ANALYSES OF FLAME RESPONSE TO ACOUSTIC FORCING IN A ROCKET COMBUSTOR

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Abstract

High frequency combustion instabilities in liquid propellant rocket engines are spontaneously occurring pressure fluctuations that are coupled with unsteady combustion processes. Under the right conditions the unsteady fluctuations can grow to a point where they affect the operation of the combustion chamber. The cause of combustion instabilities, including which processes are responsible and under what conditions they arise, are not yet fully understood. The ability to predict and prevent combustion instabilities during the design of new combustion chambers, through better understanding, would dramatically reduce the uncertainty and risk in the development of new engines.

An experimental combustor, designated BKH, is used to conduct high frequency combustion instability experiments. BKH operates with liquid oxygen and gaseous hydrogen propellants at supercritical conditions analogous to real rocket engines. The chamber features an acoustic excitation system that imposes an acoustic disturbance representative of a high frequency instability upon a cluster of five coaxial injection elements in the center of the chamber. The response of the elements to the imposed acoustic disturbance is observed using high speed optical diagnostics.

The main aim of this project is to develop methods for predicting the flame response to high frequency acoustic forcing representative of combustion instability phenomena. BKH is employed as an experimental and numerical test case for investigating the flame response. Modelling and complementary data analysis methods are developed and applied to model the chamber flow field, identify and predict the excited acoustic disturbance, identify the flame response using optical data, and to predict the flame response numerically.

The BKH experiments are first characterised by modelling the chamber numerically and determining the local acoustic disturbance acting upon the flame. A steady state chamber model with supercritical oxygen-hydrogen combustion was computed using a specialised CFD code. The model results indicate the secondary injection in BKH has a strong influence on the resulting flame distribution.

A method for reconstructing the acoustic field from dynamic pressure sensor data was developed to determine the local acoustic disturbance acting upon the combustion zone over a range of excitation frequencies. A low-order acoustic modelling approach is also shown to predict the resonant mode frequencies and the evolution of the acoustic field.

The flame response to the imposed acoustic disturbance is identified by analysing optical data from BKH experiments and unsteady CFD modelling. Multi-variable dynamic mode decomposition (DMD) analysis is used to isolate the flame response to the imposed acoustic disturbance in shadowgraph and OH* imaging data. Wave-like structures propagating along the surface of the liquid oxygen (LOx) jet and a phase difference of 45° between acoustic pressure and observed intensity fluctuations were identified.

An unsteady model of an injection element subjected to representative acoustic forcing is used to predict the flame response for a range of excitation amplitudes. Velocity ratio fluctuations caused by acoustic coupling with the oxidiser post in a pressure antinode are identified. The trend of exponential decay of the length of the LOx core with increasing transverse acoustic amplitude excitation is reproduced numerically and the flattening and flapping motion of the flame was further investigated using the numerical results.

Declaration of Originality

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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Scott K. Beinke
20^{th} April 2017

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Glossary

Nomenclature

α, β	Stoichiometric coefficients
a	Speed of sound
c	Speed of light
D	Diffusion coefficient
D_0	Diameter
f	Frequency
γ	Ratio of specific heats
H	Height
h	Planck constant
I	Image intensity
I_n	Identity matrix
J	Momentum ratio
Kn	Knudsen Number
κ	Thermal conductivity
k_b	Boltzmann constant
λ	Wavelength
L	Length
$\dot{m}$	mass flow rate
N	Response factor
n	Amplification factor
p, P	Pressure
P_v	Viscous stress tensor
q, Q	Heat release
q_d	Dipole source term
Re	Reynolds number
ρ	Density
R	Reflection coefficient
R_0	Radius
σ	Surface tension
Sc	Schmidt number
St	Strouhal number
T	Temperature
t	Time
T_s	Period
τ	Time delay factor
v, $\mathbf{V}$	Velocity
VR	Velocity ratio
μ	Viscosity
V	Volume
We	Aerodynamic Weber number
We_L	Weber number
ω	Angular frequency
Z	Acoustic impedance
z	Specific acoustic impedance

Subscripts

∞	Free stream properties
cr	Critical properties
CC	Combustion chamber properties
f	Fuel
ox	Oxidizer
LOx	Liquid oxygen
$conv$	Convection
G	Gas
L	Liquid
R	Real part
I	Imaginary part
lam	Laminar
T	Turbulent
$BPRMS$	Band-passed RMS result
RMS	Root Mean Squared result

Superscripts

a'	Perturbation or oscillating value
$\hat{a}$	Complex valued property
$\bar{a}$	Mean property
a^f	Forward reaction coefficient
a^b	Backward reaction coefficient

Acronyms

AFRL	Air Force Research Laboratory
AVBP	LES solver jointly developed by Cerfacs, IFPEN, and EM2C
AVSP	Acoustic solver developed by Cerfacs
BKD	Combustion chamber (*German: Brennkammer*) 'D', operated by DLR
BKH	Combustion chamber (*German: Brennkammer*) 'H', operated by DLR
BPRMS	Band-passed Root Mean Squared
CAA	Computational Aero Acoustics
CEA	Chemical Equilibrium Analysis
CFD	Computational Fluid Dynamics
CVRC	Continuously Variable Research Combustor, operated by Purdue University
CRC	Common Research Chamber, operated by DLR
DLR	German Aerospace Center (*Deutsches Zentrum für Luft und Raumfahrt*)
DMD	Dynamic Mode Decomposition
DNS	Direct Numerical Simulation
EM2C	Energetics and combustion lab at CentraleSupélec
FEM	Finite Element Methods
FFT	Fast Fourier Transform
FTF	Flame Transfer Function
HF	High Frequency
IFPEN	French public-sector research, innovation and training center
JAXA	Japanese Aerospace Exploration Agency
LEE	Linearised Euler Equations
LES	Large Eddy Simulation
LE-7A	Mitsubishi LE-7(A) rocket engine
LF	Low Frequency
LOx	Liquid Oxygen
MIC	Multiple-Injector Combustor, operated by ONERA
ONERA	French national aerospace research center
P8	European Test Facility for Cryogenic Rocket Propulsion
PCCDYN	Dynamic pressure sensors installed in BKH
POD	Proper Orthogonal Decomposition
RANS	Reynolds Averaged Navier Stokes
RMS	Root Mean Squared
ROF	Ratio of Oxidizer to Fuel mass flow rate
SSME	Space Shuttle Main Engine
TAU	CFD solver developed by the DLR
TIC	Transverse Instability Combustor, operated by Purdue University
TUM	Technical University of Munich (*Technische Universität München*)
URANS	Unsteady Reynolds Averaged Navier Stokes
VHAM	Very High Amplitude Modulator, operated by ONERA