Acta Astronautica 151 (2018) 655–667

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Experimental investigation of self-excited combustion instabilities with injection coupling in a cryogenic rocket combustor

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ARTICLE INFO

Keywords:
Combustion instabilities
Liquid propellant rocket engine
Thermoacoustic coupling

ABSTRACT

The cryogenic LOX/H2 multi-injector research combustor “BKD” allows the investigation of high-frequency combustion instabilities under realistic conditions. Two different types of self-excited instabilities were observed. For one instability the underlying coupling mechanism was already identified as LOX injection-driven. The second type of combustion instability was experienced for different operating conditions and is characterized by higher amplitudes, more than 75% of the static chamber pressure. Analysis of the pressure data showed that amplitude and frequency of the acoustic field vary strongly over time, which complicates interpretation of the coupling mechanism. A normalization of the shifting frequency shows that the increase of oscillation frequency depends on transverse acoustic velocity. This is an effect that has also been noticed in other experiments and simulations and is explained by improved mixing leading to a reduced length of the combustion zone. This observation suggests that during the large amplitude pressure oscillations the mode shape remains a first tangential (1T) mode with shifting frequency. By using highly resolved information of the acoustic field in the time domain, both from the combustion chamber and the injector volumes, in combination with acoustic modelling of the injector elements, insights into the coupling mechanism could be gained. For periods of lower amplitudes the pressure oscillations are LOX injector-driven, similar to the first type of instability. With increasing amplitude also the frequency of the unstable mode increases and shifts into a region, where interaction with the hydrogen injector 1L mode becomes possible.

1. Introduction

The occurrence of high-frequency combustion instabilities is a serious risk for liquid propellant rocket engines [1]. Combustion instabilities are generated by coupling of the chamber resonance modes with unsteady heat release. In a rocket combustion chamber only a small fraction of the total heat release is necessary to be transferred into the acoustic field in order to have rapidly growing amplitudes that can lead to the destruction of the engine [2].

The basic physical principle behind combustion instabilities was already described by Raleigh in 1878 [3] and specifies that the pressure amplitudes increase if unsteady fluctuations of the heat release are in phase with the acoustic pressure oscillation. A modern version of the Rayleigh criterion can be described by Eq. (1) [4].

$$\iint p'(x,t)\,\dot{q}'(x,t)\,dVdt \;\geq 0 \tag{1}$$

Among the acoustic eigenmodes of the cylindrical combustion chamber volume, the first tangential (1T) mode is considered as the most dangerous [2]. The 1T mode can be standing or rotating [2]. Also intermediate partly spinning modes with non-constant rotational speed are possible [5].

In some cases of spinning 1T modes with high amplitudes, non-linear acoustics result in a steepened wave front, which is often referred to as detonation-like travelling wave [1,6–8]. However, there is a smooth transition from linear sinusoidal acoustic waves to actual detonation-like phenomena inside the chamber and it is also difficult to distinguish between the acoustic 1T mode and a spinning detonation wave, because they show similar frequencies [8]. Since it is believed that detonation-like processes will have a large impact on the coupling between pressure and heat release rate oscillations, it is necessary to identify them.

The underlying mechanisms leading to high-frequency combustion instabilities are often divided into intrinsic mechanisms, which are only based on sub-processes inside the combustion chamber as atomization, mixing and chemical reaction couple with the chamber acoustics, or injection-coupled mechanisms in which also oscillations in the injectors

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https://doi.org/10.1016/j.actaastro.2018.06.057
Received 6 February 2018; Received in revised form 29 May 2018; Accepted 28 June 2018
0094-5765/

Nomenclature

c	Speed of sound [m/s]
f	Frequency [Hz]
p	Pressure [bar]
r	Radius [m]
T	Temperature [K]
t	Time [s]
u	Velocity [m/s]
w_{cr}	Stability limit parameter $[kg/(s\ m^{0.75})]$
x	Fitting parameter [−]
$\eta_{\Delta f}$	Norm. frequency shift [−]
θ	Angular position [rad]
ρ_0	Bulk density $[kg/m^3]$
ϕ_R	Rotational parameter [−]

Subscripts

ac	Acoustic

Superscripts

ˆ	Amplitude
‘	Unsteady

Acronyms/Abbreviations

BKD	Combustor “D”
BKH	Combustor “H”
CEA	Chemical Equilibrium with Applications
DLR	German Aerospace Center
GH	Gaseous Hydrogen
LH	Liquid Hydrogen
LOX	Liquid Oxygen
P_{CC}	Static Combustion Chamber Pressure
PSD	Power Spectral Density
RMS	Root Mean Square
ROF	Ratio of Oxidizer to Fuel
VR	Injection Velocity Ratio

interact with the chamber pressure fluctuation [9].

For the propellant combination liquid oxygen hydrogen (LOX/H2) an effect of hydrogen injection temperature (T_{H2}) on stability was found for the RL-10 and the J-2 engine [10]. The effect was also reported by other research groups [11–13], and also for the propellant methane (LOX/CH4) [14]. Several instability mechanisms as a result of cold fuel injection were proposed. A low injection velocity ratio ($VR = u_{H2}/u_{O2}$), which implies an intrinsic instability, was identified as the crucial parameter by Wanhainen et al. [9,11]. In a later report a low injection pressure drop was identified to be responsible for occurring instabilities [12]. It was hypothesized that a decreasing injection pressure loss (Δp_{H2}) allows interaction of the fuel injector with chamber acoustics, so in other words an injection-coupling mechanism [9,10]. This was also thought to be the case for the LOX/CH4 tests at Rocketdyne [14]. Experiments by Nunome et al. revealed that processes in the recess volume can excite injector resonance modes and hampering of hydrogen flow could occur [13]. Injection coupling is not only related to low fuel temperatures. Coupling of the chamber with LOX post acoustics, also at increased fuel temperatures, were reported by Jensen et al. [14] and for the J-2S engine [9,10].

However, despite a large amount of research was undertaken in the past in order to gain a better understanding and be able to prevent combustion instabilities in rocket engines, the detailed underlying coupling mechanisms are still not completely understood today [1]. For this reason the interaction between chamber acoustics and unsteady combustion is also investigated at the DLR Institute of Space Propulsion with two research combustors. An overview on DLR combustion instability research is presented in Ref. [15]. In one of the DLR combustors, designated BKH, the flame response to acoustic forcing with a siren wheel can be observed through large optical access windows. Analysis showed that the acoustic velocity of transverse modes perpendicular to the flames increases mixing and yields shortened flames or a retracted combustion zone [15,16]. Similar findings have also been reproduced numerically [17,18], and described for other experiments with acoustic forcing [19]. A frequency shift during resonant combustion was noticed, which was explained by an increased speed of sound due to the reduced flame length [20,21].

The other DLR combustor, BKD, allows the thermoacoustic driving for self-excited combustion instabilities to be investigated under representative conditions. So far two different types of instabilities have been observed. The first type of instability is characterized by moderate amplitudes and appears reproducible for certain operating conditions. The coupling mechanism of this type has already been identified as injection-driven: heat release rate oscillations with the resonance frequencies of the LOX post drive the first tangential chamber mode [22]. Experiments with different hydrogen injection temperatures were also conducted, but for cold T_{H2} values the frequency spacing between chamber 1T mode and the LOX posts was higher and the chamber became more stable [23]. Interaction of chamber resonance modes with LOX injector acoustics is not only relevant in the DLR combustor BKD, but was also reported to play a significant role in instabilities in other rocket engines of different scales [9,10,13,24], and the propellant combination LOX/CH4 [25,26].

The second type of instability in BKD shows larger amplitudes, sometimes even exceeding the measurement range of the dynamic pressure sensors. This type of instability appeared in a total number of six test runs, including different hydrogen temperatures. An exemplary spectrogram for a test run with cold hydrogen injection temperatures (LH run) is shown in Fig. 1. For this specific run unstable combustion appeared for several different operating conditions.

A more detailed view of the growing instability of the test run presented in Fig. 1 is given in Fig. 2 by the raw and high-pass filtered time trace of one of the eight dynamic pressure sensors. It can be seen that the instability is rapidly growing. In less than 5 ms the amplitudes grow from stable conditions to +30 bar.

Due to the fact that this type of instability mainly appeared for cold hydrogen test conditions, the coupling mechanisms can be analysed and compared to the ones proposed in literature. A first attempt to identify the mechanism suggested that coupling with the hydrogen injector element may play a role [27]. However, a study of the acoustic pressure field dynamics revealed that both amplitude and frequency of the oscillation vary rapidly in time [28]. Also a transition from standing to spinning 1T mode was observed for increasing amplitudes - effects very similar to the aforementioned detonation-like instabilities.

In order to further analyse the underlying driving mechanism of the type 2 instability, the acoustic pressure field dynamics are investigated and discussed first. The result of this investigation will then help to analyse the coupling mechanism in more detail. Finally, it will be shown that a varying chamber resonance frequency leads to a triple-coupling system with both the LOX and the hydrogen injectors.

2. Experimental setup

2.1. Combustor BKD

The hot-fire tests were conducted with the DLR research combustor BKD at the European Research and Technology Test Facility P8 for cryogenic high pressure combustion. BKD is a cylindrical combustor,