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Simulation of Combustion Instabilities in Liquid Rocket Engines with Acoustic Perturbation Equations

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The authors present a new method for predicting combustion instabilities in liquid rocket engines. This method is based on the solution of the linearized governing equations for a three-dimensional combustor geometry in the time domain. The aim of this paper is to show the general feasibility of the approach and to explain the general behavior of the model. The computational domain comprises the combustion chamber itself and the convergent part of the nozzle. The heat release is included via a source term in the linearized energy equation. In the example of the European Aestus engine, it is shown that the model is able to predict the different oscillation modes without any preliminary assumptions about them. An analysis of the influence of the nozzle illustrates that its behavior is automatically included in the approach by design. In comparison to the solution of the full Navier–Stokes equations, the method has the advantage of a much lower numerical cost.

Nomenclature

a = velocity of sound
b = half-value radius of Gaussian pulse
D = diameter
E = acoustic energy density
f = frequency
I = acoustic flux
i = imaginary unit
k = wave number
L = length
M = Mach number
n = interaction index
$\mathbf{n}$ = normal vector
p = pressure
$\dot{q}$ = heat release rate
R_{CH} = radius of the combustion chamber
r = radius (polar coordinates)
T_S = oscillation period
t = time
u = velocity component in direction of the symmetry axis
V = volume
x = coordinate
Y = admittance
Z = impedance
α = decay/growth coefficient
θ = angle (polar coordinates)
κ = ratio of specific heats
ρ = density
τ = delay time
φ = phase angle
ω = angular frequency

Subscripts

CH = combustion chamber
c = center
char = characteristic
Im = imaginary part
N = nozzle
num = numerical
max = maximum
Re = real part
sim = simulation
theo = theoretical
V = volumetric

Superscripts

$'$ = fluctuating quantity
$\bar{\ }$ = mean quantity
$+$ = complex conjugate
$*$ = nondimensional quantity

I. Introduction

HIGH-FREQUENCY combustion instabilities are a dangerous phenomenon in rocket engines. They are responsible for a large number of problems and failures. The phenomenon of combustion instability in liquid and solid rocket engines was discovered in the late 1930s. However, this phenomenon can also arise in gas rockets, afterburners, modern gas turbines, or industrial furnaces.

Efforts to suppress combustion instabilities date back to the 1940s, when baffles and acoustic resonators were used to eliminate the so-called high-frequency resonant burning. Since then, many rocket development programs have been facing the problem of combustion instabilities. Examples are the F-1 engine of the Saturn launch vehicle or the Russian RD-0110 engine of the Soyuz vehicle [1]. Despite the numerous efforts to predict the stability of the various engines by theoretical and analytical methods, most of the stability problems had to be solved by trial and error. This includes expensive full-scale tests. These examples illustrate that the reliable prediction of engine stability is still a challenging problem.

A large amount of literature exits on how to cope with and predict combustion instability. Harrje and Reardon [2], for example,

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