Modal Analysis of Instability Phenomena in Shock-Induced Combustion using Decomposition Techniques

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1 Introduction

Shock-Induced Combustion (SIC) is a phenomenon in which the leading shock wave aerodynamically compresses the combustible mixture and self-ignites. In the ballistics experiments, unsteady modes of combustion were observed when the projectiles are fired near CJ Mach number. In the unsteady case of Lehr's experiment [1], regularly oscillating combustion regimes were also observed. Numerical simulation involves various challenges such as effectively capturing the discontinuities, selection of reaction mechanisms. In our previous paper [2], we have reported that even with the modern reaction mechanisms, the flowfield develops a disturbance in the regularly oscillating case and slowly grows into a low-frequency instability phenomenon like that of the Large disturbance regime (LDR) for regular regime case. Investigation of the source and characteristics of these instabilities is crucial in understanding the complex combustion instability phenomena.

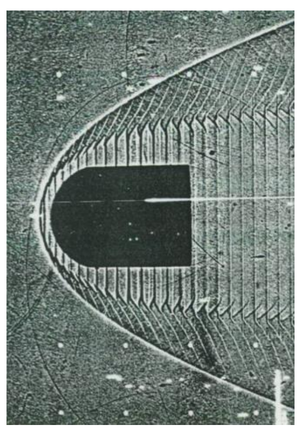

Figure 1 Experimental shadowgraph of periodically oscillating Shock-Induced Combustion observed in Lehr's experiment [1]

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Robust decomposition techniques [3] were developed in the recent times, through which the coherent structures from any non-linear flow fields can be extracted and the flow physics can be analyzed. Among various decomposition techniques, Proper Orthogonal Decomposition (POD) was widely studied in which the coherence structures are extracted and ranked based on the accumulated energy content. Dynamic Mode Decomposition (DMD) has gained attention because of its robustness and its ability to extract the spatial coherent structure mapped to its temporal characteristics which is fluctuating frequency. In this study, these two decomposition techniques were used to analyze the instabilities in the unsteady Shock-Induced Combustion.

2 Instabilities in Shock-Induced Combustion

In the detailed report on the numerical issues in Shock-Induced Combustion, it was reported that grid resolution with a minimum of 100 x 150 is sufficiently enough to predict the oscillation in the SIC flowfield [4,5]. In our previous paper, we have reported that some of the reaction mechanisms develop instability with high resolution schemes at higher grid resolutions [3]. An overview of flowfield contours, wave interaction graph and pressure probed at the stagnation point of one of the cases with 300 x 450 grids for M 4.48 of Lehr's experiment with Dryer mechanism [numerical schemes and grid details can be found in [3] and references therein], which develops such instability, is shown in Figure 2. From the result, it is clear the flow starts as a regular oscillation with slight disturbance, but gradually the disturbance gets converted

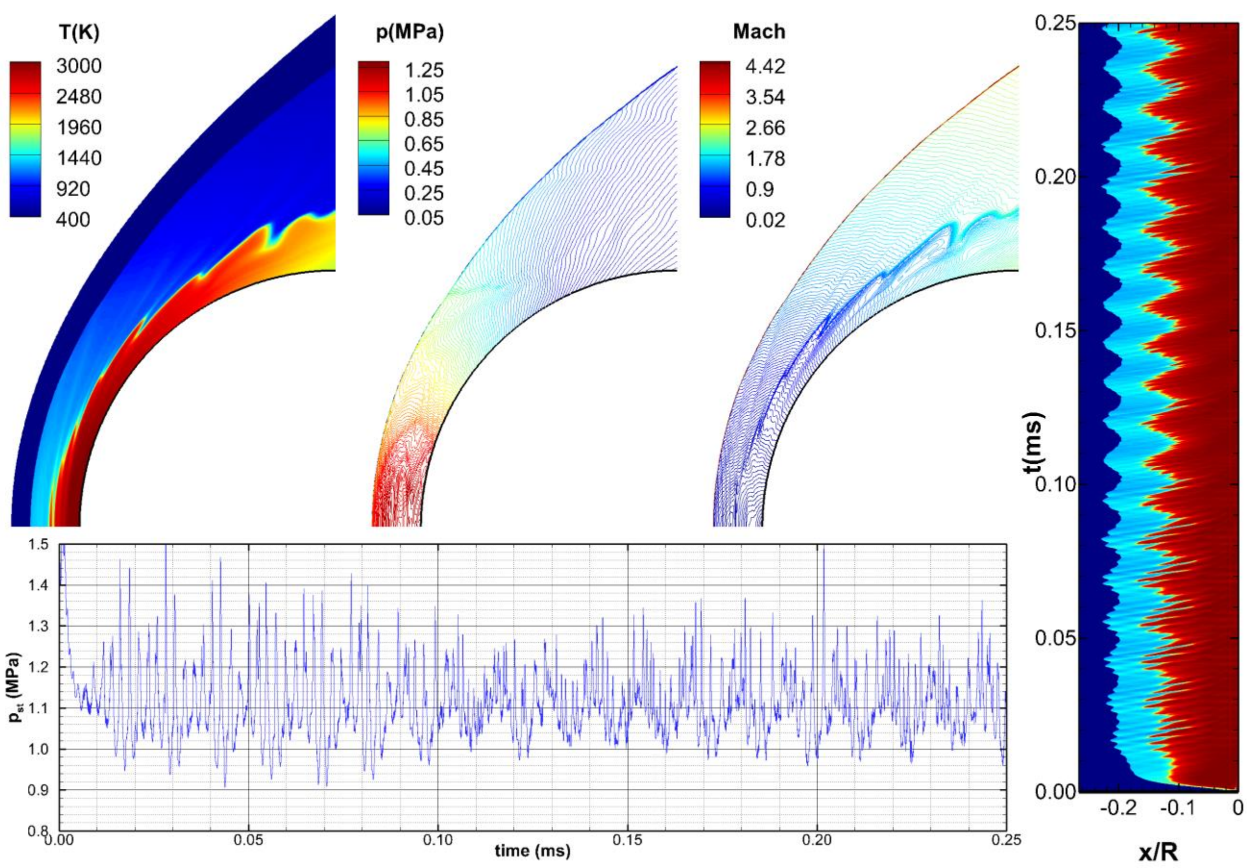

Figure 2 Overview of the numerical result with Dryer reaction model with 300x450 grid systems

into LDR. FFT analysis, as shown in Figure 3, of the pressure probe result shows the peak low frequency of around 80 kHz rather than the experimental frequency which is around 425 kHz for this case. However, FFT analysis is not sufficient to find the cause or source of the instability.

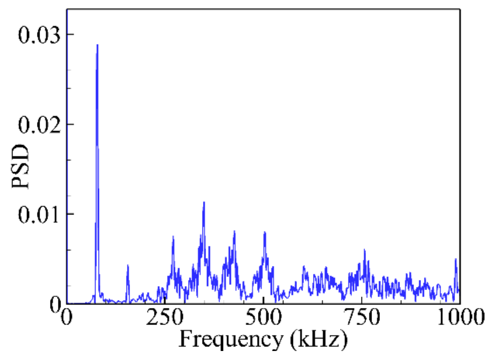

Figure 3 FFT result of pressure probe data extracted along the stagnation point.

3 Modal analysis

Through decomposition techniques the whole flowfield variables are decomposed and the coherent structure of different modes are obtained through which the source of the instability was analyzed. The POD analysis decomposes into different modes and the modes are ranked by the accumulated energy content of each mode [6]. As shown in Figure 4, the first mode has the maximum energy content, and it corresponds to the average distribution of the flowfield variable (in this study pressure variable is used throughout) which is similar to CFD averaged solution. Figure 5 shows the first POD mode with Dryer mechanism and it is similar to that of the averaged CFD solution normalized with initial conditions. For the first mode, ϕ represents the distribution of the variables and the value of 1 represents there is no change while the highest values the maximum change from the initial condition. For the other modes, ϕ represents the fluctuation happening in that cycle. The positive and negative extremes indicate the zone where the impact of the fluctuation for that mode is influential. For better understanding of the POD results, the result of the regularly oscillating case, with UCSD reaction mechanism [refer [3] for the regularly oscillating results with UCSD mechanism], was considered. The first mode of both the Dryer and UCSD mechanism were almost same.

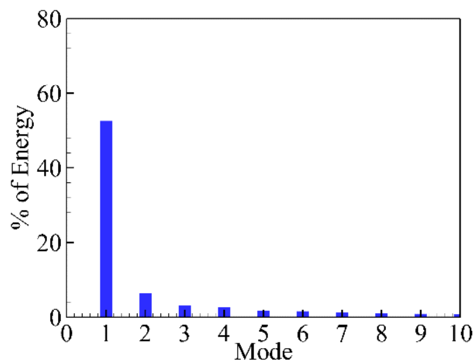

Figure 4 Energy distribution of the POD modes

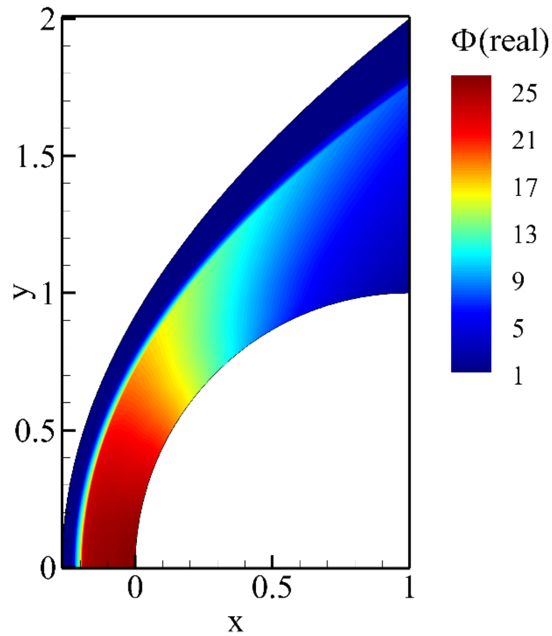

Figure 5 First POD mode with Dryer mechanism

The energy content of the POD modes of UCSD mechanism were also same as that of the Dryer mechanism. As shown in Figure 6, the second influential POD mode of Dryer and UCSD mechanism differs significantly. The pressure in the induction zone and along the projectile surface (at x=0) fluctuates simultaneously with UCSD mechanism whereas with Dryer mechanism, both fluctuates in the same cycle.

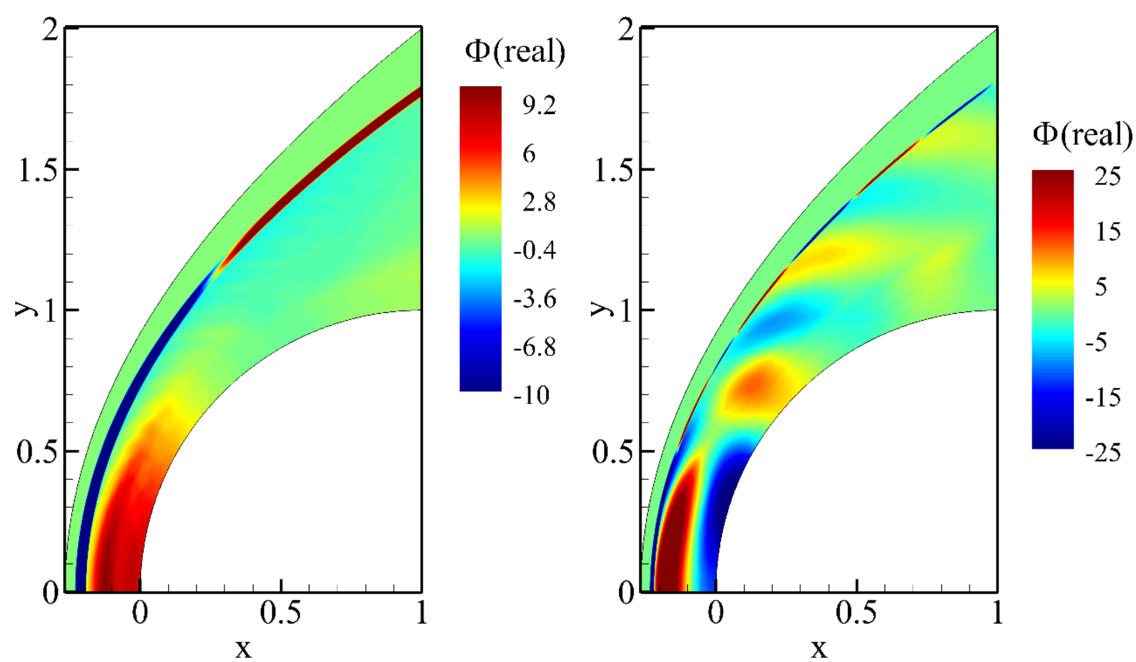

Figure 6 Second POD mode for a) Dryer mechanism b) UCSD mechanism

The advantage of using DMD method is that each coherent structure was mapped to its temporal characteristics which is the fluctuating frequency. But ranking the decomposed modes in DMD is complex and not as reliable as POD ranking method. Hence the coherent structures were extracted first and compared with the POD modes. Experimental DMD modes (modes with experimental frequency) of Dryer and UCSD model were shown in Figure 7. From Figure 6 and 7, UCSD experimental DMD mode with 419 kHz frequency is comparable to that of the second POD mode which means the experimental mode is influential in the flowfield as the first POD is the averaged mean mode.

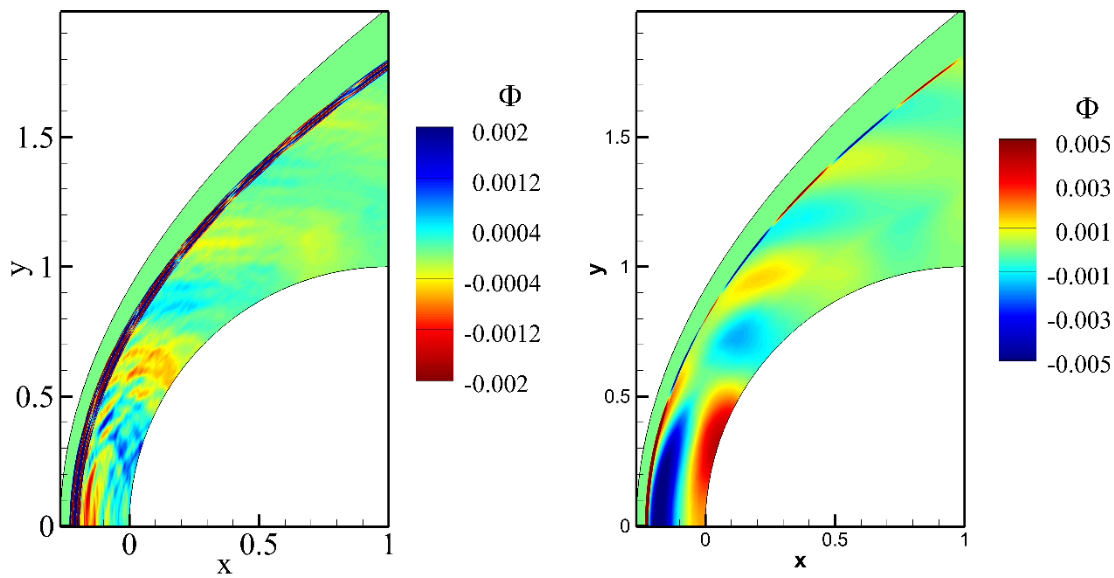

Figure 7 Experimental DMD modes a) Dryer mechanism at 436.2 kHz b) UCSD mechanism at 419 kHz

But with Dryer mechanism, similar second POD mode, which has higher energy distribution, were observed at 79 kHz DMD mode which means that the low frequency mode is highly influential. FFT result also predicts a peak frequency of around 80 kHz with Dryer mechanism in this case. From the UCSD result, it is clear that the pressure simultaneously fluctuates at two different locations, one near the projectile surface and the other towards the induction zone. The fluctuation near the projectile starts to move along the flowfield direction and does not interacts with incoming pressure wave. But with Dryer model, this interaction happens as can be seen from POD second mode which is also the DMD mode for 79 kHz. Initially, the pressure wave getting reflected from the projectile towards the shock wave is strong enough to create a mild disturbance to the regularly oscillating flowfield as can be seen around 100 μs in the wave interaction graph in Figure 2. Slowly this grows and attenuates into a regime like that of the LDR.

4 Conclusion

Modal decomposition is very useful in understanding the complex physical phenomena such as combustion instability, detonation cases. In this study, modal decomposition analysis is applied to study the instability phenomena in unsteady Shock-Induced Combustion. The source of the instability as observed begins as early as 10 μs but does not develop into LDR. Using the decomposition analysis, the structure of the modes was analyzed to understand the phenomena that causes this instability in the numerical simulation of unsteady Shock-Induced Combustion. With Dryer mechanism, initially a mild disturbance is created at the interaction of the reflected and incoming pressure waves in the reaction zone. This additionally triggers combustion in the reaction zone and creates stronger pressure wave which moves towards the projectile surface and gets reflected to interact with the incoming wave. This again triggers the combustion further and this process repeats, eventually converting the regular mode of oscillation into an instability.

Acknowledgement

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