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Acoustics, Vortex Shedding, and Low-Frequency Dynamics Interaction in an Unstable Hybrid Rocket

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This paper deals with an experimental investigation into the stability behavior of a hybrid rocket where gaseous oxygen is fed with either an axial conical subsonic nozzle or a radial injector. The influence of the oxidizer-injection configurations on the motor stability is thoroughly examined. These distinct oxidizer-injection techniques allowed unveiling key and so far unreported features of the hybrid rocket combustion stability, especially emphasizing the role of vortex shedding which occurs in both the pre- and postcombustion chamber. Axial and radial injectors caused completely stable and unstable combustor operations, respectively, and this fact has been attributed to the fluid dynamics and unsteady heat release at the entrance of the fuel grain port. In particular, the unstable combustion in the radial-flow injector motor was dominated by low-frequency pressure oscillations, around 10–20 Hz. These low-frequency pressure oscillations were always accompanied by longitudinal acoustic modes. In some cases, the pressure oscillations abruptly increased, reaching peak-to-peak amplitude close to 70% of the mean chamber pressure, which is somewhat unusual for hybrid engines. Vortex shedding in the aft-mixing chamber is considered as the main driving mechanism of this latter behavior.

Nomenclature

c = average speed of sound in the combustion chamber, $\sqrt{\gamma(RT)_{\text{av}}}$
c^* = characteristic exhaust velocity
D = fuel port diameter
$\bar{D}$ = time–space-averaged fuel port diameter
D_t = exhaust nozzle throat diameter
f = frequency
$\bar{G}_{\text{ox}}$ = time–space-averaged oxidizer mass flux
L = combustion chamber length
L_f = fuel grain length
l = exhaust nozzle length
$\dot{m}$ = mass flow rate
O/F = oxidizer to fuel mixture ratio
p = combustion chamber pressure
R = gas constant
$\bar{\dot{r}}$ = time–space-averaged regression rate
Sr = Strouhal number
s = fuel grain thickness
T = gas temperature
U = average gas velocity
$\mathcal{V}$ = combustion port volume
γ = specific heat ratio
η = combustion efficiency
τ = ultrasound time of flight
Ψ = function of specific heat ratio

Subscripts

H = Helmholtz mode
hy = intrinsic hybrid instability
j = gas jet
ox = oxidizer
s = sampling
th = theoretical
VS-aft = vortex shedding in the postchamber
VS-pre = vortex shedding in the prechamber
$1L$ = first longitudinal acoustic mode

I. Introduction

PROPULSION systems such as solid and liquid propellant rockets and airbreathing engines, like ramjets, are known to have a tendency toward unstable operation, that is, toward what is commonly referred to as combustion instability [1,2]. From a general point of view, strong instabilities in combustors have to be avoided because they can cause excessive mechanical vibrations on the engine and the vehicle structure, which can damage delicate payloads and control systems, or even lead to structural failure. Mild instabilities, on the other hand, may even improve combustion efficiency by promoting fuel–oxidizer mixing as, for example, in pulse combustors [3] and hybrid rockets [4]. The latter, like the aforementioned propulsion systems, suffer from combustion instability. In fact, the open literature [5,6] reports that hybrid rockets typically show finite amplitude, up to 20% rms of the mean, low-frequency chamber pressure oscillations. These pressure oscillations have a predominant frequency in the range of tens of hertz, and they often take place together with acoustic frequency oscillations. Here, as acoustic oscillations are intended, the chamber pressure oscillations having a frequency close to that of the chamber longitudinal acoustic modes.

The low-frequency instability is intrinsic of hybrid engines; it has been described by means of a linear model [7,8] that combines the thermal lag in the solid grain, the gas-phase combustion, and the gas dynamics in the combustion chamber, yielding a universal scaling formula for the primary hybrid oscillation frequency

$$f_{\text{hy}} = \frac{0.48}{\tau_{\text{bl}}} = 0.234\left(2 + \frac{1}{O/F}\right)\frac{4}{\pi}\frac{\dot{m}_{\text{ox}}(RT)_{\text{av}}}{L_f p D^2} \tag{1}$$

where τ_{bl} is the so-called boundary-layer delay time [7], that is, the characteristic response time to disturbances in the boundary layer over the grain surface.

However, although this theoretical model can predict the pressure oscillation dominant frequency, it is unable to explain if and when these low-frequency instabilities will develop in the combustor. Actually, there are hybrid motors where pressure-time trace is very

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