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Dynamic Mode Decomposition Study of a RDRE Exhaust for Swirl Attenuation Using Various Nozzle Configurations

Taha Rezzag[1], Robert Burke[2], Alexander Rodriguez[3], Kian Garcia[4]
Bernhard Stiehl[5] and Kareem Ahmed[6]
University of Central Florida, Orlando, Florida, 32816, USA

The attenuation of circumferential flow inherent in Rotating Detonation Rocket Engines (RDRE) through nozzle configurations is studied. The method used in this investigation consist of capturing highspeed side images of the exhaust to visualize the swirling flow. The images were processed through a dynamic mode decomposition code to resolve the main frequencies of the flow field at the exhaust. The obtained results were compared to the operational frequency of the engine computed with back-end images. Nozzle configurations were shown to have an influence on wave dynamics due to the induced back pressure. Results from the DMD method show similarity to those obtained from detonation surfaces. The nozzle configurations investigated are: 1) baseline without a nozzle, 2) aerospike nozzle only without the outer nozzle and 3) the inner and outer nozzles in conjunction.

I. Introduction

The use of conventional Brayton cycle gas turbines for transportation and power generation and the need for increasing work output has called for a new form of power generation where considerable efforts went into mitigating greenhouse gas emissions and increasing fuel economy through improving thermodynamic efficiencies. However, with conventional gas turbines reaching maturity, any efforts result in small but costly improvements in efficiency. In order to overcome this obstacle and reach much higher efficiencies, a pressure gain combustion (PGC) based thermodynamic cycle is developed. The PGC concept consists of transitioning from a constant pressure Brayton cycle to a constant volume cycle, such as the Humphrey cycle, resulting in a reduced entropy rise thus enabling the turbine to extract more work [1]. In addition, constant volume detonation engines have been theorized to output more work. As much as 22% increase in work output from constant pressure cycles to detonation cycles, and 2% increase from constant volume cycles have been theorized.1,2 Detonation engines have higher thermodynamic cycle efficiency, are mechanically simplistic, and have shorter combustion time scales.1,3,4 Furthermore, idealized thermodynamic cycles at steady state show that a significant increase in thermodynamic efficiency is achieved when transitioning from constant pressure cycles to constant volume or detonation cycles [1,2]. A comparison study of three detonation cycles; namely the Humphrey, Fickett-Jacobs (FJ) and Zel'dovich-von Neumann-Doring (ZND) models, was performed by Vutthivithayarak et al. [3]. It was found that the Humphrey and FJ cycle underestimated performance parameter affecting the entire thermodynamic system. This is due to the fact that these cycles do not properly capture the detonation physics. The ZND model, however, seemed to perform better and is considered to be the most appropriate model to use for analysis. Nordeen et *al*. [4, 5] have compared a modified ZND theory to results obtained from a numerical simulation and with good agreement. Furthermore, it has been stated that the model is also in good agreement with experimental findings. In addition, detonation engines are mechanically simpler, have shorter

[1] Graduate Research Assistant, Mechanical and Aerospace Engineering, and AIAA Student Member.
[2] Graduate Research Assistant, Mechanical and Aerospace Engineering, and AIAA Student Member.
[3] Undergraduate Research Assistant, Mechanical and Aerospace Engineering, and AIAA Student Member.
[4] Undergraduate Research Assistant, Mechanical and Aerospace Engineering, and AIAA Student Member.
[5] Postdoctoral Research Scholar, Mechanical and Aerospace Engineering, and AIAA Student Member.
[6] Assistant Professor, Mechanical and Aerospace Engineering, and AIAA Associate Fellow.

combustion time scales and have the potential to be used as standalone propulsion devices [1, 6, 7]. Of particular interest, the rotating detonation engine (RDE) has demonstrated various key advantages compared to other detonation engines such as the pulse detonation engine (PDE). For instance, RDEs operate on detonation waves constantly consuming fresh reactants providing a continuous flow through the exhaust while PDEs operate relatively slower due to the need of purging combusted reactants. A knowledge gap regarding the fundamental operation of RDEs still exists however, despite feasibility having been realized.

Efforts in investigating the feasibility of incorporating the RDE into gas turbine engine have been made. Tellefsen et *al*. [8] attempted to combine a RDE with a Jet Cat P-200 turbine. In an effort to simulate back pressurization (turbine operating condition) of connecting a turbine at the back of an RDE, a convergent nozzle was placed at the RDE exit. Results show that ignition occurs in the turbine at the start of a test which can cause detrimental effects and even failure. Furthermore, the convergent nozzle was seen to have significant influences on the detonations such as destabilizations and lower wave speeds. Naples et *al*. [9] have investigated the implementation of a RDE into an open-loop T63 gas turbine engine. Results show that the RDE compressor and shaft powers were higher than the stock combustor's for various engine power settings. The unsteady pressure fluctuations seen in RDEs were found to be mitigated before entering the turbine. Overall, the turbine performance was found to be comparable if not superior when a RDE is incorporated in place of a stock combustor.

Due to the inherently high unsteady flow environment observed in RDEs where pressure distributions across the annulus vary considerably, some losses in kinetic energy occur and translates to swirling flow motion. In order to mitigate the swirling motion, the use of nozzles was investigated. Nordeen et al. [10] numerically investigated radial effects on RDE swirl for three configurations: RDE body only, RDE attached to a center body and a RDE attached to a C-D nozzle. Results show that the C-D nozzle causes noticeable swirl attenuation compared to the other configurations. Furthermore, the numerical study of Harroun et al. [11] reveal that the performance of the RDE is enhanced when using a nozzle. In particular, results show an improvement in specific thrust of up to 16%. Experimental efforts were performed by Burke et al. [12,13] where the RDRE exhaust swirl attenuation for various nozzle configurations was quantified through side imaging using PIVlab toolbox. In an attempt to further explore this issue, this paper uses dynamic mode decomposition on side images of the exhaust where the swirling effect is clear. Once the frequency of the flow at the exhaust has been computed, it will then be compared with the operational frequency obtained from back-end imaging and the constructed detonation surface.

II. Experimental Methods

Images used in the current study were captured at the University of Central Florida, within the Propulsion and Energy Research Laboratory. The RDRE has a channel gap of 0.2", center body diameter of 2.8", axial length of 3" and an outer wall of 3". Detonations in the RDRE are initiated with the help of a Shchelkin spiral tube that is oriented azimuthally. The deflagration event accelerates from the pseudo-spiral which induces initial turbulence and then excites a deflagration to detonation. The pre-detonator is run on a stoichiometric hydrogen – air mixture, in order to induce the smallest detonation cell size. The RDRE is operated on a gaseous methane and oxygen mixture.

The setup consists of a Fastcam Photron SA-Z, as seen in Figure 1, which was operating at 180,000 FPS with an exposure time of 1/FPS, and an image size of 128x128 pixels. In order to protect the high-speed camera from the RDRE's exhaust, a mirror was mounted downstream instead tilted to the side where the camera was positioned, see Figure 1. This setup enabled safe and successful capture of high-speed imaging of the detonation waves. The highspeed backend images are used to construct detonation surfaces which are then subject to a 2-dimensional FFT in order to extract the desired wave dynamics such as the engine's operational frequency. The highspeed side images are run through a dynamic mode decomposition code to acquire the swirling frequency of the exhaust. The tests were performed using the same flow conditions of a mass flow rate of 0.6 lbm/s and at an equivalence ratio of 1.1.

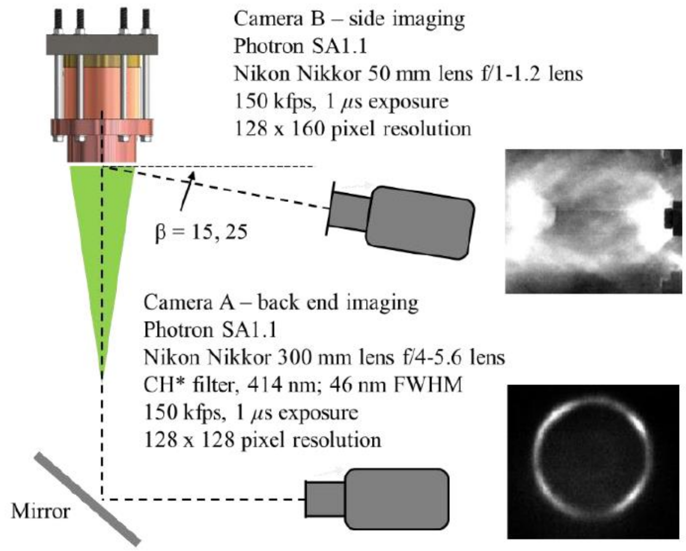


Fig. 1 Experimental Setup.

Figure 2 shows the modular rotating detonation rocket engine with the nozzle section. This section contains both the nozzle spike and the nozzle outer body.

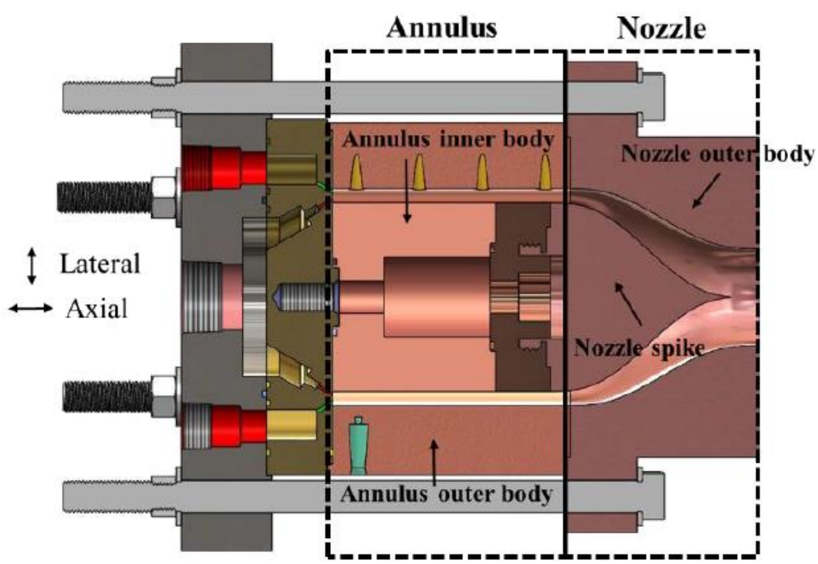


Fig. 2 Modular RDRE

Figure 3 displays the three nozzle configurations tested in this study: the RDRE without a nozzle, the RDRE with a nozzle but without a spike and the RDRE with a nozzle and a spike.

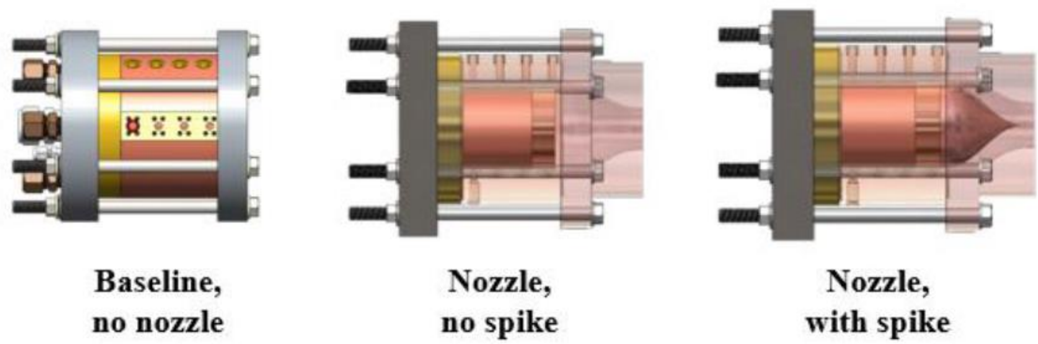
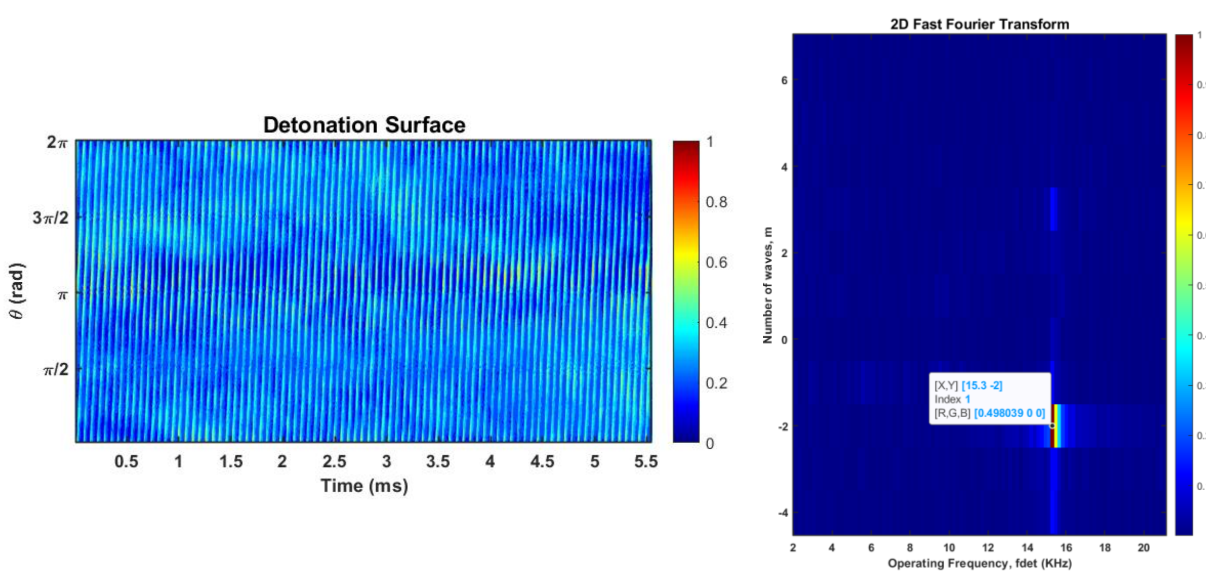


Fig. 3 Test Nozzle Configurations

III. Results and Discussions

A. Influence of the Nozzle on Wave Dynamics

Results from back-end imaging show that for the chosen flow conditions, the baseline RDRE will operate on a two-wave mode for an operational frequency of 15.3KHz corresponding to a wave speed of 1709 m/s. A detonation surface and a 2D FFT are shown in Figure 4 below. The addition of a nozzle configuration causes a significant increase in back pressure which effects on wave dynamics were seen from back-end imaging. Results show that the nozzle configuration with or without the spike enabled for a three-wave mode operation where the operational frequency is 20.7KHz resulting in a wave speed of 1542 m/s. A test of a configuration where the spike was on without the nozzle showed results similar to those from the baseline case.



a) b)

Fig. 4 RDRE Baseline a) Detonation Surface and b) 2D FFT

B. Side and Back-End Imaging Results

DMD Modes, Eigen Plots and DMD results for the three RDRE configurations are given in Figures 5 to 10 below. Results show that the frequency of the exhaust's swirl matches that of the operational frequency acquired from the back-end imaging. This indicates the reliability of the dynamic mode decomposition method in determining the operational frequency of the engine. While using the DMD method, both the Fast Fourier Transform and Welch with discrete Fourier transform are used and shown in Table 1 below where the results obtained from both the side and back-end imaging methods are summarized and compared.

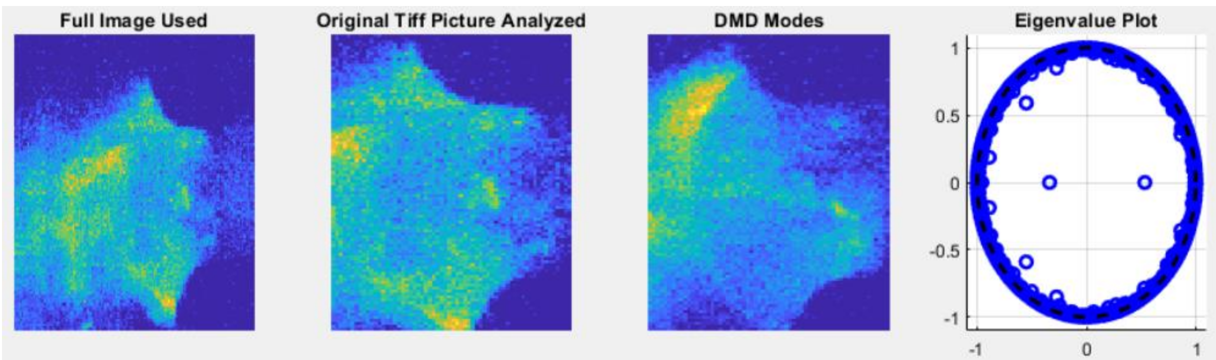


Fig. 5 DMD Modes and Eigen Plot for the Baseline RDRE Side Imaging

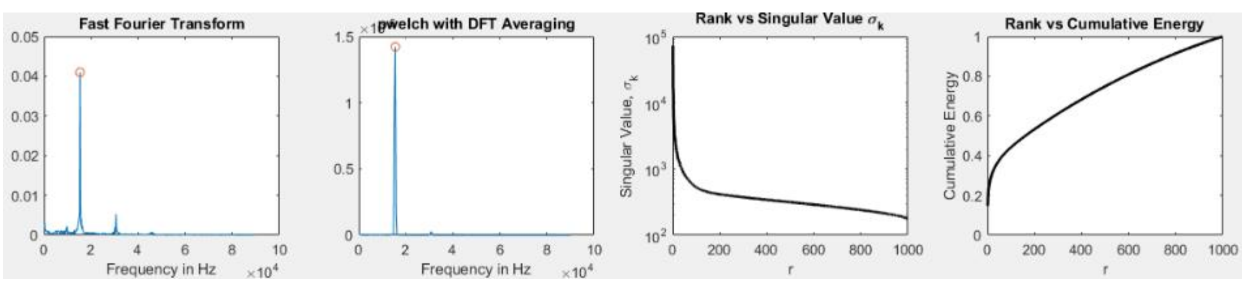


Fig. 6 DMD Results for the Baseline RDRE Side Imaging

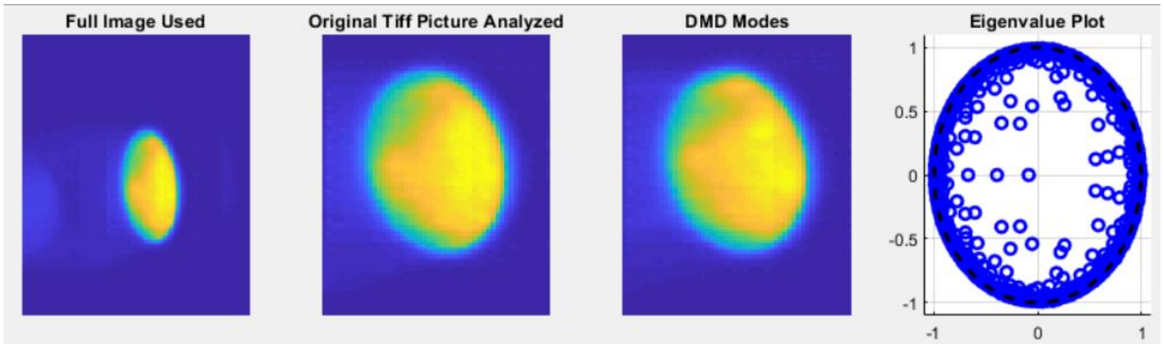


Fig. 7 DMD Modes and Eigen Plot for the RDRE with the Nozzle (no Spike) Side Imaging

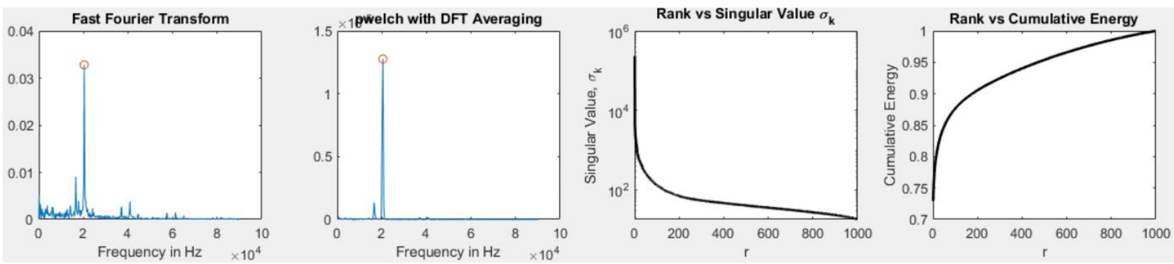


Fig. 8 DMD Results for the RDRE with the Nozzle (no Spike) Side Imaging

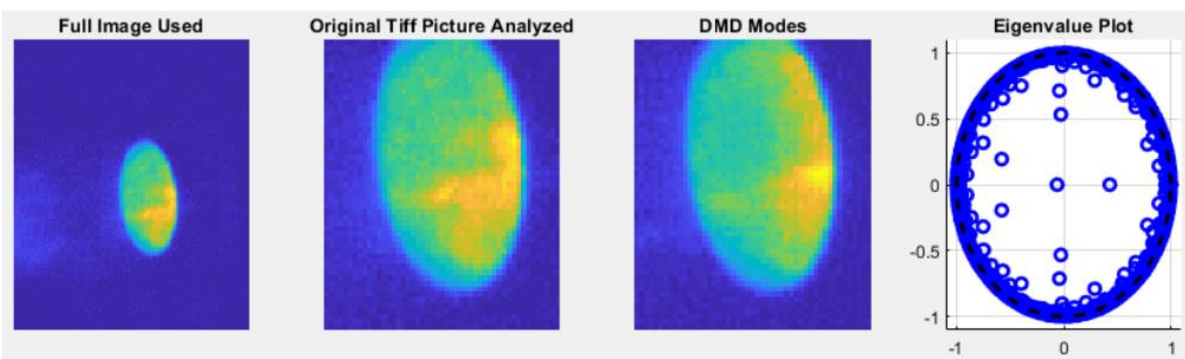


Fig. 9 DMD Modes and Eigen Plot for the RDRE with the Nozzle (with Spike) Side Imaging

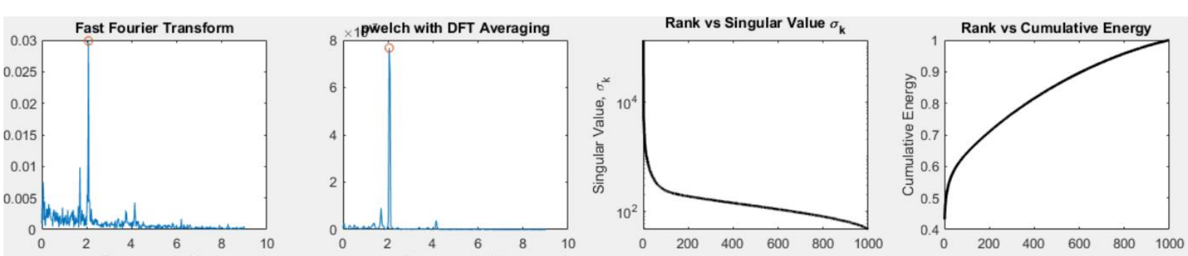


Fig. 10 DMD Results for the RDRE with the Nozzle (with Spike) Side Imaging

Table 1- Summary of Results

	Back-End	DMD	
	2D FFT	FFT	Welch with DFT Averaging
Baseline	15300Hz	15315Hz	15480Hz
Nozzle (no Spike)	20520Hz	20360Hz	20520Hz
Nozzle (with Spike)	20700Hz	20720Hz	20520Hz
Spike (no Nozzle)	15660Hz	15675Hz	15840Hz

IV. Conclusion

The frequency of the RDRE exhaust swirl for three nozzle configurations acquired from a dynamic mode decomposition code of highspeed side images is compared to the operational frequency of the engine obtained from highspeed back-end images and detonation surfaces. The same flow conditions where used across all tests and images from different highspeed cameras correspond to the same timing. Results show that for the given flow condition, the baseline configuration exhibit a two-wave mode regime. It was seen that a three-wave mode is present for the nozzle configurations which is explained by the resulting back pressure. Furthermore, results from the DMD method showed very good agreement with those obtained from the detonation surfaces.

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