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Numerical prediction of combustion instability limit cycle oscillations for a combustor with a long flame

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ABSTRACT

A coupled numerical approach is investigated for predicting combustion instability limit cycle characteristics when the combustor contains a long flame. The test case is the ORACLES combustor, with a turbulent premixed flame a metre long: it exhibits limit cycle oscillations at $\sim$ 50 Hz and normalised velocity amplitude ahead of the flame of $\sim$ 0.29. The approach obtains the flame response to acoustic excitation using Large Eddy Simulations (LES), and couples this with a low-order wave-based network representation for the acoustic waves within the combustor. The flame cannot be treated as acoustically compact; the spatial distribution of both its response and the subsequent effect on the acoustics must be accounted for. The long flame is uniformly segmented axially, each segment being much shorter than the flow wavelengths at play. A series of “local” flame describing functions, one for the heat release rate response within each segment to velocity forcing at a fixed reference location, are extracted from the LES. These use the Computational Fluid Dynamics toolbox, OpenFOAM, with an incompressible approximation for the flow-field and combustion modelled using the Partially Stirred Reactor model with a global one-step reaction mechanism. For coupling with the low-order acoustic network modelling, compact acoustic jump conditions are derived and applied across each flame segment, while between flame segments, wave propagation occurs. Limit cycle predictions from the proposed coupled method agree well with those predicted using the continuous 1-D linearised Euler equations, validating the flame segmentation implementation. Limit cycle predictions (frequency 51.6 Hz and amplitude 0.38) also agree well with experimental measurements, validating the low-order coupled method as a prediction tool for combustors with long flames. A sensitivity analysis shows that the predicted limit cycle amplitude decreases rapidly when acoustic losses at boundaries are accounted for, and increases if combustor heat losses downstream of the flame are accounted for. This motivates more accurate determination of combustor boundary and temperature behaviour for thermoacoustic predictions.

1. Introduction

Lean premixed combustion is preferred in modern aero-engines and industrial gas turbines due to its effect in reducing NO_x emissions [1]. However, lean premixed systems are highly susceptible to combustion instabilities, which originate from the coupling between acoustic disturbances and unsteady heat release rate fluctuations in the combustor [2,3]. Combustion instabilities may lead to early ageing of the combustion chamber, or, in extreme cases, to severe structural damage [2,3]. The ability to predict, and if necessary suppress, these thermoacoustic instabilities during the early design stage of a combustor would offer enormous benefits, but this still constitutes a challenge due to the complex mechanisms and combustor geometries involved [2,4].

Approaches for numerically simulating and analysing combustion instabilities generally fall within two categories. The first involves direct numerical calculation of the coupled acoustic oscillations and unsteady flame heat release within the combustor, via complete 3D compressible Computational Fluid Dynamics (CFD) simulations [5]. For example, investigations were conducted on self-excited azimuthal modes using LES in a full scale helicopter combustion chamber [6].

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The second, much less time-consuming, approach is to decouple the calculations of the perturbed flame response and the acoustic waves. The unsteady heat release rate from the flame resulting from acoustic excitation is characterised via a flame transfer function (FTF) for linear analysis [7,8] or a flame describing function (FDF) for weakly nonlinear analysis [9,10]. It can be obtained from experiments [11–13], analytical models [7,14,15] or numerical simulations [16–19]. The generation, propagation and reflection/transmission of the acoustic waves are captured by either a low-order acoustic network model or a Helmholtz solver. Both exploit the fact that the acoustic wave behaviour remains linear in gas-turbine combustors, even during limit cycle oscillations [20]. Low-order acoustic network models represent the combustor geometry as a network of simple geometry modules, each sustaining acoustic waves superimposed on a mean flow. The acoustic wave behaviour is assumed low-dimensional typically just longitudinal and circumferential waves, and the mean flow variables are assumed constant within each geometry module. Neighbouring modules are connected by acoustic transfer matrices [21–24]. The alternative, Helmholtz solvers, assume zero mean flow velocity and numerically solve the wave equation in the frequency domain (the Helmholtz equation) for general geometry and temperature variations [25–27]. They must account for convective effects via corrections.

Both low-order acoustic network models and Helmholtz solvers typically make the assumption that the flame can be considered compact compared to the wavelength of the dominant acoustic waves [25]. This enables the coupling of the acoustic and flame models via acoustic jump conditions across the flame [8,22,25]. When the length of the flame approaches the order of dominant wavelengths, this assumption breaks down and the flame cannot be treated as a single compact perturbation source or sink [28–30]. Any prediction of thermoacoustic behaviour will then need to account for the spatial variation in the heat release rate response to acoustic disturbances along the flame, and in the generation of new acoustic waves by the flame.

The spatial distribution of the flame's response introduces the concept of a "local" and continuously varying flame model, characterising the axially varying flame response to normalised velocity perturbations at a fixed reference position. However, current analyses using the continuous concept are mainly based on analytical models with many assumptions [28,29]. For example, distributed FTFs or FDFs with spatially uniform gains and local time delays determined using a "particle flight time" method [31] were incorporated in Helmholtz solvers [32,33]. Practical implementation considers a discrete series of FTFs or FDFs, applied at different downstream locations within the flame [34,35]. When either measuring or simulating local FTFs or FDFs, their accuracy will invoke a trade-off; increasing the number of discrete flame elements captures the non-compactness more accurately, but also deteriorates the signal to noise ratio (SNR) as each flame zone contains less fluctuating heat release rate.

Simulating the response of the flame requires time-intensive, high fidelity numerical simulations which capture the unsteady flow and flame structures of turbulent combustion [25,36]. Recent work has used "low-Mach number" or "incompressible" large eddy simulations to achieve this [17–19,37,38], based on the assumption that the flame is largely unaffected by compressibility effects and responds mainly to hydrodynamic fluctuations [39,40]. This offers the benefit of allowing a larger time step (now restricted by the inverse of the flow speed rather than the speed of sound). These previous simulations assume an acoustically compact flame, whose heat release rate is extracted by spatially integrating the entire reacting zone.

The present work also employs "incompressible"[1] LES, but uses this as the basis for extracting local FDFs for a succession of axial flame segments. The obtained local FDFs are substituted into a low-order acoustic network model, where they appear as discrete compact flame elements. It is shown rigorously that compact acoustic jump conditions can be applied across each discrete flame segment. The mean flow variables (such as axial velocity, temperature, speed of sound) are permitted to vary across flame elements. This coupled approach, invoking a segmented flame, local FDFs and a series of compact acoustic jump conditions, is then used to predict combustion instability, including nonlinear features such frequency and amplitude of limit cycle oscillations.

The target case of the present study is a rectangular dump combustor, containing a perfectly premixed flame, named One Rig for Accurate Comparisons with Large-Eddy Simulations (ORACLES) and developed in a European research programme framework [42]. The combustion chamber has a length of 2 m, with the flame extending downstream approximately half the length of the chamber. The combustor is unstable; low frequency limit cycle oscillations at $f \sim 50\,\mathrm{Hz}$ occur, with a normalised velocity amplitude of $A \sim 0.29$ upstream of the flame. Note that although the flame length L_f is approximately half the combustor length, it is the flame length compared to the acoustic wavelength $\bar{c}_{b,\mathrm{avg}}/f$ in the combustion chamber that matters for acoustic compactness, with $\bar{c}_{b,\mathrm{avg}}$ being the average speed of sound in the combustion chamber. At the low frequency of the oscillations, this ratio is $fL_f/\bar{c}_{\mathrm{avg}} \sim 1/15$ ($\bar{c}_{b,\mathrm{avg}} \approx 750\,\mathrm{m\,s^{-1}}$ (see Fig. 9(b))), implying that flame non-compactness, while being higher than typical, is not extremely high. Furthermore, it should be noted that there are not many instability benchmark experiments for combustors with long flames. The present work will investigate the benefits of flame segmentation for limit cycle predictions at this acoustic compactness ratio.

The objectives of the present study are to: (1) adapt a low-order thermoacoustic network model to account for a segmented flame and series of local FDFs; (2) to determine the local FDFs using LES for the first time; (3) to validate the limit cycle characteristics predicted using the coupled approach, by comparing with those determined using a reference technique implementing the 1-D linearised Euler equations (LEEs); (4) to validate the coupled limit cycle predictions by comparing with available experimental results; (5) to investigate the sensitivity of the limit cycle predictions to the (unknown) level of acoustic damping at the combustor boundaries.

The remainder of the paper is organised as follows. The ORACLES combustor and the main experimental results are described in Section 2. The low-order network representation of the combustor geometry, boundaries and segmented flame, along with the reference LEEs method are presented in Section 3. The numerical details of the LES used to obtain the local FDFs are presented in Section 4. Section 5 presents the mean flow and thermodynamic properties of the combustor as predicted by the LES, the local FDFs for the flame segments and the continuous FDF for the LEEs method. It then presents predictions of the limit cycle oscillations. The sensitivity of these predictions to the acoustic damping at the combustor boundaries is presented in Section 5. Conclusions are drawn in the final section.

2. Experimental test case

The ORACLES combustor considered in the present study is schematically illustrated in Fig. 1(a), with more information available in [42,43]. The test rig contains three main sections: (1) two straight settling chambers followed by smoothly converging units in which air and propane, supplied at the left end, are fully mixed;

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[1] Changes in density are uniquely associated with changes in temperature [41].