Analysis of high amplitude acoustic pressure field dynamics in a LOX/H2 rocket combustor

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High-frequency combustion instabilities present a serious problem for liquid propellant rocket engines. These interactions between combustion chamber acoustics and variations of the heat release rate are difficult to predict, because the underlying coupling mechanisms are still not fully understood. For this reason self-excited combustion instabilities are investigated with a cryogenic research combustor at DLR Lampoldshausen. In order to get a better understanding of the coupling mechanisms the acoustic pressure field inside the combustion chamber needs to be described precisely. Due to the highly turbulent nature of the processes in a rocket combustor it can be expected that also the acoustic pressure field shows some variation during unstable combustion. In the framework of this report new methods with high time resolution were applied to experimental data to analyze the dynamics of the pressure field for different types of instability. The results reveal that the applied methods give further insight into the excited pressure field and may help to identify the coupling mechanisms in the future.

1. Introduction

High-frequency combustion instabilities in liquid propellant rocket engines (LPRE) present a serious issue during engine development since the beginning of rocket propulsion [1]. Combustion instabilities are driven by positive coupling between periodic heat release fluctuations, as a result of unsteady combustion, with the combustion chamber pressure oscillations, which is known as the Rayleigh criterion. Due to very high heat release rates in rocket engines only a small fraction of the released energy needs to be transferred into acoustic energy to cause rapidly growing oscillation amplitudes, which can even lead to the destruction of the engine [2, 3].

Even though high-frequency combustion instabilities were observed during the development of a large number of flight engines, for example the F-1, J-2S [2] or the LE-X [4], and have been studied experimentally and numerically by different research groups, the coupling mechanisms are still not completely understood. Often it is distinguished between intrinsic and injection-coupled mechanisms [2]. Intrinsic coupling describes mechanisms caused by variation of sub-processes inside the chamber as atomization, mixing and combustion, whereas injection coupling specifies, pressure or mass flow oscillations in the injectors that couple with chamber eigenmodes and amplify them. In the present research combustion chamber of the DLR, two different types of instability were observed, which both seem to be related to injection-coupling [5, 6]. In

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order to analyze injection coupling, usually the resonance frequencies of the injectors and the combustion chamber are compared.

Tests with another DLR research combustor with forced acoustic excitation showed that pressure oscillations influence the speed of sound distribution inside the chamber [7, 8]. Thus the chamber resonance frequencies are a function of the amplitude of the eigenmode [9]. In other experiments, evidence was found that the rotational behavior of a tangential pressure field might also be connected to the amplitude [10, 11]. From previous studies it is known that for both types of instabilities in BKD the amplitude is not constant and therefore dynamic response of the on-resonance pressure field could occur. So in order to analyze the coupling mechanisms it is important to not only calculate time-averaged characteristics of the pressure oscillation, such as Power Spectral Densities (PSDs), but to also gain insight into the dynamic variations of the acoustic pressure field.

2. Experimental Setup

2.1. Combustor BKD

The current analysis was performed with experimental data of the DLR research combustor BKD. This research combustor is operated with the cryogenic propellant combination LOx/H2 at the test bench for high pressure combustion, P8. BKD allows self-excited combustion instabilities to be studied under representative conditions such as supercritical chamber pressures with respect to oxygen, relevant propellant mixture ratios and a large number of injection elements. As shown in Fig. 1, the combustor consists of three main elements: injector head and the water-cooled combustion chamber, which is divided into a cylindrical and a nozzle segment. The dimensions of the combustor are a diameter of 80 mm, a throat diameter of 50 mm and a characteristic chamber length of $L^* = 0.64$ m. The LOx is fed by two parallel tubes entering into the oxygen manifold on one side of the injector head, whereas the H2 is supplied by six evenly distributed
connectors. The propellants are injected through 42 recessed and tapered shear coaxial elements and the injector pattern is shown in Fig. 2.

To investigate the pressure field a special measurement ring is placed between the injector head and the cylindrical combustion chamber segment. Eight water-cooled Kistler 6043A dynamic pressure sensors are flush-mounted in the ring, as shown in Fig. 2. The pressure sensors are circumferentially distributed with a spacing of 45°, which allows reconstruction of tangential resonance modes. The measurement range of the sensors was set to ±30 bar and the data were sampled with a frequency of 100 kHz.

2.2. Operating conditions

BKD is operated at representative conditions for cryogenic rocket engines. In past test campaigns a large number of different operating conditions, mostly defined by the combustion chamber pressure PCC, the propellant mixture ratio \( \text{ROF} = \frac{\dot{m}_{\text{O}_2}}{\dot{m}_{\text{H}_2}} \) and the hydrogen injection temperature \( T_{\text{H}_2} \), were tested. The P8 test bench allows to operate with different hydrogen injection conditions by the use of two different H2 feed systems, the GH2 for gaseous hydrogen, and the LH2 interface for liquid hydrogen. At the GH2 interface, the hydrogen is stored at ambient temperature and a liquid nitrogen heat exchanging system can be used to cool down the propellant. The hydrogen of the LH2 interface is stored as a cryogenic fluid. For BKD this results in hydrogen injection temperatures of approximately 45 K using the LH2 interface and 95 K with the GH2 interface. Test runs of both interfaces were used within this study and the abbreviations will be used to determine the H2 injection conditions. However, it should be noted that in both cases the hydrogen is supercritical.

2.3. Summary of combustion instabilities in BKD

So far two different types of self-excited high-frequency instabilities have been observed in BKD data. In the following paragraph a brief summary of these two instability types is given.

The first type of instability is characterized by an excited first tangential chamber
resonance mode (1T) at 10 kHz, which occurred for the load point PCC 80 bar and ROF 6 with hydrogen injection temperatures of 95 K. For these conditions the amplitudes reach maximum peak-to-peak values of 16–34 bar and 1 s-averaged RMS (Root Mean Square) values were between 2.5 and 3.4 bar, which indicates that the amplitude of this instability varies over time [5]. The observations were explained with an injector-driven mechanism. It was shown that the combustion process is modulated with frequencies matching the longitudinal resonance modes of the LOx posts. As soon as the chamber 1T frequency, defined by the operating conditions (PCC, ROF and $T_{\text{H}_2}$), matches a frequency of the LOx post, the Rayleigh criterion can be fulfilled and the acoustic oscillations are amplified [5].

Recently, a second type of instability has been discovered. The new instability mode is characterized by relatively strong chamber pressure oscillations, reaching peak-to-peak amplitudes of up to 86% of PCC and 1 s-RMS values up to 18 bar were observed. With time averaged methods such as PSDs or spectrograms the peak frequency of this instability mode seems to be higher than the expected 1T frequency and can be found between 10.8–12.1 kHz. While the LOx post related 10 kHz instability was observed for a certain load point only, this type of instability occurred in 6 test runs at different oper-
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At the current time the coupling mechanism of this type of instability is unknown. However, in a previous study several observations were presented, which suggest that hydrogen-side injection coupling plays a significant role in the instability mechanism [6].

Figure 3 shows the spectrogram of one of the test runs with the LH2 interface. The type 2 instability is present between 14–32 s. The load point of 70 bar and ROF 4 of this test run, from 16 to 20 s, was used exemplarily for the analysis of type 2 instability within the scope of this report. It can be seen that the peak frequency is found around 2 kHz above the usually expected 1T frequency at 10 kHz. Also the on-resonant acoustic spectrum has much broader peaks and the amplitudes over the whole range of frequencies are increased. Figure 3 also shows that $T_{\text{H2}}$ seems to be increased during unstable combustion. It is believed that this increase is a result of unsteady H2 flow at the location of the thermocouple due to the strong pressure fluctuations. However, also other effects as increased heat transfer through the faceplate might contribute to the temperature change. A more detailed discussion is given in [6].

The different character of the two instability modes is clearer in Fig. 4, where the PSD for stable operation is compared against the known LOx post driven type 1 instability and the new type 2 instability. PSDs were calculated over a duration of 1 s with the Welch method using a Hanning window with 8192 samples and an overlap of 4096 samples. Again the type 1 instability is characterized by a very sharp peak at 10.2 kHz, whereas the type 2 instability shows a very broad peak with a higher peak frequency. For this reason it is initially unclear which chamber resonance mode is excited for the second type of instability.

3. Methodology

3.1. Pressure field reconstruction algorithm

The first method, which was applied to existing test data, is the DLR pressure field reconstruction algorithm, a DLR in-house development. The basic principle of this algorithm is to fit the bandpass-filtered signals of the eight dynamic pressure sensors to the analytic solution of the first tangential pressure field in a cylindrical volume. A detailed description of the method can be found in [12]. The output of this algorithm is the

![Figure 4. Comparison of PSDs for the different type of instabilities in BKD.](image-url)
instantaneous 1T pressure field defined by the instantaneous 1T amplitude and the orientation of the nodal line. On the basis of the instantaneous orientation of the nodal line, the rotational character of the 1T mode can be analyzed. The rotational parameter $\Phi_R$ can take values between -1 and 1. A value of -1 describes spinning in counter-clockwise direction, $\Phi_R = 0$ a standing mode and $\Phi_R = 1$ a clockwise spinning 1T mode. All other values between 0 and 1 are possible and describe partially spinning modes with varying rotational speed. However, it is assumed that the direction of the rotation does not have a major influence on injection coupling and therefore only the absolute value of $\Phi_R$, as defined in Eq. (3.1), will be evaluated.

$$|\Phi_R| = \begin{cases} 
1, & \text{spinning 1T mode} \\
0, & \text{standing 1T mode} 
\end{cases}$$

(3.1)

### 3.2. Instantaneous frequency estimation

In another DLR combustor, designated BKH, it was observed that under forced acoustic excitation of tangential modes, the chamber resonance frequencies shift to higher values. This effect was explained with improved mixing due to tangential acoustic velocity [7, 9]. For both types of instabilities in BKD it is known that the amplitude varies over time. This effect is even stronger for type 2 instability, where the variation of amplitude is more than twice as large as for type 1 and it seems like the amplitude of the instability is modulated with a lower frequency. However, for both instabilities in BKD it has not yet been analyzed if the frequency of the instability is a function of its own amplitude. For this purpose it was aimed to calculate the instantaneous frequency of the resonance mode.

The applied method for the instantaneous frequency estimation is based on the Hilbert transform. It is assumed that, after band-pass filtering between 9–12 kHz, the pressure signals are mono-frequent and can be described as shown in Eq. (3.2). The instantaneous phase of the analytic signal, calculated with the Hilbert-transform $H(f(t))$, is defined with Eq. (3.4). Finally, the instantaneous frequency is estimated according to Eq. (3.5) with the time derivative of the unwrapped instantaneous phase. The described method was cross-validated with a second method based on the zero crossing rate, which yielded identical results but was computationally less efficient.

$$p'(t) = A(t) \cdot \sin(\varphi(t))$$

(3.2)

$$p'_a(t) = p'(t) + iH(p'(t))$$

(3.3)

$$\varphi(t) = \arg(p'_a(t))$$

(3.4)

$$f(t) = \frac{1}{2\pi} \cdot \frac{d\varphi(t)}{dt}$$

(3.5)

### 4. Results

#### 4.1. Type 1 instability: LOx post driven 1T mode

Figure 5 shows the calculated instantaneous characteristics of the on-resonance pressure field for type 1 instability over a duration of 0.1 s. Usually the experimental data of
BKD is analyzed in windows of 1 s duration. However, in order to visualize the dynamics of the pressure field a shorter length was chosen here. Nevertheless, it was verified that the presented characteristics are similar over the whole length of the common analysis windows.

It can be seen that the 1T amplitude fluctuates around a mean value of 3.5 bar. The standard deviation over the period of 1 s is 1.2 bar, so the amplitude stays at a rather moderate level. The rotational characteristics of the 1T mode shows a higher irregularity, almost every possible value between 0 and 1 can occur during operation of the combustor. However, simply inspecting at the curve of $\Phi_R$ gives the impression that standing modes ($\Phi_R = 0$) are more likely. This was also confirmed with a statistical analysis in form of a histogram calculated over the whole duration of a typical analysis window of 1 s, shown in Fig. 6. The observed tendency towards standing 1T mode for type 1 instability is in agreement with previous studies, in which it was found that for type 1 instability there is a trend towards a standing mode with a statistically preferred orientation of the nodal line, which indicates some kind of asymmetry of the system [13]. In addition to
known behavior of the amplitude and rotation of the pressure field the frequency of the 1T mode has been analyzed in more detail. Figure 5 also shows the estimated instantaneous frequency averaged over all 8 sensors, which stays almost constant at 10.2 kHz. This is in agreement with the green PSD shown in Fig. 4, where a very sharp peak indicates a rather constant 1T frequency at 10.2 kHz. The very constant 1T frequency can be explained with the coupling mechanism of this type of instability. As was shown in [5] this combustion instability is driven by heat release rate fluctuations with longitudinal resonance frequencies of the LOx posts, which is mostly defined by the oxygen temperature that is held almost constant over the duration of a test run. For this reason the driving frequency is fixed and amplitudes decrease as soon as the frequency spacing between LOx post and chamber resonance mode increases [5].

4.2. Type 2 instability: high amplitude pressure oscillations

The same analysis was also performed for the new instability mode referred to as type 2 instability. The results are again plotted for a duration of 0.1 s and can be seen in Fig. 7. For type 2 instability the dynamics of the pressure field are completely different and variations are significant. The amplitude is periodically driven and damped. Therefore the amplitude of the pressure field varies between stable periods and violent oscillations of up to 30 bar. Also the frequency of the pressure oscillations increases periodically and seems to follow the amplitude variation. At low amplitudes the instantaneous frequency starts at approximately 9.5 kHz and with increasing amplitudes frequencies of up to 12 kHz can be observed. The changes of the instability frequency happen very fast, in about 10 ms the conditions can change from low amplitude 9.5 kHz mode to the high amplitude 11.5 kHz and back again. Thus the utility of PSDs over 1 s is limited.

In order to analyze if the high frequency mode is in fact a 1T mode with increased frequency and not for instance the first combination mode 1T1L, which is in the same frequency range for unperturbed conditions, a PSD for a short window with constantly high amplitude and increased frequency was calculated. The PSD, shown in Fig. 8, was calculated over a short duration of 0.006 s, which is highlighted with a gray background in Fig. 7, and therefore has a poor frequency resolution of about 200 Hz. In the acoustic spectrum three tangential and radial chamber resonance modes were identified, which all show a frequency shift of roughly 20% compared to stable conditions. This suggests
that the type 2 instability cannot be a 1T1L mode and is most likely a 1T mode with increased frequency as a result of high amplitudes. The relation between the pressure field frequency and amplitude was then analyzed in more detail over a duration of 1 s and the results are presented in the form of a scatter plot in Fig. 9. A clear trend can be observed showing that increasing amplitude leads to the increased frequency.

A similar effect has been discovered with another DLR research combustor, BKH, under forced excitation [7]. With an optical access window and high-speed cameras it was shown that the acoustic velocity of a driven tangential mode improves mixing and reduces the length of the combustion zone. For this reason the temperature and speed of sound in the near-faceplate region increases which leads to shifted frequencies. In BKH frequency shifts of 5.5% for 7–8 bar amplitudes were observed, so the frequency shifts in BKD of up to 22% seem to be feasible for the obtained amplitudes. In addition the speed of sound corresponding to the maximum frequencies of 12 kHz is still below the theoretical frequency for chemical equilibrium conditions, which is 13 kHz. So it is hypothesized that the driven chamber resonance mode for type 2 instability is a 1T mode with increased frequencies as a function of amplitude due to improved mixing.

In contrast to the observations of type 1 instability, it can now be detected that there is also a correlation between the amplitude and spinning behavior of the pressure field.
In Fig. 7 it seems that the rotational parameter $\Phi_R(t)$ responds to increases of the amplitude with a certain time lag, such that increasing amplitudes lead to a 1T pressure field that rapidly shifts from standing to fully spinning. The statistical histogram analysis, presented in Fig. 10, also shows this characteristic. Both standing and fully spinning modes have a high probability, whereas values of $\Phi_R(t)$ between 0 and 1 are less likely and only appear in the transition from standing to spinning mode.

In other experiments with excited acoustic 1T modes in cylindrical volumes for both cold gas [11] and hot-fire rocket engine conditions [10], similar observations were described. Spinning modes are related to higher amplitudes, indicating that the spinning modes are more energetic [11]. At the moment the reason for the transition from standing to spinning modes remains unknown and requires further investigation. Nevertheless, similar to type 1 instability, the driving seems to be highest for standing modes. In contrast to type 1 instability, the coupling mechanism of type 2 instability seems to allow the 1T frequency and amplitudes to further increase. When a certain level of amplitude is reached, transition from standing to spinning takes place. After a few oscillation periods, the high amplitude pressure wave damps out and driving starts again with a standing 1T mode.

### 5. Summary and Discussion

Two different types of high-frequency instabilities have been observed in the DLR research combustor BKD. Both modes show a variation of pressure amplitude in the raw signals. From other experiments it is known that the amplitude of tangential modes can influence the resonance frequencies of the combustor and the rotational character of the modes. In order to analyze the coupling mechanisms of the combustion instabilities, the pressure field inside the combustor needs to be described accurately. Therefore it was the goal of this paper to analyze the dynamics of the pressure field in BKD at on-resonance combustion. For this purpose the existing pressure field reconstruction algorithm, in combination with other methods, was used to estimate the instantaneous pressure field of the instability.

Analysis of the well-known LOx post driven 10 kHz instability mode confirmed previous observations. There is a statistical trend towards a standing 1T mode, and the...
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frequency and amplitude of the mode stay relatively constant during unstable combustion. The tendency towards a standing mode with a statistically preferred orientation indicates an asymmetry in the system. The identification of this asymmetry is work in progress. There are two hypothesis regarding the moderate limit cycle amplitude around 4 bar and the almost constant instability frequency: either the growth rate of this coupling mechanism is much lower compared to type 2 instability, so that the limit cycle amplitude is reached at around 4 bar and the influence on frequency seems to be insignificant, or secondly, the driving heat release rate fluctuations with the nearly constant LOx post resonance frequencies, do not allow 1T mode frequencies to shift away from the excitation frequency, which also limits the growth to higher amplitudes due to the relation between amplitude and frequency. However, further analysis of the growth rates and type 1 frequency shift is required in order to verify one of the theoretical limitations.

Within this study it was shown that changes of the type 2 pressure field characteristics, such as the amplitude, the rotational character and the frequency, are significant and even seem to be connected to each other. Whereas the relation between mode frequency and amplitude can be explained with improved mixing due to the tangential acoustic velocity, it remains unknown which effect leads to the transition from a standing to rotating 1T mode. Due to the rapid and drastic changes of the acoustic field during type 2 instability, the use of common analysis methods as PSDs over the analysis window of 1 s yields results that are difficult to interpret or lack key information. Current analysis also addressed identification of the unstable mode, and suggests that the type 2 instability is also dominated by the first tangential chamber mode, but with increased speed of sound. In contrast to the first type of instability, the coupling mechanism of type 2 instability seems to allow positive coupling over a wider range of resonance frequency.

Altogether the current analysis showed the importance of instantaneous information about the dynamic pressure field during unstable combustion. For the analysis of injection coupling, or the comparison with simulations, the influence of amplitude on mode frequencies must be considered. The instantaneous frequency estimation approach used here may help to gain further insight into the coupling mechanisms in future analyses.

Acknowledgments

Financial support has been provided by the German Research Foundation (Deutsche Forschungsgemeinschaft – DFG) in the framework of the Sonderforschungsbereich Transregio 40. The authors would like to thank the crew of the P8 test bench for performing the test runs.

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