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Suppression and excitation of the precessing vortex core by acoustic velocity fluctuations: An experimental and analytical study

S. Terhaar*, B. Ćosić, C.O. Paschereit, K. Oberleithner

Chair of Fluid Dynamics, Hermann-Föttinger-Institut, Technische Universität Berlin, 10623 Berlin, Germany

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ABSTRACT

Swirl-stabilized flames can feature a self-excited hydrodynamic instability known as the precessing vortex core (PVC). In the present study it is shown how this instability is affected by axisymmetric acoustic velocity fluctuations as encountered at thermoacoustically unstable conditions. High-speed flow and flame measurements are conducted in a swirl-combustor subject to strong acoustic forcing. In post-processing, the fluctuations of the PVC and forced structures are extracted from the data exploiting their respective symmetries. The experiments are complemented with a linear hydrodynamic stability analysis of the measured mean flow and density fields. Two interaction mechanisms are identified from the experimental data and the stability analysis. The first, termed *mean flow correction*, applies for flows that are strongly convectively unstable at the forcing frequency. The coherent structures excited by the forcing gain significant energy from the mean flow and modify the same through the generation of coherent Reynolds stresses. This indirectly affects the PVC instability that is determined by the mean flow. The mean flow corrections may lead to suppression or, as encountered presently, to an excitation of the PVC through axisymmetric forcing. The second interaction mechanisms is termed *mean flow modulation* and it applies to flows that are convectively stable or weakly convectively unstable at the forcing frequency. As mean flow corrections are weak, the instability of the PVC is not affected by the forcing. However, frequency and growth rates of the PVC are modulated by the forcing frequency which creates interaction patterns that depend on the ratio between the forcing and PVC frequency. In extreme cases, this leads to a complete suppression of the PVC frequency. The observed interaction patterns are reproduced by a model of parametrically forced Van der Pol oscillator. The two identified mechanisms provide a generalized explanation for several previous experimental and numerical observation. Furthermore, new insight into the interaction of self-excited flow instabilities and forced flow structures is obtained.

1. Introduction

Nowadays, almost all state of the art stationary gas turbines employ swirling flows for flame stabilization. A strong swirl is imparted on a jet that emanates into the combustion chamber. The centrifugal forces due to the swirl lead to radial and axial pressure gradients and eventually cause a stagnation point near the centerline. This phenomenon is called vortex breakdown and it results in large zones of reversed flow and turbulent shear layers between the jet and the recirculation zones. Both, the flow recirculation and the high turbulence in the shear layers drastically improve the flame stabilization [1].

At the same time, the complex flow fields of swirl-stabilized combustors are often prone to hydrodynamic instabilities that result in large-scale coherent flow structures, such as Kelvin–Helmholtz instabilities. Coherent flow structures play an important role for heat release fluctuations since they may couple to an acoustic combustor mode and lead to thermoacoustic instabilities [2–4].

For the present study it is important to distinguish between two types of large-scale coherent structures. The first type consists of axisymmetric vortex rings that are generally caused by mass flow fluctuations at the combustor inlet. Typically, these mass flow fluctuations are induced by a thermoacoustic instability in the combustor [2–4]. However, their effect can be mimicked by acoustically forcing the system, as it is done in the present study. The ring vortices are shed at the combustor inlet and are amplified in the shear layers. When reaching the flame, they create flame surface fluctuations and lead to fluctuations of the integral heat release rate [5–8]. The second type represents antisymmetric, helical flow structures that are synchronized to a precession of the vortex core of the swirling flow. While the occurrence and

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* Corresponding author.
E-mail address: steffen.terhaar@tu-berlin.de, steffen.terhaar@ge.com (S. Terhaar).

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Nomenclature

A	Normalized coherent kinetic energy (-)
D_h	Hydraulic diameter of the burner outlet (m)
I_{OH}	Planar normalized OH*-chem. intensity (-)
Re	Reynolds number based on D_h and U_0 (-)
$\mathrm{Re}_{\mathrm{eff}}$	Reynolds number considering the eddy viscosity (-)
S	Inlet swirl number (-)
T_{in}	Inlet temperature (K)
U_0	Bulk velocity at combustor inlet (m/s)
$\hat{u}_0/U_0$	Normalized forcing amplitude (-)
$\mathbf{V} = (U, V, W) = (U_1, U_2, U_3)$	Mean velocity vector (m/s)
P	Mean pressure (Pa)
$\mathcal{P}_{c,i}$	Production term of the coherent kinetic energy (m^3/s^3)
a_j	Temporal coefficient of the j'th POD mode (-)
f	Frequency (Hz)
f_a	Frequency of the acoustic forcing (Hz)
f_h	Frequency of the helical instability (Hz)
m	Azimuthal wavenumber (-)
$\dot{m}$	Mass flow (kg/s)
p	Time-dependent pressure (Pa)
t	Time (s)
x_s	Axial location of the wavemaker (m)
$\mathbf{x} = (x, y, z)$	Cartesian coordinates (m)
$\mathbf{x} = (x, r, \Theta)$	Cylindrical coordinates (m)
$\mathbf{v} = (u, v, w) = (u_1, u_2, u_3)$	Time-dependent velocity vector in Cartesian coordinates (m/s)
$\mathbf{v} = (v_x, v_r, v_\Theta)$	Time-dependent velocity vector in cylindrical coordinates (m/s)
$\boldsymbol{\Omega} = \left(\Omega_{xy}, \Omega_{xz}, \Omega_{yz}\right)$	Vorticity vector (s^{-1})
$\boldsymbol{\Phi}_j$	j'th spatial POD mode (-)
$\alpha = \alpha_r + \alpha_i$	Complex axial wave number (1/m)
β	Parameter for the eigenfrequency of the parametric Van der Pol oscillator (-)
γ	Parameter for the linear damping of the parametric Van der Pol oscillator (-)
μ	Parameter for the nonlinearity of the parametric Van der Pol oscillator (-)
ν	Kinematic viscosity (m^2/s)
ν_t	Eddy viscosity (m^2/s)
ω	Angular frequency (rad/s)
$\omega_0 = \omega_{0,r} + \omega_{0,i}$	Complex local absolute frequency (-)
$\omega_g = \omega_{g,r} + \omega_{g,i}$	Complex global frequency (-)
ϕ	Equivalence ratio (-)
ρ	Fluid density (kg/m^3)
$\hat{\xi}$	Amplitude of the parametric excitation of the Van der Pol oscillator (-)
$(\cdot)^c$	Coherent part
$(\cdot)^s$	Stochastic part
$(\cdot)'$	Fluctuating part
$(\cdot)^h$	Phase-resolved data with respect to the helical instability
$(\cdot)^a$	Phase-resolved data with respect to the acoustic forcing
$\hat{(\cdot)}$	Amplitude function
$\langle\langle \cdot, \cdot\rangle\rangle$	Inner product
CB	Centerbody
FFT	Fast Fourier transform
IRZ	Inner recirculation zone
LES	Large Eddy Simulation
LSA	Linear stability analysis
PIV	Particle image velocimetry
POD	Proper orthogonal decomposition
PVC	Precessing vortex core
VdP	Van der Pol

frequency of the axisymmetric structures are usually coupled to velocity oscillations associated with the acoustic boundary conditions, the precessing vortex core (PVC) is a self-excited flow phenomenon. It solely depends on the flow field present in the combustor and it is usually excited in isothermal strongly swirling jets, while its occurrence at reacting conditions was reported somewhat ambiguously [9].

In the last years, large progress in the understanding of the excitation mechanisms of the PVC has been made. It is known that the PVC is the manifestation of a global flow instability - a resonance mode - of the entire flow [10–14]. Recently, linear hydrodynamic stability analysis (LSA) has been successfully employed to predict the onset of the PVC in swirling combustor flows at isothermal and reacting conditions [15–17]. The main findings of these studies are that the often observed suppression of the PVC at reacting conditions depends on the effect of the flame on the local density field and on the amount of backflow in the inner recirculation zone.

The high relevance of axisymmetric coherent structures is evident due to their possible coupling with thermoacoustic instabilities [2–4]. In contrast to that, the heat release fluctuations caused by the PVC are essentially helical [18], and no integral heat release fluctuations are caused and no direct coupling to acoustic modes is possible. However, if the mean flow is not completely axisymmetric, as it can be expected in multi-burner arrangements [19], the helical structure may cause integral heat-release fluctuations [20]. Furthermore, the PVC has a strong effect on mixing processes and the flame stabilization [21–25].

In the present work, the interaction of the self-excited helical coherent structure (PVC), with the forced axisymmetric coherent structures is investigated. Despite the large importance of both flow instabilities, only limited knowledge is available about the interaction of the two. In previous studies, the focus was placed on the suppression of the helical mode by the symmetric mode. Paschereit et al. [3] found that low amplitude acoustic forcing at the frequency of the helical instability leads to a suppression of the helical mode in a reacting swirl-stabilized combustor. Iudiciani and Duwig [26] conducted reacting LES simulations and found the acoustic forcing to damp or suppress the PVC (depending on the forcing amplitude), when the forcing was applied at lower frequencies than the natural helical frequency. In contrast to this, forcing