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NUMERICAL IDENTIFICATION OF PRECESSING VORTEX CORE IN AN AIRBLAST SWIRL BURNER USING POD

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Acoustic response and stability of swirl burners operating in lean conditions is of great interest considering the stricter emission regulations. Lean operating modes exhibit a heightened sensitivity to thermoacoustic instability. This paper is aimed at understanding the natural acoustic characteristic of a prefilming Airblast atomizer operating at pressurized conditions. The presence of a helical precessing vortex core and its corresponding frequency as well as the natural fluctuations in the turbulent reactive flow is simulated using a large eddy simulation approach. Proper orthogonal decomposition is used to extract the prominent flow structures and infer their associated time dynamics within the swirl burner. This analysis is performed in absence of any external forcing to the system and can provide some insight into the stable operating modes of the swirl atomizer.

Keywords: Airblast atomizer, Non-premixed turbulent combustion, Proper orthogonal decomposition, Thermoacoustic instability

1. Introduction

Following a growing concern for global climate crisis, there has been a steady climb towards stricter combustion emission regulations. These regulations have set the stage for the design and operation of combustion systems. Traditional combustion system design has favoured fuel consumption and combustion efficiency with an eye for controlled emission levels of which the rich-burn, quick-mix and lean-burn (RQL) method is a prominent example [1]. This combustion method has been particularly beneficial in reducing nitric oxide (NOx) combustion emissions. However, in order to meet even lower emission levels and satisfy stricter emission regulations a shift towards lean premixed combustion (LPM) is preferred [2]. An important distinction between the premixed combustion regime and non-premixed combustion is the presence of a diffusive burning surface at the fuel boundary which contributes to higher NOx emissions. This highlights the need for advanced premixing technologies to promote mixing of fuel and oxidizer and improve emission levels of the engine. LPM is highly sensitive to thermoacoustic instabilities which is a feedback loop between the combustion process and the acoustics of the flame situated in the combustion chamber. This instability is perhaps best summarized by the Rayleigh criterion which defines a growing thermoacoustic instability in the case that the heat release rate of the combustion process (HRR) is reasonably in phase with the acoustic pressure present within the chamber [3].

Designing an aeroengine is particularly delicate since employing an LPM combustion method in a burner that is designed with stability in mind requires careful consideration of thermoacoustic instabilities. Aeroengines employ methods such as multiple swirling flows and airblast atomization to provide a suitable and stable combustion process. To study thermoacoustic instabilities in aero engine relevant conditions, an airblast swirl burner has been designed and manufactured in ET faculty of University of Twente (UT Burner). This burner exhibits a compact flame and a relatively low pressure drop which should make it suitable for the study of combustion instabilities [4].

One of the important characteristics of swirl burners is the presence of a precessing vortex core (PVC) in the centreline of the burner [5]. This precession results in a dominant acoustic behaviour within the burner and is consequential in its thermoacoustic stability [6].

In this study we aim to identify the PVC frequency by means of proper orthogonal decomposition (POD) of the pressure field generated from computational fluid dynamics (CFD) simulation results. Proper orthogonal decomposition can be considered as a non-supervised machine learning method to identify prominent flow structures present within the burner [7]. This could provide insight in the analysis of POD modes and establish a correlation between the dominant modes and PVC frequency which can be useful in the design process of aero engines or similar combustion systems.

2. Mathematical Formulation

We can start by formulating the time variant dynamical system using a separation of variables method to distinguish between the spatial (x) and temporal (t) aspects.

$$y(x,t) = \sum_{j=1}^{m} u_j(x) a_j(t) \tag{1}$$

In this formulation, m represents the number of modes used to describe the system and proper orthogonal decomposition keeps this value to a minimum [8]. We can further elaborate this formulation by means of an assembly matrix Y which holds are the relevant data. Assuming n spatial degrees of freedom and m temporal snapshots we have:

$$Y = \begin{bmatrix} y(x_1,t_1) & \cdots & y(x_1,t_m) \\ y(x_2,t_1) & \cdots & y(x_2,t_m) \\ \vdots & \ddots & \vdots \\ y(x_n,t_1) & \cdots & y(x_n,t_m) \end{bmatrix} \tag{2}$$

POD is thus the singular value decomposition that can find the following relationship between the columnar matrix of eigenvectors U, the singular value matrix $\sum$ and the row coefficient matrix V.

$$Y = U\Sigma V^* \approx U_r \Sigma_r V_r^* \tag{3}$$

In this formulation the truncation value r is arbitrarily chosen to discard the larger matrix and focus on the most dominant modes of the decomposition [9]. For the purpose of this study, the scalar value y is taken as the pressure of the CFD simulation located at location x. This means the assembly matrix is simply columnar pressure data present in the field where each column represents a snapshot of the CFD simulation that runs for m snapshots. POD modes rank according to their energy content. This can also be demonstrated by the square of singular values representing the kinetic energy of modes and located on the diagonal of the Σ matrix in a descending manner [10].

To identify the PVC frequency, we focus on the top modes of the decomposition in Eq. 3. This is done by selecting a low truncation value of $r = 4$, limiting the decomposition to the first 4 modes only. The spectral data can be inspected by examining the corresponding row in the V matrix such that the first 4 rows of the matrix represent the coefficients associated with the selected modes.

The truncation of POD analysis is a sound basis for order reduction and formulating Reduced Order Models (ROM) of a dynamical system.

The spectrum is then analysed by means of a power spectral density (PSD) estimate using Welch's overlapped segment averaging estimator [11]. This is then contrasted with a Fast Fourier Transform (FFT) of the pressure data at a specific point in the domain to compare the dominant PVC frequency and validate the POD findings.

3. Numerical Setup

UT burner features two separate air entry ducts. The two airflows meet in an atomization zone that provides the basis for airblast operation. The overall design can be seen in Figure 1 depicting the bottom series of air entries and the secondary entries situated above them. Fuel is injected upstream from the base of the burner creating a thin film which subsequently travels down and into the atomization region.

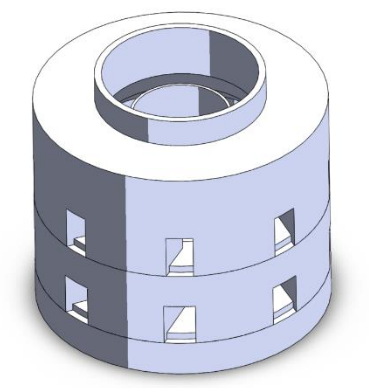

Figure 1: UT Burner geometry and design

Large eddy simulation (LES) analysis is performed using Ansys® CFX v19.2. The 3D setup consists of a semi structured numerical grid containing 20 million elements including the combustion chamber and an upstream casing in which the swirler is situated. Liquid jet fuel is injected at a desired location with a predefined size distribution to closely match the atomization process, details of which are described in [4].

Fuel is modelled by using a surrogate blend of trimethylbenzene (TMB) and n-Decane. The combustion process is simulated by means of a flamelet tabulation method for jet fuel at the operating conditions of 473 K and 3 bar using the available Burning Velocity Model (BVM). Standard Smagorinsky model was selected to describe subgrid scale [12].

The pressure data is then extracted by means of a post processing script that stores the pressure values from a defined cross section plane that cuts through the swirl burner such that the PVC is sure to traverse this plane as it rotates within the chamber. This is critical to ensure the presence of the PVC is detected in the POD analysis.

4. Results and discussion

The LES results can be visualized by means of a traversing cross section cutting through the swirler and the combustion chamber. The velocity and gauge pressure fields are of particular interest as they can show the helical PVC traversing the cross section in multiple locations as seen in Figure 2Figure 2. The pressure data used for the POD analysis is the scalar pressure value of points that rest on this cross section of the domain.

The velocity field illustrates the atomization region in the flow where the airblast atomization takes place. Corner recirculation zones can also be identified as well as the reverse flow downstream of the swirler creating a region of vortex breakdown which is one of the hallmarks of aero engine flame anchoring features. The reverse flow in the vortex breakdown region appears to be prominent which contributes to reducing the effective area of the swirler throat, creating a higher flow in the airblast region of the burner.

Pressure field corresponding to the velocity snapshot is also displayed indicating a region of low pressure at the base of the swirler. This low-pressure zone induces the reverse flow and supports the flame anchoring in the desired location.

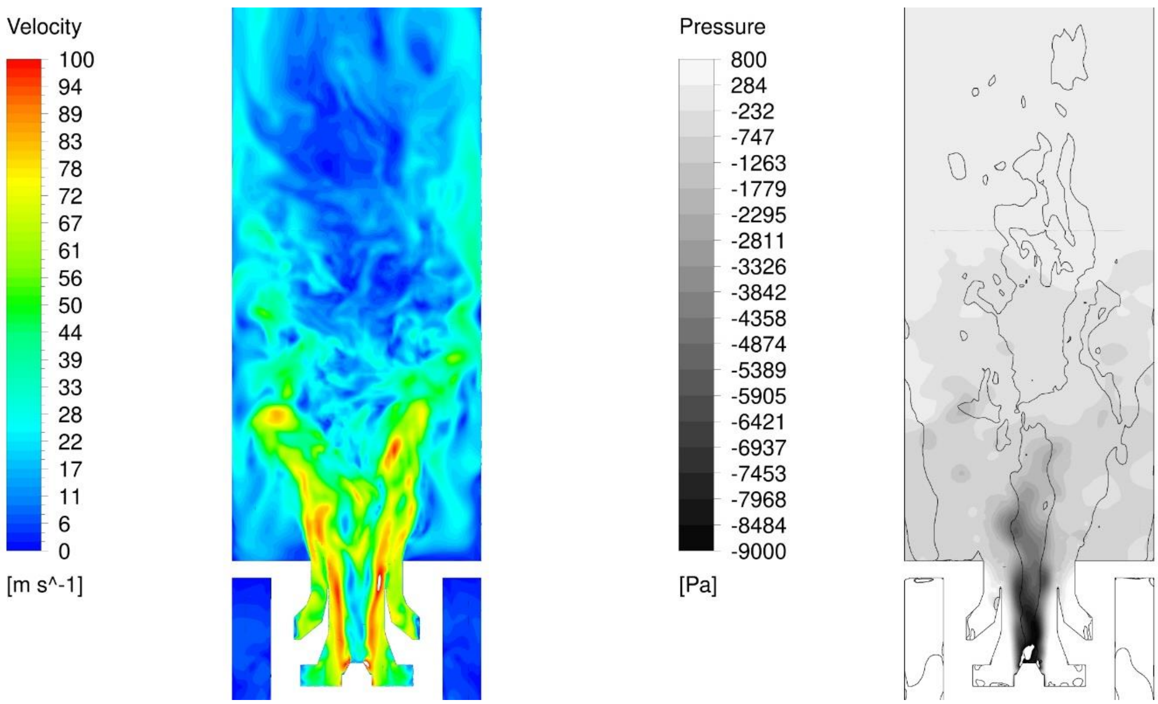

Figure 2: Simulated velocity and pressure contours

Additionally, the contour of zero axial velocity is overlayed on the pressure data to appreciate the vortex breakdown region outside the swirl burner as well as the corner recirculation zones. PVC can be seen as a series of lower pressure regions that wrap around the contours of zero axial velocity at the base of the burner. Looking further at a representative point close to the region associated with PVC, FFT of the pressure data can be computed as seen in Figure 3. Here, the higher frequency data has been truncated to focus on the more relevant lower frequency characteristics of the burner.

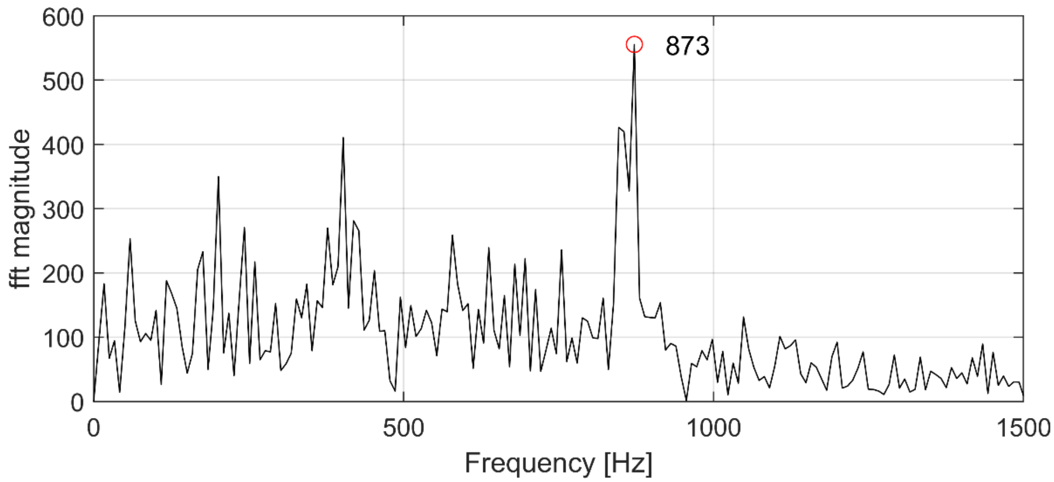

Figure 3: FFT of pressure data

Associated PVC frequency of around 873 Hz can be identified from this analysis. This method is prone to misidentification as it is highly sensitive to the location of the extraction point and multiple attempts are required to ensure current calculation. Other peaks can also be identified at the half PVC frequency of around 420 Hz. Due to relatively strict requirements of LES for very small timesteps in simulating turbulent combusting flows, sampling the pressure data at every timestep can be costly.

Alternatively, the POD method is agnostic to manual selection of data points as it is an unsupervised algorithm. The first modes of POD analysis are displayed in Figure 4 representing the most energetic modes of the pressure field after subtracting the field mean from each snapshot.

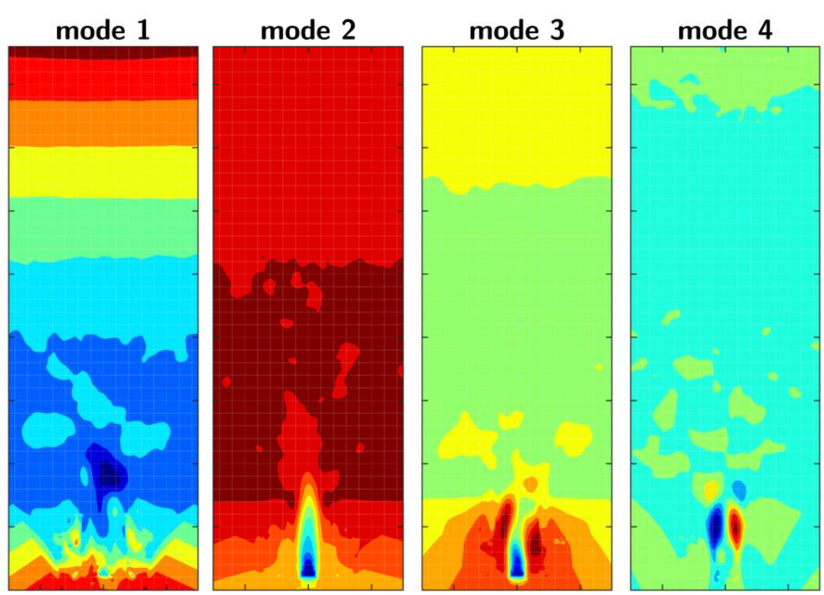

Figure 4: Visualization of first 4 POD modes of Pressure data

Interpretation of these modes can be a challenging undertaking but we can identify the pressure gradient present in the chamber as the first mode followed by a series of monopoles and dipoles present at the bottom of the chamber. Closer examination of the coefficients associated with these modes reveals the frequencies associated with these structures as shown in Figure 5.

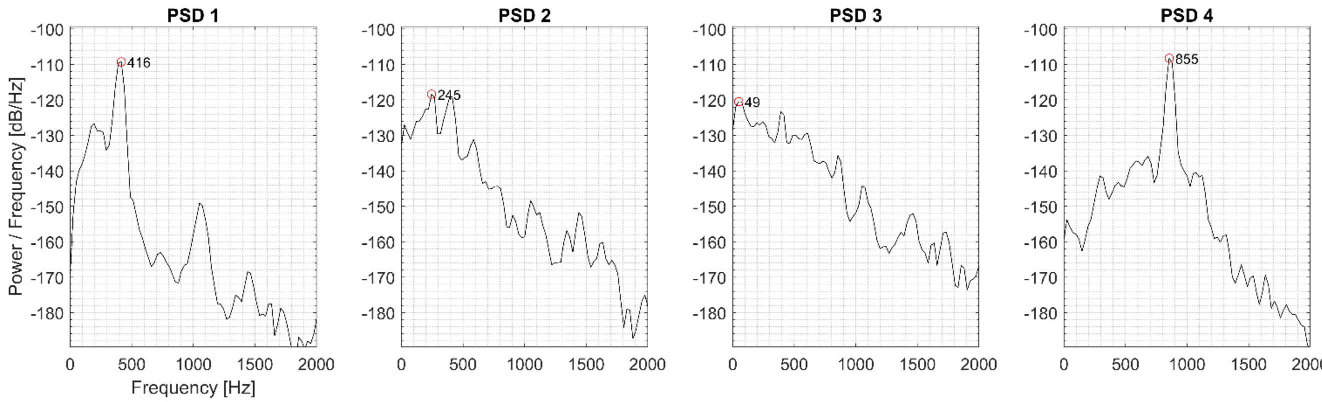

Figure 5: Power spectral density (PSD) of mode coefficients

The dominant frequency of the fourth mode closely resembles the frequency manually extracted by means of FFT analysis which has been identified as the PVC frequency associated with the UT Burner. This also corroborates the observations from unsteady RANS studies on the same burner pointing to a similar value for PVC frequency.

Stability requirements for LES simulations of combusting flows demand a relatively small time marching. Storing contour snapshots for further post processing can become prohibitively large. However, the time shift between the POD assembly matrix snapshots as described in Eq. 2 is arbitrary and can be selected to reflect the frequency range of interest. In this study, this range was selected to be below 2 kHz.

5. Conclusions

Considering their environmental impact and design challenges, the study of acoustic characteristics of aero engines and representative burners are of great interest. Following the design and manufacturing of the UT burner, its acoustic behaviour has been studied. LES of the turbulent combustion was performed on a semi structured numerical grid using a flamelet combustion tabulation method representing the combustion of Jet-A fuel at operating conditions of 473 K and 3 bar. Smagorinsky subgrid scale model was employed and the liquid fuel was injected into the domain with a predefined diameter distribution.

Identification of PVC in swirl burners by means of numerical simulation is subject to manual selection of data extraction points which might not be situated in the PVC path and yield unreliable data. The frequency associated with the PVC present in the UT burner was identified by means of extracting pressure data from a domain cross section. Proper orthogonal decomposition method was applied to the pressure data and by means of a spectral density analysis the PVC frequency was identified. This method provides reliable measurement comparable to manual point selection and applying Fourier transform on the pressure data.

Dominant flow structures rank high among the POD modes as they carry higher energy. This helps to identify the frequencies associated with them in a seamless and robust manner. The assembly matrix for POD analysis can be truncated to only represent these higher modes and discard the lower modes that might not be of relevant interest. Interpretation of these modes and coefficients, however, is subject to closer consideration.

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