause destructive interference and partial wave quenching, reducing engine performance [1].

Although instabilities such as backflow and pressure reflections are widely studied [7], relatively few investigations address timing mismatches and destructive interference between multiple detonation fronts in RDEs. This paper identifies wave-wave collisions as a novel source of instability and proposes a geometric synchronization strategy using a passive third-branch delay. By addressing both established and emerging instability mechanisms, this work aims to improve the overall stability and efficiency of detonation-based propulsion systems. A simplified mathematical model is introduced in the next section to explore this wave timing control strategy.

3 Mathematical Model

To facilitate the analysis of wave interactions, the annular configuration of the combustion chamber was geometrically unwrapped and modeled as an equivalent two-dimensional linear domain. In this model, the detonation wave propagates along two parallel branches that represent distinct flow paths it may follow due to chamber geometry or pressure-induced redirection. Treating the branches as distinct paths allows the model to isolate timing mismatches between detonation waves, differences that can lead to interference or wave collapse in multi-front RDE systems.

The domain is modeled as a dual-branch structure, each with a horizontal segment length X. The lower branch includes an additional vertical segment of length L, representing the axial travel of the wave. The vertical distance between the two branches is denoted by H, which contributes to the difference in wave travel time. Following initiation, the detonation wave travels through both branches with a constant velocity of U. Through these assumptions, the travel time through the upper branch is given by:

$$t_u = \frac{\sqrt{X^2 + H^2}}{U} \tag{1}$$

while the time through the lower branch, which includes the two vertical segments and axial segment, is:

$$t_l = \frac{\sqrt{X^2 + 4L^2}}{U} \tag{2}$$

Since $t_u < t_l$, the wave from the upper branch arrives at the junction first, reflects downward, and propagates toward the incoming lower-branch wave. This out-of-phase interaction results in destructive interference, which the model aims to mitigate. This interaction is illustrated in Fig. 2, where the purple arrow indicates the trajectories of the detonation wave as it splits and propagates through the upper and lower branch. The detonation wave splits at the top junction and propagates through both branches. Due to the reduced travel time in the upper branch, the corresponding wavefront arrives at the lower junction before the wave in the lower branch. Upon arrival, it reflects downward and propagates toward the oncoming lower-branch wave, initiating a wave-wave interaction. The point where the two wave-fronts interact and continue propagating as shock waves is marked by a star in Fig. 2.

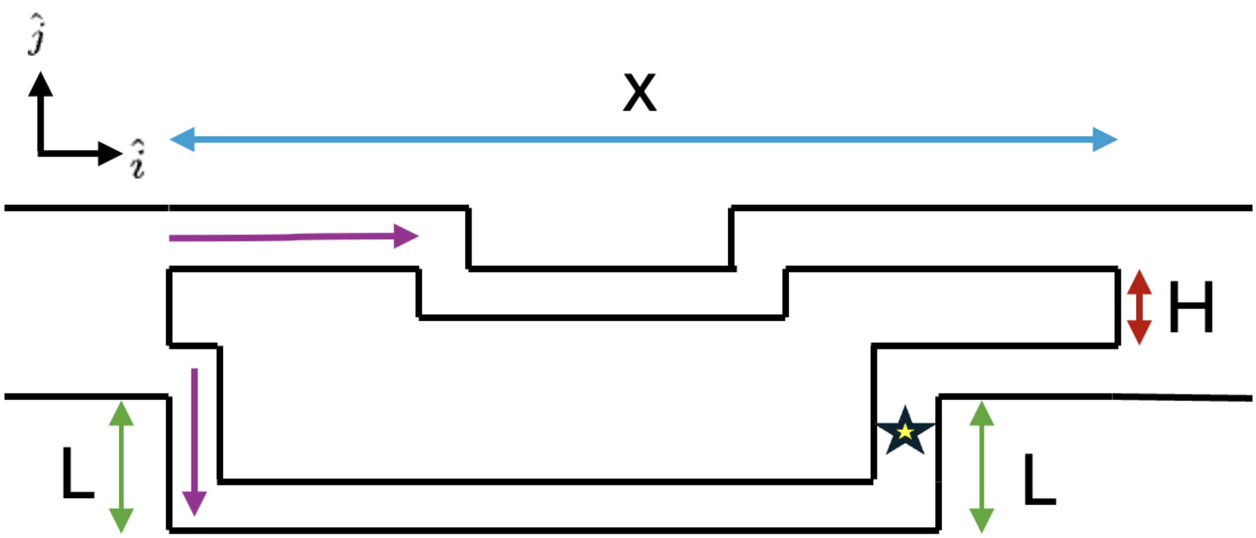

Figure 2: Two-branch linear timing model showing detonation wave paths (purple). The upper wave reflects early, arriving before the lower wave and causing destructive interference at the marked star location.

To prevent destructive interference, a third branch is introduced to synchronize the arrival times of the waves at the junction. By incorporating an additional geometric branch, the wave propagating along the upper path is directed into a downward trajectory and reflected. This effectively increases the travel time, inducing a phase delay to temporally offset its interaction with the lower-branch wavefront. The goal of this configuration is to ensure that the two waves meet in phase, combine, and become a singular more substantial shock wave (e.g. constructive interference). The parameter Z represents the third branch length, whose optimal value is derived to satisfy wave synchronization constraints based on the arrival times of the interacting wavefronts. The updated configuration is shown in Fig. 3, where the geometry remains consistent with the previous figure: L, X, and H are labeled as before, and the purple arrows again indicate wave propagation trajectories.

To promote constructive interference, the wave from the upper branch must arrive at the junction at the same time as the wave from the lower branch. In this updated configuration, the wave originating from the upper branch travels vertically by distance H, enters the third branch of length Z, undergoes reflection at the lower boundary, and propagates upward along the same path to rejoin the main domain. This results in a total upper-path travel time of:

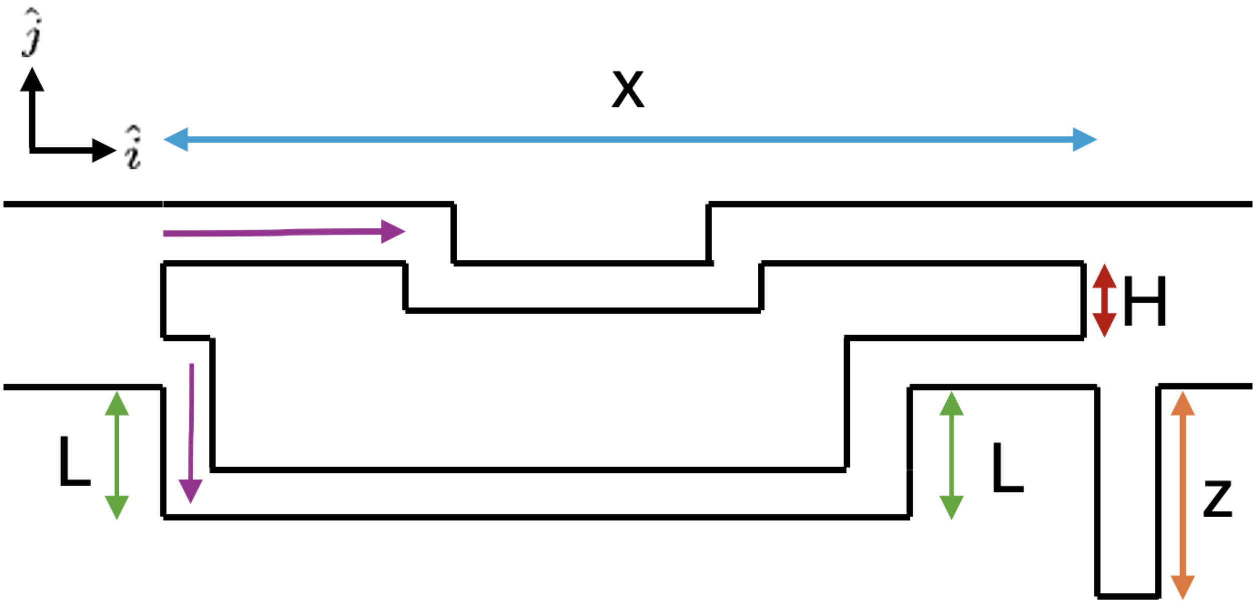

Figure 3: Three-branch timing model with added delay segment (Z). The upper wave reflects and re-enters the junction at the same time as the lower wave ($t_l = t_u$), enabling constructive interference and improving detonation stability.

$$t_u = \frac{\sqrt{X^2 + (H + 2Z)^2}}{U} \tag{3}$$

Equating this with the previously defined lower-branch travel time t_l yields the condition:

$$Z = L - \frac{H}{2} \tag{4}$$

This expression establishes a timing criterion that enhances the potential for constructive interference and guides the selection of the third branch length for approximate phase alignment. The model assumes constant wave velocity, ideal reflection, and one-dimensional propagation to isolate timing effects within a simplified geometry. While these are idealizations, they provide a tractable foundation for exploring path-dependent delays. Validation using numerical tools such as MATLAB and PeleC will assess the robustness of this approach under more realistic, multidimensional detonation dynamics. These insights are essential to improve the stability and performance of rotating detonation engines.

4 Conclusions

This work presented an idealized analytical formulation to investigate timing-induced wave interference within the context of RDEs. A two-dimensional linear system was developed to abstract path-dependent wave propagation delays within an unwrapped annular geometry. The model captures timing discrepancies between detonation waves traversing different flow paths, with these offsets potentially resulting from chamber geometry, pressure-driven flow deflection, or non-synchronous injection events. Destructive interference was identified as a key source of instability when detonation waves arrive out of phase at the downstream junction. To mitigate this, a tertiary path was introduced to impose a path-dependent delay and promote phase alignment at the point of convergence. The resulting expression defines the branch length required to promote constructive interference. When this condition is satisfied, wave interaction reinforces detonation continuity and system stability.

While idealized, assuming constant wave speed and 1D propagation, the model provides a tractable framework for isolating timing effects in detonation dynamics. This analytical framework will be validated through numerical methods. Wave timing and path-dependent delays will be explored using MATLAB within the linearized system. Concurrently, PeleC will simulate compressible, reacting, multidimensional flow to assess detonation dynamics under more realistic conditions. Together, these efforts bridge theoretical modeling and high-fidelity simulation, laying the groundwork for optimized detonation control in future aerospace engines. Future work will incorporate non-ideal effects, such as variable wave velocities (for detonations and shockwaves, accounting for the local flow velocity) and non-uniform inlet conditions. These additions would enhance the model's applicability to realistic engine environments.

Nomenclature

X	Horizontal axial segment [m]
L	Vertical length of the lower branch [m]
H	Vertical offset between the upper and lower branch [m]
Z	Vertical length of the additional third branch [m]
U	Detonation wave velocity [m/s]
t_u	Travel time through upper branch [s]
t_l	Travel time through lower branch [s]

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