Orderly Wave Initiation in a Rotating Detonation Engine

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1 Introduction to the University of Washington RDE Experiment

The rotating detonation engine (RDE), featuring a pressure gain combustor (PGC), is a promising propulsion technology for its potential to increase total pressure in the combustor while mitigating the entropy increase penalty associated with heat addition at finite Mach. Its application is proposed for both air-breathing engines and bi-propellant rockets. At the University of Washington (UW), we succeeded in initiating detonation waves in a RDE by applying a wave generator (WG) in a research program whose preliminary results were reported in Ref.1-3. In this paper, we present additional data accrued from the use of the WG, with particular emphasis placed on the importance of digital signal processing for examining detonation wave characteristics.

The UW RDE combustor is 14-cm-long with an outer diameter of 15.4 cm and an annular gap of 1.12 cm. It is fabricated from SS304 alloy with a 1-cm-thick outer tube wall [1]. The combustor exhaust duct is connected via a thick-walled pipe and a high-temperature butterfly valve, used for backpressure control, to a final dump tank. Combustor instrumentation includes recess-mounted piezoelectric pressure transducers (PCB 113) and several static pressure taps located axially at the same azimuth. The sampling rate for the piezoelectric transducers is 1.25 MHz while the rest of the sensors are sampled at a rate of 2 kHz. Propellant gases are pressure-regulated and pass through venturi flow meters prior to entering the manifolds. Using compressible flow relations, flow rates are determined with about 3% uncertainty.

One unique feature of this RDE is its detonation initiation method. Instead of a commonly used transversely fired pre-detonator, a circumferential array of spark plugs is installed in the exterior wall at the propellant injector end of the annular combustion chamber (Fig. 1). The use of twelve spark plugs was initially meant to generate 1 to 4 transverse moving shock waves to initiate detonation in a specified direction. It was later found that six spark plugs

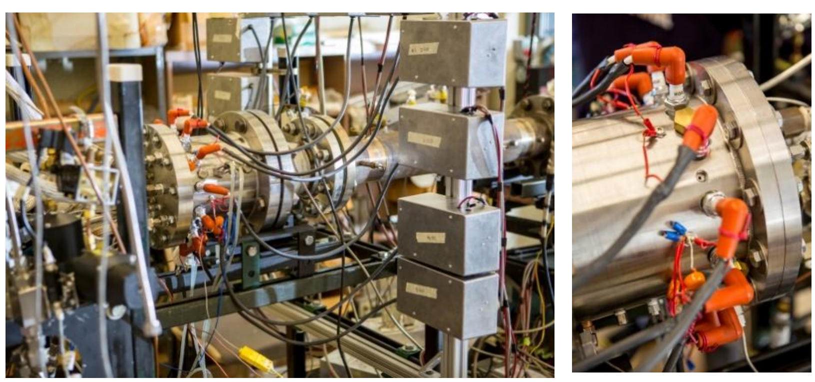

Figure 1. (left) Installed RDE test apparatus with WG spark boxes, (right) a close-up of the WG spark plugs at injector end of RDE.

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sufficed for many situations, although neither a single spark nor multiple firing with less than 6 plugs at the same time resulted in stable detonation. To date, there have been over 300 test firings with this apparatus.

2 Wave Generator Operation in RDE

Sequential firing of multiple spark plugs at a particular frequency generates circumferentially moving shock waves. Illustrated in Fig. 2 is the initiation of two waves spinning in the counterclockwise direction by the simultaneous firing of opposing spark plugs in sequence. The pulse duration and energy deposited by each spark is approximately 100 ns and 10 mJ, respectively. The spark frequency corresponds to that of a wave rotating exceeding the acoustic speed of the unburned propellant. By appropriately firing 2, 3, or 4 sparks simultaneously, up to four shock waves can be generated with an array of twelve spark plugs.

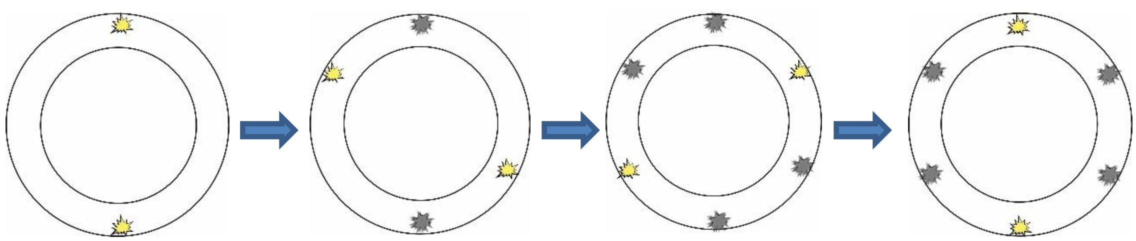


Figure 2. Generation of two waves spinning counterclockwise direction by sequential sparking of six spark plugs (yellow flash = spark activation, dark flash = spark inactivation).

In general, there is a need for specifying the initial wave spin direction even though detonation waves, once generated, are typically robust and self-driven. It is not unusual for the detonation initiation process to drive a wave, which is able to self-sustain its spin by chemical energy release, in one direction while at the same time initiating a second detonation wave that spins in the opposite direction. Both waves, once generated, can persist for a long time in an operating condition for RDEs known as the “slapping” mode. The resulting pressure spikes, occurring wherever the detonation waves collide, cause rough engine operation. Such counter-rotating waves can co-exist for a prolonged time, resulting in persistent unstable operation. It has been found that the initiation mechanism can play a powerful role in eliminating the formation of counter-rotating detonation waves. The new wave generator device initiates detonation waves while avoiding this inadvertent co-generation of counter-rotating waves.

Typical experiments used stoichiometric H2+O2 propellant at mass fluxes ranging from 0.4 to 2.0 kg/m^2 (20 to 100 g/s), which resulted in combustor static pressures ranging from 30 to 80 kPa. Representative data for a 1 ms time window from a recessed piezoelectric pressure transducer in an experiment in which two detonation waves were initiated, as illustrated in Fig. 2, are shown in Fig. 3. These data come from a point in the experiment several tenths of a second after turning off the WG. Note, the off time-delay for the spark plugs was usually set in the range of 0.1-0.3 s after initiating the inflow of unmixed fuel and oxidizer [1]. The max signal deflection was about 10 mV, which corresponds to approximately 14 kPa pressure differential across the shock wave. This is an order of magnitude lower than expected for a detonation wave, which indicates that the transducer is detecting the passage of an oblique shock wave being generated by, and attached to, the rotating detonation waves. The detonation spin frequency determined via FFT analysis was approximately 9 kHz, which corresponds to the frequency of two equally spaced waves passing over the transducer while traveling at a velocity 30-40% less than the theoretical CJ speed in this annular duct (15.4-cm-OD).

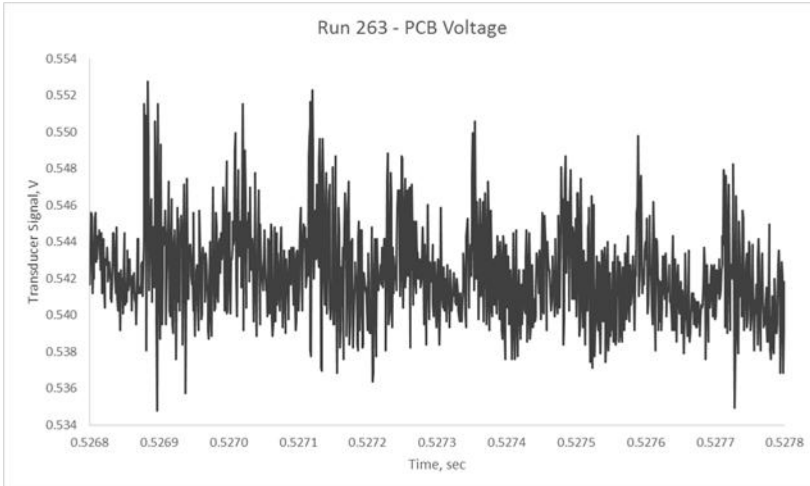


Figure 3. Piezoelectric transducer data of test Run 263, which utilized the WG process shown in Fig. 2.

3 Detonation Wave Analysis in Frequency Domain

Although a periodic pattern of sharp-pointed peaks is evident in Fig. 3 data, beyond this one cannot go much further with just time domain analysis. By switching from time- to frequency- domain, however, additional features of the wave can be examined. Discrete Fourier Transform (DFT) facilitates this by processing a raw time signal and converting it into the frequency spectrum, which can display frequency components together with their corresponding amplitudes.

Before signal processing Fig. 3 data in frequency spectrum, we illustrate this conversion from time domain to frequency domain for a hypothetical similar saw-tooth signal. An illustrative time signal with a period T is shown in Fig. 4a, and in Fig. 4b is the frequency spectrum of this signal processed with DFT, where the abscissa is frequency with the fundamental frequency $f = 1/T$, together with higher harmonics such as $2f$, $3f$, etc., and the ordinate is their amplitudes. Shown in Fig. 4c is the corresponding spectrogram with abscissa as time and ordinate as frequency. Regular pulsations in the time-amplitude domain show up as uniformly spaced striations in the time-frequency domain.

The frequency spectra and spectrogram plots based on DFT analysis of piezoelectric transducer data during the propellant injection time window (1 s) are shown in Fig. 5. Note, the WG sparks were turned off about 0.2 s after propellant injection begins. The cessation of sparking is evident in the time-frequency data shown in Fig. 5b by the cessation of chaotic signal frequencies and formation of distinctive frequency bands without significant signal noise. The fundamental frequency of 8.8 kHz in both of the Fig. 5a data traces implies that the wave number $N = 2$, since for $N = 1$, f is found to be 4.4 kHz for stoichiometric H2-O2 propellant [1]. In other words, peaks in the frequency spectrum of Fig. 5 correspond to $2f$, $4f$, $6f$, etc., like those shown in Fig. 4e.

The blue and red colored traces in Fig. 5a correspond to spectra from two PCB piezoelectric transducers installed at different axial and azimuthal positions. The consistency of their respective spectra data implies that there are two spinning waves, 180° apart, sweeping over the sensors. The horizontality of frequency traces in the spectrogram (Fig. 5b), in the time frame between the end of the transient state associated with WG initiation and the termination of the test run dictated by the cessation of propellant flow, demonstrates that the waves were propagating at steady velocity like those of Fig. 4f. Such stable operation in other experiments operating with wave numbers such as $N = 1$, 3, and 4 has been observed [1].

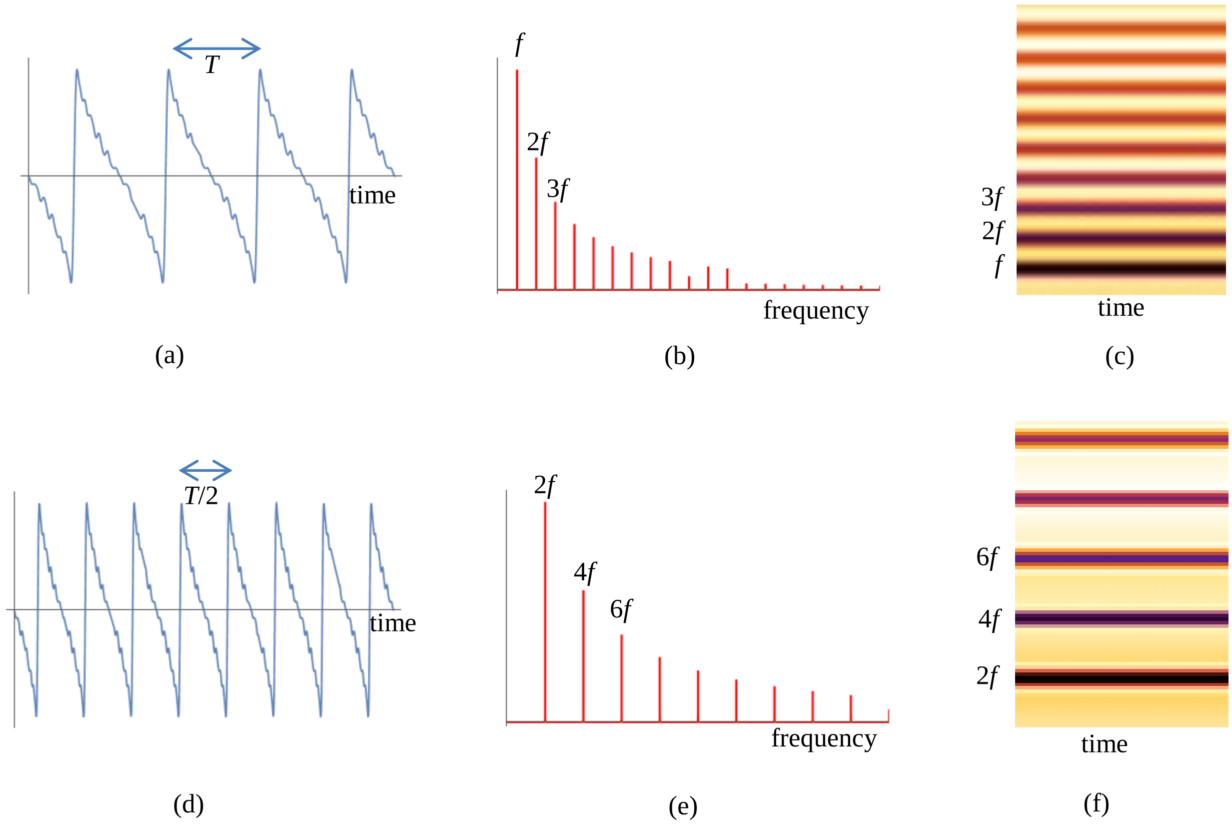


Figure 4. Illustrative wave form: (a) time signal with a period T, (b) frequency spectrum of (a) with fundamental frequency $f = 1/T$, (c) spectrogram of (a); (d) time signal with a period $T/2$, (e) frequency spectrum of (d) with fundamental frequency $2f = 2/T$, (f) spectrogram of (d)

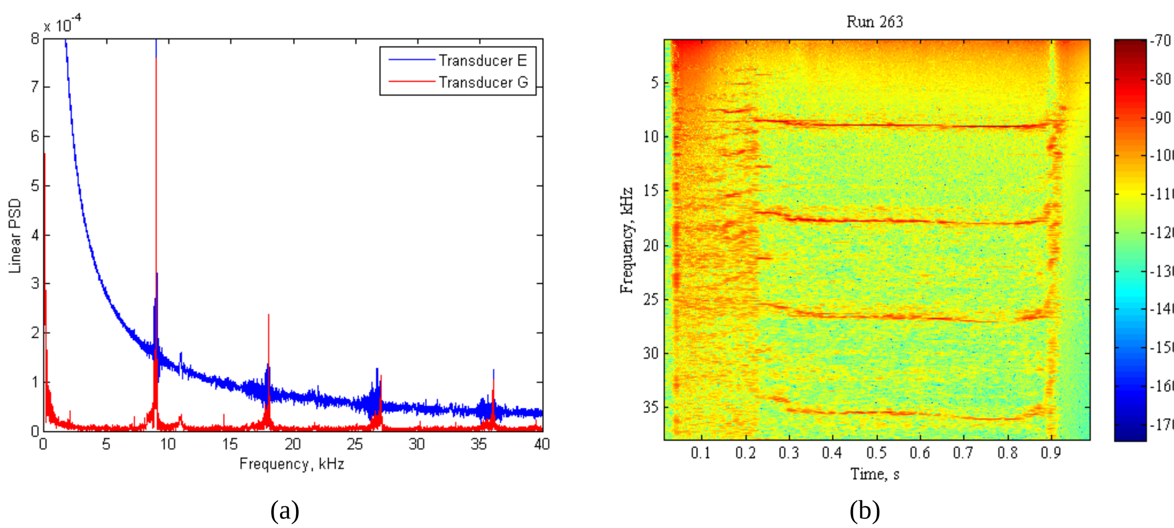


Figure 5. Frequency spectrum (a) and spectrogram (b) of Fig. 3 data

4 Influence of Initial Shock Wave Number on Detonation Initiation

Reducing the number of spark plugs to three equally spaced at 120° adversely affects the operating characteristics of the RDE. The firing sequence for three spark plugs is shown in Fig. 6. In this case, only a single counterclockwise shock wave should be generated. If the propellant mass flow rate is within the correct range, this results in a $N = 1$ detonation wave with the fundamental frequency of $f = 4.4$ kHz and its higher harmonics, like those illustrated in Figs. 4b and 4c.

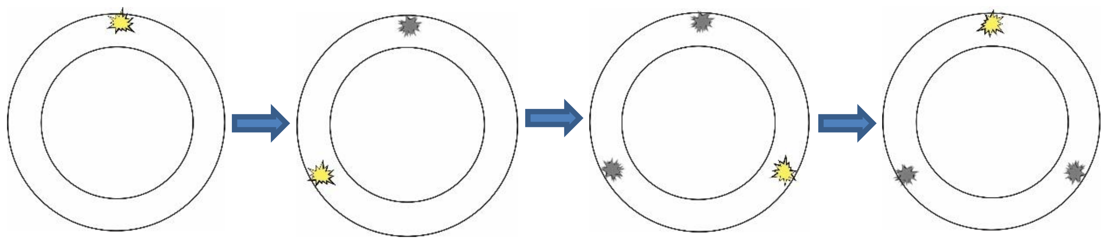


Figure 6. Sequential firing of 3 spark plugs generates one counterclockwise shock wave.

Shown in Fig. 7 are the raw data from the PCB piezoelectric transducer in an experiment at relatively high propellant mass flux when using only three spark plugs. Due to low signal-to-noise ratio, no pressure amplitude measurements from the piezoelectric transducers were available from this experiment. DFT analysis identified the significant frequencies; however, these peaks were not related by distinct frequency intervals, as shown in Fig. 8a. Even though the peaks at $f_1 = 3.8$ and $f_2 = 4.8$ kHz are close to the fundamental frequency of 4.4 kHz, they are definitively offset. Since additional peaks at $f_2 - f_1 = 1$ kHz, and $2f_2 - 2f_1 = 2$ kHz are observable, these peaks in the frequency spectrum probably represent two counter-rotating waves spinning at f_1 and f_2 frequencies [1]. In the spectrogram (Fig. 8b), their persistence until the end of the test demonstrates that once counter-rotating waves are initiated, they do not necessarily die away and may have significant impact on the RDE operational characteristics.

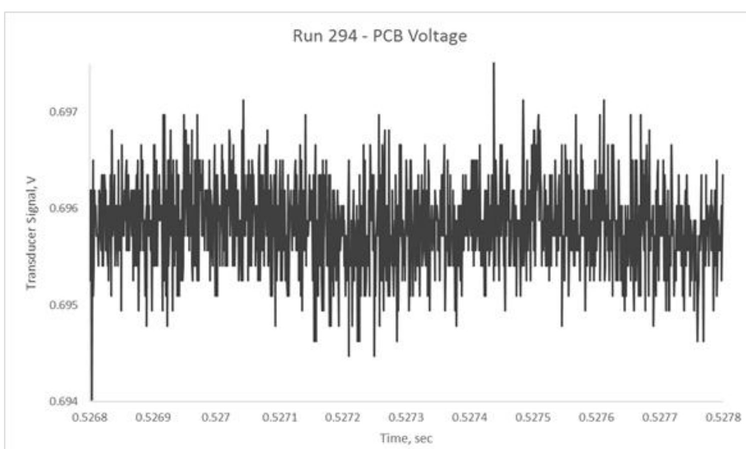
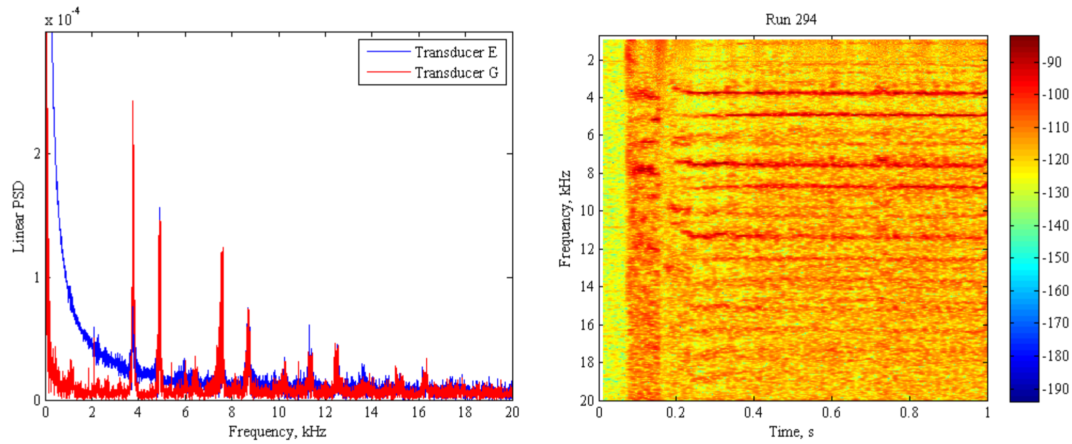


Figure 7. PCB transducer data of test Run 294, which utilized the WG process shown in Fig. 6.



(a) (b)

Figure 8. Frequency spectrum (a) and spectrogram (b) of Fig. 7 data.

5 Conclusions

Effective initiation of detonation waves in an RDE using H2-O2 propellant is achieved with the sequential firing of spark plugs by the wave generator. Establishing circumferential directional control of shock wave propagation enables orderly detonation initiation even when the propellant composition differs significantly from stoichiometric. When combustion initiation is attempted by either pulsing the spark plugs simultaneously or only producing a weak shock wave (by having too few spark plugs or too low of firing rate), multiple detonation waves form with random spin directions. This unstable combustion activity persists after turning off the WG and until propellant flow is ceased, which highlights that the start-up process can exert a long lasting effect on combustor operation. To achieve stable operation and acquisition of reproducible experimental data over a wide range of operating conditions, a RDE detonation wave initiator such as the wave generator describe here is crucial.

References

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