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Modelling Acoustic Excitation for the Simulation of Combustion Instability Experiments

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Abstract

An experimental combustor, designated BKH, has been developed at DLR Lampoldshausen to investigate combustion instability. The combustor operates with cryogenic liquid oxygen and hydrogen propellants at supercritical pressure conditions analogous to real rocket engines. It features an excitation system for driving acoustic disturbances in order to study combustion instability phenomena. BKH experimental results are being used to develop and validate numerical models. Methods of simulating the influence of the excitation system on the BKH chamber have been examined and the results compared with BKH experiments under cold flow operating conditions.

Introduction

Combustion instabilities refer to a spontaneously developing and self-sustaining coupling between acoustic and combustion processes inside combustion chambers. Acoustic pressure disturbances may interact with combustion processes such that mutual reinforcement occurs. If left unchecked, the amplitude of the pressure fluctuations may grow and affect the internal flow field within the combustion chamber. If the instability is large enough it can compromise the structure or affect the operation and lifetime of rocket engine combustion chambers, possibly leading to a premature failure of the engine and loss of a rocket mission.

High frequency combustion instabilities, occurring at frequencies greater than 1000 Hz, are the least understood and most damaging type of instability. At high frequencies the acoustic behaviour is attributed to the resonant modes of the combustion chamber volume. The mechanisms behind high frequency combustion instabilities are not fully understood and, to date, cannot be accurately predicted. The only way to ensure an engine is free from combustion instabilities before operation is to complete extensive ground testing of the engine over its operational envelope. An extensive summary of combustion instability research and treatment techniques was compiled in 1972 [7]. Further guidelines to ensure rocket engine combustion chambers are free from combustion instabilities have been published by Priem [15].

The necessity to perform ground testing, and the potential risk of further development work being required after combustion instabilities are discovered, adds significant time and cost to the development of new rocket engines. The ability to accurately predict combustion instabilities during the design phase with numerical tools would reduce risk and allow for more economical rocket engine development in the future.

The current work aims to develop and validate a modelling approach for simulating combustion instability experiments. High frequency combustion instability experiments have been conducted using an experimental combustion chamber, dubbed BKH, at DLR Lampoldshausen. The BKH experiments offer unique data at conditions analogous to real rocket engines for numerical validation. Numerical boundary conditions used to acoustically excite the chamber during simulations are being investigated and validated against BKH experimental results.

Acoustic Excitation Systems

The use of naturally unstable combustion chambers for combustion instability research is problematic as the frequency and amplitude of the disturbance is difficult to control. Therefore naturally stable combustion chambers with acoustic excitation systems are used to conduct high frequency combustion instability experiments. The purpose of the acoustic excitation system is to produce a continuous and controlled acoustic disturbance to excite the acoustic modes of the combustion chamber volume. In ambient and cold flow operating conditions, electronic actuator acoustic excitation systems may be used. For example Chehroudi et al. [1, 2] used a piezo-siren acoustic excitation system to study the influence of acoustics on nitrogen jets at sub- and super-critical nitrogen pressure conditions. However, electronic actuators cannot produce sufficient amplitudes for high frequency combustion instability research during hot fire operation of combustion chambers.

Leocourt and Foucaud [10] were the first to apply an acoustic excitation system to liquid propellant rocket engines for high frequency combustion instability research. The acoustic excitation system drives acoustic disturbances by modulating the throat area of a nozzle attached to the chamber. The throat area is modulated using a rotating toothed wheel aligned such that the teeth cover nozzle throat. As the wheel rotates the flow through the nozzle is periodically interrupted causing an acoustic pressure disturbance to propagate from the nozzle back into the chamber.

A limitation of the nozzle and exciter wheel system is that, unlike electronic actuator systems, the amplitude and form of the disturbance is poorly understood. Limited data have been collected to describe the flow conditions in the vicinity of a nozzle and exciter wheel system. The systems are designed to produce a smooth sinusoidal disturbance, yet in reality overtones and other phenomena are often observed. Hardi et al. [6] lists and describes modern examples of high frequency combustion instability experiments conducted using nozzle and exciter wheel systems; the Common Research Combustor (CRC) operated by the DLR and the French National Center for Scientific Research (CNRS), the multi-injector combustor (MIC) and very high amplitude modulator (VHAM) operated by the French Aerospace Lab (ONERA) and CNRS, and the BKH combustion chamber operated by DLR. To model experiments which use a nozzle and exciter wheel system, a better understanding of the disturbance and a methodology for implementing appropriate boundary conditions are sought.

Experimental Setup

The BKH combustor, shown in Figure 1, is used for high frequency combustion instability experiments. BKH operates at pressures ranging from 40 bar (sub-critical oxygen pressure) to 60 bar (super-critical oxygen pressure) using cryogenic oxygen and hydrogen propellants. The combustion chamber features a rectangular geometry with windows located on each side for optical access to the injection zone, and a nozzle and exciter wheel for excitation. The combustion chamber volume is 305 mm long, 50 mm wide and 200 mm high. The rectangular geometry was designed to match the resonant mode frequencies of full scale upper stage rocket engines. BKH experiments are conducted at the European Research and Technology test Facility P8 for cryogenic rocket engines at DLR Lampoldshausen. Additional BKH information can be found in Ref. [5,6].

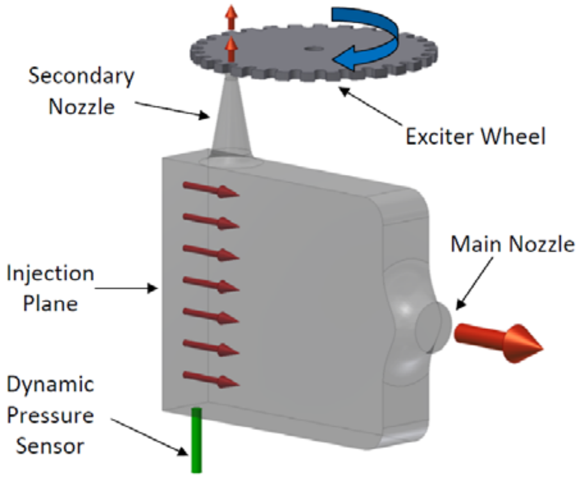

Figure 1. Concept diagram of the BKH chamber and excitation system

The BKH excitation system consists of a secondary nozzle located in the top wall of the chamber and exciter wheel. The orientation of the secondary nozzle perpendicular to the flow direction favours excitation of the transverse acoustic mode. The secondary nozzle throat area is approximately 16 times smaller than the main nozzle throat area. The rotational velocity of the exciter wheel is controlled during a test to ramp through a range of frequencies and excite the resonant modes of the chamber. With the excitation system, BKH experiments have recorded acoustic pressure fluctuations greater than 9% mean chamber pressure when exciting at the resonant frequency of the chamber.

Cold flow tests are completed primarily to test new experimental hardware. During a cold flow test only hydrogen gas is injected into the chamber and no combustion occurs. Therefore cold flow tests provide an opportunity to study the chamber acoustics without the influence of combustion processes.

BKH cold flow tests have been conducted with operation of the acoustic excitation system. The frequency of the acoustic disturbance applied by the excitation system is ramped during the test, such that the response of the chamber to a range of frequencies is recorded. A noticeable increase in the amplitude of the acoustic disturbance is observed when the excitation frequency corresponds to a resonant frequency of the combustion chamber. Periods are chosen for comparison with numerical results when the excitation frequency is of interest. Pressure data are collected from 6 dynamic pressure sensors symmetrically located in the top and bottom walls of the BKH combustion chamber.

Simulation of Acoustics Disturbances

Simulation of high frequency combustion instabilities requires consideration of the coupling between acoustics and heat release. When moving beyond simplified cases an analytical approach is not possible due to the number of complex processes affecting heat release, such as atomisation, mixing, and combustion, which are also affected by acoustic processes. The increasing computational power and resources available today has led to the use of flow solvers to simulate the flow field and combustion. The acoustic processes are then calculated by either a separate acoustic solver, or by the flow solver itself. The method by which the acoustic disturbance is imposed upon the model is dependent on the overall approach taken.

Nicole and Habiballah [13] and Laroche et al. [9] used a flow solver to model both the flow field and acoustics. Acoustic disturbances were imposed by superimposing an acoustic disturbance upon an initial flow field solution and observing its decay during transient simulations. This method allowed the damping of the chamber to be assessed, but cannot be applied to a continuously driven system.

Schmid and Sattelmayer [17,18] employ an acoustics solver coupled to a flow solver. The flow solver is used to simulate single injection elements. Acoustic disturbances are imposed on the injection elements by applying a calculated mass flow across the computational domain. The mass flow is calculated by the acoustics solver, such that it matches the acoustic disturbance at the location of the injection element. The response of the element to the acoustic disturbance calculated by the flow solver is then reported to the acoustics solver. As the computational domain of the flow solver is reduced this method is numerically less expensive when simulating a chamber with a large number of injection elements.

Rey et al. [16] describe a method whereby transverse acoustic disturbances acting upon a reduced computational domain of multiple injection elements by imposing a flow velocity into and out of the domain at the boundaries. Mery et al. [10] and Hakim et al. [4] have used this method to model the MIC with VHAM excitation producing a transverse disturbance across the injection region using a flow solver.

Nicole [12] and Hakim et al. [5] have also simulated the entire VHAM geometry with an acoustic excitation system. The influence of the acoustic excitation system was approximated by a sinusoidal pressure or mass flow at the boundary of the nozzle during transient simulations.

The aforementioned methods, when applied to a combustion chamber that uses an acoustic excitation system, require various assumptions. Knowledge of amplitude and structure of the acoustic disturbance generated, along with how the internal flow field is effected would allow such methods to be applied with greater confidence.

Numerical Methodology

Acoustic disturbances inside the BKH chamber are generated by the interrupted flow through the secondary nozzle. To model the transfer of fluid motion into acoustic pressure, the DLR TAU-code flow solver was selected to simulate both flow and acoustic processes. Simulation of the acoustic excitation system in detail is outside the scope of the current work. Instead, different boundary conditions are implemented at the secondary nozzle exit plane boundary and the resulting acoustic disturbance is compared with BKH experimental results to determine the best approach.

The DLR TAU-code is a hybrid structured/unstructured second-order finite-volume flow solver for the compressible Euler and

Navier-Stokes equations in the integral form. It has been validated for a range of steady and unsteady flow cases [3]. Turbulence models ranging from RANS one and two equation models to detached and large eddy simulations have been implemented in TAU.

Karl and Lüdeke [8] validated the TAU-code for acoustic damping cavities. They employed the AUSMPUP upwind solver which is an extension of the AUSM+ scheme. A Jameson-type dual time stepping scheme was used for unsteady calculations. The same numerical method is used for the current work.

Description of Boundary Conditions

Two different boundary condition methodologies, to numerically represent the influence of the siren wheel, have been examined. Transient computations are begun from an initially unperturbed flow field solution.

Open/Closed Boundary

The secondary nozzle exit plane boundary condition is alternated between an outflow, representing the nozzle being open, and a solid wall. The controlling parameter for this approach is the proportion of time per cycle the boundary is open or closed. For this work the boundary condition was alternated such that the nozzle is open and closed for equal periods of time.

Sinusoidal Pressure Boundary

The secondary nozzle exit plane boundary condition is prescribed as an outflow condition. The pressure prescribed at this boundary, P_{out} , is then modified to reflect the rise in pressure produced by the exciter wheel interrupting the flow through the secondary nozzle. The pressure is modulated assuming a sinusoidal pressure disturbance by Equation 1.

$$P_{out} = P_{start} + P_d(1-\cos(\omega t)) \tag{1}$$

The start pressure, P_{start}, was set to ambient pressure to match the initial unperturbed conditions where the nozzle is open. The disturbance pressure, P_d, was set to just over half the mean chamber pressure. Therefore the prescribed pressure fluctuates between ambient pressure corresponding to a fully open nozzle, and slightly more than the mean chamber pressure representing the nozzle being blocked.

This approach is based on the assumption that the secondary nozzle is not completely blocked by the siren wheel at any point. Therefore the flow through the nozzle is never completely halted. The amplitude of the disturbance P_d may be controlled to better match experimentally observed values.

Results

Figure 2 shows dynamic pressure data recorded by a sensor located in the lower wall of the BKH chamber opposite the acoustic excitation system as shown in Figure 1. The data were recorded during a cold flow test with the acoustic excitation system operating at an off-resonance frequency of 3000Hz. Figure 3 shows a PSD plot of the same pressure data. The tallest sharp peak corresponds to the excitation frequency. The other peaks, visible at multiples of the excitation frequency, are overtones.

The experiment was simulated with acoustic excitation at the same off-resonance frequency of 3000 Hz. Pressure data from the transient numerical results were extracted from the same location as the pressure measurements taken during the BKH experiment. Figures 4 and 5 show the pressure disturbance simulated with each boundary condition. The pressure data were extracted from the numerical results at the same location as the sensor used to collect the data shown in Figure 2.

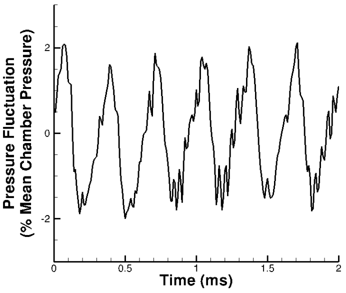

Figure 2. Pressure data recorded during a BKH cold flow test

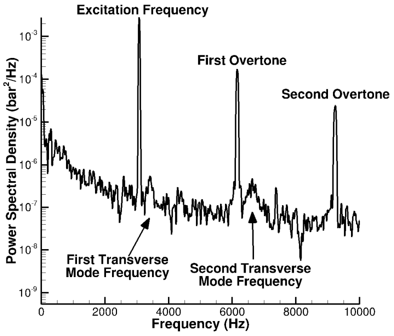

Figure 3. PSD plot of dynamic pressure data

Qualitatively, the open/closed boundary condition results shown in Figure 4 appear to produce a disturbance similar to that observed experimentally. The sinusoidal pressure boundary condition results shown in figure 5 produce a noticeably different disturbance with a second peak. The second peak is attributed to local flow phenomena at the nozzle when the flow transitions from subsonic to sonic for part of the excitation period.

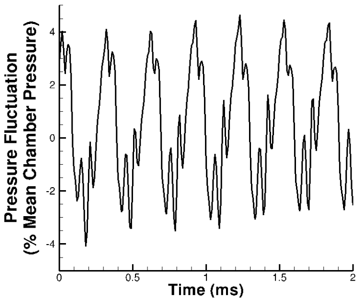

Figure 4. Simulated pressure data results from the open/closed boundary condition method.

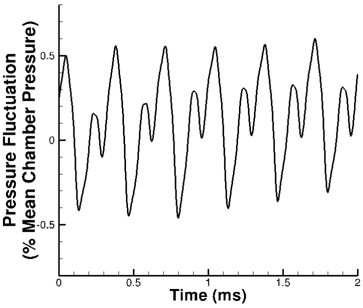

Figure 5. Simulated pressure data results from the sinusoidal pressure boundary condition method.

Quantitatively, the amplitude of both disturbances produced numerically is within an order of magnitude of the experimental results. The discrepancy in the amplitude of the response may be due to the acoustic damping of the nozzles which has not been incorporated into numerical model. New experimental data will be collected closer to the secondary nozzle in future BKH experimental campaigns to facilitate tuning of each method to deliver the correct amplitudes.

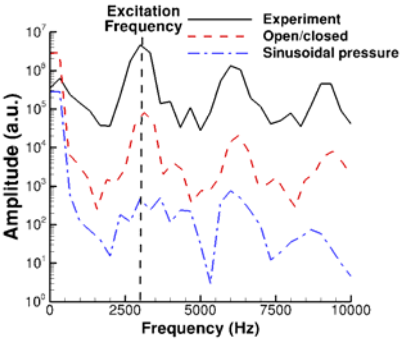

Figure 6. Comparison of Frequency spectrum results for each method
Note: signal offsets have been adjusted for presentation purposes.

To compare the excitation spectrum, Discrete Fourier Transforms were calculated for each method from a 3 ms sample of data. The frequency spectra produced, Figure 6, show that the excitation frequency and its overtones are excited by each method similar to that observed experimentally. However, the spectra produced using the sinusoidal pressure boundary condition does not exhibit the sharp peak at the excitation frequency as observed experimentally. Therefore it is concluded that the open/closed boundary condition better matches the experimental results.

Conclusion

Boundary conditions, to accurately represent the influence of acoustic excitation systems, are important for future simulations of high frequency combustion instability experiments. The results produced using different boundary condition methods have been compared against experimental results. The results indicate that the excitation system can be approximated by appropriate boundary conditions. Future BKH experiments will incorporate new instrumentation to better evaluate the influence of the acoustic excitation system.

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