Aerospace Science and Technology ••• (••••) •••–•••

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

UNCORRECTED PROOF

The frequency characteristics of the shear layer oscillation in hybrid rocket post-chamber

Sulha Lee [a], Do-Yeong Kim [b], Changjin Lee [a,*]

[a] Department of Aerospace Engineering, Konkuk University, Seoul 05029, Republic of Korea
[b] Aerospace R&D Center, Hanwha Corp., Chungnam 31409, Republic of Korea

ARTICLE INFO

Article history:
Received 9 December 2016
Received in revised form 21 June 2017
Accepted 7 August 2017
Available online xxxx

Keywords:
Shear layer
Hybrid rocket
Post-chamber
Expansion ratio
Wall blowing
Strouhal number
Vortex

ABSTRACT

Visualizing flame images revealed the occurrence of LFI (Low Frequency Instability <20 Hz) in hybrid rocket combustion is significantly related with pressure and combustion fluctuations of around 500 Hz in the post chamber. In this study, numerical calculations for cases with different ER (Expansion Ratio) and the wall blowing effect were conducted to investigate which factor has a more influence on pressure fluctuation of 500 Hz band. In addition, the flow structure change in each case was examined and compared with the baseline. Results show that both wall blowing and the increment of ER increases the turbulent energy of the time-averaged flow and pushes the reattachment point to downward. And it seems that the wall blowing effect considerably increases the recirculation length by modifying the turbulent flow structures. Moreover, results indicate that the wall blowing effect promotes the vortices generation from the inlet and supplies the vortices with more energy to appear in the wake. In the spectrum analysis, also, the wall blowing effect was found to oscillate re-attachment point, resulting in the appearance of additional oscillatory characteristics of $St = O(0.3)$ in the downstream otherwise completely dissipated. Note that the oscillation frequency of $St = O(0.3)$ is corresponding to a dimensional frequency of 490 Hz, which approximately coincides with a measured frequency band of 500 Hz. Therefore, the pressure oscillation in about 500 Hz band in the experiment is strongly related with temporal characteristic of the modified flow structure by wall blowing.

© 2017 Published by Elsevier Masson SAS.

1. Introduction

Low frequency instability (LFI, <100 Hz) in hybrid rocket combustion has been one of the interesting research topics because the occurrence seems to be related with the interaction of many complicated physics such as vortex flow, shear layer oscillation and the additional combustion in post chamber. Even though the comprehensive understanding on the occurrence of LFI remains still unveiled, many reports suggested that heat transfer characteristic of solid fuel was the most influencing factor in determining the oscillatory behavior of the combustion pressure (p') at the LFI [1–3]. It is well known that the combustion instability can be developed by the resonance between combustion pressure and unsteady heat release fluctuations. In this regard, the amplification of combustion pressure of about 20 Hz can be possible only when a positive coupling is established with heat release fluctuations at the same frequency. However, the physical process of generating the heat release fluctuations (q') of about 20 Hz and the coupling mechanism driving into the LFI are still unknown.

A recent study visualizing flame images in the post chamber [4] revealed that the combustion fluctuations of around 500 Hz are newly observed along with the pressure oscillations of around 500 Hz in unstable combustions. Moreover, the establishment of positive coupling between pressure and heat release fluctuations was observed at the LFI. Despite the lack of understanding on the coupling mechanism of combustion pressure and heat release fluctuations of 500 Hz at the LFI, experimental results suggest that the occurrence of LFI is significantly related with the occurrence of pressure fluctuations of around 500 Hz [4].

Interestingly, the pressure oscillations of around 500 Hz were also observed in studies of other researches. Carmicino et al. [3] reported that pressure oscillations of about 500 Hz occur prior to the occurrence of LFI in the tests with HTPB/GOX. And he claimed that the LFI begins at the moment that two different oscillations match; the acoustic oscillations of about 500 Hz and vortex shedding oscillations in the post chamber. Also, Jerome et al. [1] observed the occurrence of pressure oscillations of around 500 Hz in their tests. However, they found that the pressure oscillations of about 500 Hz were not detected in the downstream when swirl

---

* Corresponding author.
E-mail addresses: sulha100@naver.com (S. Lee), doyeongkim@hanwha.com (D.-Y. Kim), cjlee@konkuk.ac.kr (C. Lee).

http://dx.doi.org/10.1016/j.ast.2017.08.007
1270-9638/© 2017 Published by Elsevier Masson SAS.

UNCORRECTED PROOF

oxidizer flow applied. Thus, the generation of pressure fluctuations of around 500 Hz seems to be related with the oscillations of the flow rather than fluctuations caused by acoustic excitations in the post-chamber.

In particular, Kim et al. [5] has done numerical simulation to study the origin of the pressure oscillations of about 500 Hz using LES methodology. They reports that small-size vortices in the combustion gas by the interaction between fuel evaporation and axial oxidizer flow could alter the turbulent flow characteristics and eventually it causes the flow to fluctuate with a peak frequency of around Strouhal number ($\mathrm{St} = f \times h/U_0$, h: step height, U_0: inlet bulk velocity, f: frequency) 0.28 in the post chamber. It is worth noting that the dimensional frequency corresponding to $\mathrm{St} = 0.28$ is about 480 Hz when it is converted using physical properties in the tests [2]. And this can prove that the pressure oscillation of around 500 Hz occurs as the result of the change in turbulent flow structure due to small-size vortices contained in the combustion gas. However, no research has been done what flow structures are responsible for the development of the pressure fluctuations of about 500 Hz.

Meanwhile, Sung et al. [6] did very interesting numerical calculations to investigate the change in turbulent flow structure by applying the periodic injection with a specific frequency at the edge of backward facing step. Results showed that vortex structure begins to roll up and is moving much further downstream than the conventional flow without the injection. Also, numerical calculations by Schafer et al. [7] confirmed that the flow oscillation of $\mathrm{St} = 0.27$ appears in shear layer in the downstream of backward step due to the interaction of upward and downward recirculating flow.

It is well known that a shear layer begins to form from the step edge as the flow passes over the backward-facing step and recirculation zone is formed under the shear layer. Also, the recirculation zone ends at the reattachment point where the shear layer reattaches to the wall surface. Thus, the flow structures in the downstream could be determined by some parameters such as Re (Reynolds number), ER (Expansion Ratio) and initial turbulent structures contained in the inlet flow. Many studies reported that flow oscillations of St = O (0.3) dominates in the initial region of the shear layer due to Kelvin–Helmholtz instability. And flow oscillations of St = O (0.1) is dominantly observed near the reattachment point by the interaction of shear layer and recirculation zone.

In hybrid rocket combustion, the step height is decreasing during the combustion since the diameter of solid fuel is regressed changing ER and eventually this affects to modify the flow structures in the downstream. Therefore it is helpful to understand how the post chamber flow responds to the change in ER and wall blowing especially in terms of oscillatory behavior of the flow. Although, Kim et al. [5] reported small-scale vortices in the inlet flow could take a decisive role in generating the pressure fluctuations of around 500 Hz in the post chamber, a comprehensive study has not yet been made on how the flow parameter changes, such as the inflow of small-size vortices due to wall blowing or ER change, affect the flow characteristics of the flow

This study will examine the effect of enhanced small-scale vortices at the inlet due to wall blowing and the change in step height with different ERs on the generation of pressure fluctuations of about 500 Hz, which was observed in the tests. To this end, numerical simulation was performed for three cases with different ERs and inlet turbulent conditions to identify the dominant parameter in generating pressure fluctuations. Also the change in the flow structure will be examined in detail to understand the origin of the pressure oscillations. Even though this study was done with non-reactive flow, results are expecting to provide many valuable insights and understandings on the physical processes how the pressure fluctuations of about 500 Hz initiates and what flow structures is responsible for the generation of the pressure fluctuations in the hybrid rocket combustion.

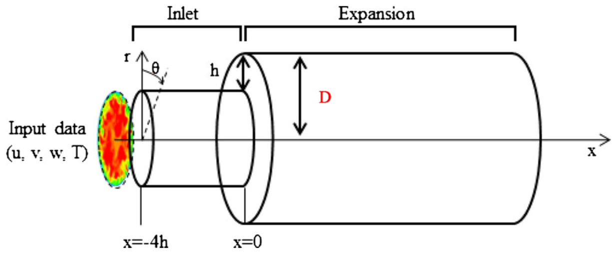

Fig. 1. Computational domain and boundary conditions.

2. Numerical simulation

2.1. Governing equations for LES

A LES code has been developed for the study including preconditioning method, and compressibility effect in low Mach number domain. Normalized governing equations are continuity equation, Navier–Stokes equation, and energy equation that are filtered as in Eq. (1) where τ and t are time variables. Here Q is primitive variable vector and W is conservative variable vector respectively. And F_i and F_{vj} represent inviscid and viscous flux vector at each direction respectively. Also Γ is a preconditioning matrix.

$$\Gamma \frac{\partial Q}{\partial \tau} + \frac{\partial W}{\partial t} + \frac{\partial (F_i - F_{vj})}{\partial x_j} = 0 \qquad (1)$$

$$Q = \begin{bmatrix} p \\ u_i \\ T \end{bmatrix}, \qquad W = \begin{bmatrix} \rho \\ \rho u_i \\ \rho E \end{bmatrix}, \qquad F_i = \begin{bmatrix} \rho u \\ \rho u_i u_j + p\delta_{ij} \\ \rho u_j H \end{bmatrix} \qquad (2)$$

$$F_{vj} = \begin{bmatrix} 0 \\ \tau_{ij} + \tau_{ij}^{*} \\ u_i(\tau_{ij} + \tau_{ij}^{*}) - q_j + (\mu_1 + \sigma_k \mu_t)\frac{\partial k}{\partial x_j} \end{bmatrix} \qquad (3)$$

Here ρ and p are the filtered density and pressure, and u_i and u_j is velocity vectors for each axis in orthogonal coordinate system. And τ_{ij} and τ_{ij}^{*} are laminar and turbulent stress tensor respectively and q_j represents the total heat flux at each direction. Also, Dynamic Smagorinsky model (DSM) is used for SGS stress model. A modified Roe-type flux difference scheme is also adopted which is suitable for LES. And viscous terms are calculated by central differencing and time integration is done using a dual- time stepping method allowable for larger time-step size. The solver is parallelized using an MPI-based domain decomposed strategy. The calculation usually took about 4 weeks with 64 CPUs.

2.2. Numerical domain and boundary conditions

The flow in the post chamber can be approximated by the expanded pipe flow. Note that the expansion ratio ($\mathrm{ER} = D/h$) defined as the ratio of the fuel diameter to post chamber diameter continuously decreases and it is in the range of 1.4 to 2.5 during the combustion in the reference [5]. In this study, ER of the baseline was defined as 2.0. And numerical calculation with $\mathrm{ER} = 1.5$ was also done to analyze the impact of the variation of ER on the changes of flow structure in the post chamber. Fig. 1 shows a schematic of computational domain used in the calculation. The domain consists with two parts: an inlet part and the expansion part simulating a post chamber of hybrid rocket configuration. For the inlet flow, the calculation result of reference [8] was used. The inlet flow contains numerical results of the interaction for

Please cite this article in press as: S. Lee et al., The frequency characteristics of the shear layer oscillation in hybrid rocket post-chamber, Aerosp. Sci. Technol. (2017), http://dx.doi.org/10.1016/j.ast.2017.08.007

Download English Version:

https://daneshyari.com/en/article/5472617

Download Persian Version:

https://daneshyari.com/article/5472617

Daneshyari.com