

# SIMULATION METHODS FOR COMBUSTION INSTABILITIES

There are two main numerical methods used today to study CIs which both can be drastically improved by the introduction of high-fidelity large-scale simulation codes running on massively parallel systems:

**(1) Brute force Large Eddy Simulation (LES):** recent progress in LES of reacting flows has allowed to simulate full combustion chambers, first for laboratory-scale burners (Branley and Jones 2004, Lartigue et al 2005) and more recently for real industrial configurations (Staffelbach et al 2009, Schmitt et al 2007, Fureby 2010). LES is a method where all flow equations are solved in time on a discretized space (using unstructured grids in most cases). It involves only a limited set of assumptions (mainly a filtering operation of the spatial small scales of the flow), leading to the most precise method today for such geometries but also being the most expensive. The image of a 'virtual burner' can be used here too: a brute force LES of a combustor exhibiting CIs would provide a 'virtual unstable combustor', easier to explore than an experiment. This is an attractive method made possible by recent progress in HPC technologies on machines using 10 000 to 300 000 processors and demonstrated by various research groups in the last years. Many of them use the AVBP code developed in Toulouse in my group (Sengissen et al 2007, Roux et al 2007, Staffelbach et al 2010). **This approach is straightforward, and yet, far from being mature and facing multiple difficulties:** a) it does not yet incorporate all details required to mimic CIs in real combustors (acoustic damping, geometrical complexity, detailed kinetics, two-phase flows, wall phenomena, radiation, supercritical flows for future high pressure systems... b) each LES is only a realization of a single operating point (one inlet temperature, one pressure, one fuel, one injection type, one set of acoustic impedances imposed at the inlet(s) and outlet(s) of the combustion chamber...) in a given combustor. The results change as soon as one of these parameters changes. The LES approach in itself does not bring new insight into the reasons why a given chamber is unstable. It does not indicate which change of parameter could lead to a stabilization of the CI. In other words, **brute force LES**, once sufficiently improved to reproduce real flames, will be able to provide **results that are very similar to a perfectly instrumented experiment**: it can help us understand CIs provided we have a theory to guide us but **it can not replace this theory**. Thus a complete method to address and to control CIs must include brute force LES but also smarter theoretical methods as described below. These methods also involve HPC but they have the advantage that they are not restricted to a single operating point. They decompose the physics of CIs in a few building blocks allowing to understand and to control them and not only to observe them. Nevertheless, brute force LES remains a strong asset because it allows testing the accuracy of these 'smart' acoustic methods.

**(2) Thermoacoustic codes (called here TA codes) coupled to forced response LES:** in most CIs, acoustics is the dominant resonant mechanism and multiple studies performed in the last sixty years (most of them inspired by the pioneering work of L. Crocco (1951)) have shown that a proper method to **decompose and analyse the physics of CIs** was to use

'acoustic' codes that can track the propagation of sound waves in the combustor and the growth of eigenmodes. In this approach, the mean flow is frozen and the flames are replaced by active acoustic components (which can be compared to loud speakers that would produce sound waves depending on the acoustic waves they are submitted to). Provided the impact of these active elements can be properly represented, the global stability properties of the combustor can be predicted in the linear as well as in the non-linear regimes. A major interest of this approach is that it allows **isolating the elements leading to CIs into different blocks** (something a brute force LES cannot do): a) the acoustics of the combustor, b) the impedances of the outlet(s) and inlet(s) and c) the response of the flame which is quantified by a function called the Flame Transfer Function (FTF) describing the amount of unsteady heat release produced by a flame when it is submitted to an unsteady velocity. TA codes can operate either in the frequency domain or in the time domain but in all cases, they are **faster than brute force LES** and their information **more useful to mitigate CIs**. Their development however, is far from satisfactory today: one main difficulty of TA codes is **their dependency on the accuracy of the FTF**. FTF can be measured experimentally but they will have to be computed in the future and the **proper method to compute FTF is LES again**. However, such LES are simpler than brute force LES because FTF can be measured by forcing a part of the combustor using acoustic waves and quantifying the flame response. This response is independent of upstream or downstream boundary conditions and can be viewed as an intrinsic characteristic of the flame. A second difficulty of TA codes is that they must still include the complete combustor geometry and require **sophisticated methods to track eigenmodes**. The difficulty is no longer to predict the stability of a single case (like in brute force LES) but to predict the effects on stability of multiple parameters on stability. This leads also to a significant challenge in terms of computations, something that until now has not been done with the level of precision required for effective CI control.

For more details on codes see also [Software section](#).

## REFERENCES

N. Branley and W. P. Jones. Large eddy simulation of a turbulent non-premixed flame. *Combust. Flame*, **127**:1914-1934, 2001.

D. G. Crighton, A. P. Dowling, J. E. Ffowcs-Williams, M. Heckl, and F. Leppington. « Modern methods in analytical acoustics. Lecture Notes ». Springer Verlag, New-York, 1992.

L. Crocco. Aspects of combustion instability in liquid propellant rocket motors. Part I. *J. American Rocket Society*, **21**:163-178, 1951.

A. P. Dowling. Nonlinear self-excited oscillations of a ducted flame. *J. Fluid Mech.* **346**, 271-290, 1997

F. E. C. Culick and P. Kuentzmann. « Unsteady Motions in Combustion Chambers for Propulsion Systems ». NATO Research and Technology Organization, 2006.

- F. Duchaine, L. Selle, and T. Poinso. Sensitivity analysis of transfer functions of laminar flames. *Combust. Flame*, **158** : 12 : 2384-2394, 2011.
- C. Fureby. LES of a multi-burner annular gas turbine combustor. *Flow, Turb. and Comb.*, **84**:543-564, 2010.
- R. Leandro, A. Huber, and W. Polifke. taxmanual. Technical report, TU Munchen, 2010.
- C.K. Law. Fuel Options for Next-Generation Chemical Propulsion. *AIAA J.* **50**, 1, 19-36, 2012.
- T. Lieuwen and V. Yang. Combustion instabilities in gas turbine engines. operational experience, fundamental mechanisms and modeling. In *AIAA Prog. in Astronautics and Aeronautics*, **210**, 2005.
- F. Nicoud and T. Poinso. Thermoacoustic instabilities: should the Rayleigh criterion be extended to include entropy changes ? *Combust. Flame*, **142**:153-159, 2005.
- N. Noiray, D. Durox, T. Schuller and S. Candel. A unified framework for nonlinear combustion instability analysis based on the flame describing function. *J. Fluid Mech.* **615**, 139-167, 2008.
- E. Riber, M. Garcia., V. Moureau, H. Pitsch, O. Simonin, and T. Poinso. Evaluation of numerical strategies for LES of two-phase reacting flows. *J. Comput. Phys.*, **228** : 539-564, 2009.
- A. Roux, L. Y. M. Gicquel, Y. Sommerer, and T. J. Poinso. Large eddy simulation of mean and oscillating flow in a side-dump ramjet combustor. *Combust. Flame*, **152** (1-2):154-176, 2007.
- S. Roux, G. Lartigue, T. Poinso, U. Meier, and C. Berat. Studies of mean and unsteady flow in a swirled combustor using experiments, acoustic analysis and large eddy simulations. *Combust. Flame*, **141**:40-54, 2005.
- T. Sattelmayer. Influence of the Combustor Aerodynamics on Combustion Instabilities From Equivalence Ratio Fluctuations. *J. Eng. Gas Turbines Power* **125**, 1, 11, 2003.
- P. Schmitt, T. Poinso, B. Schuermans, and K. P. Geigle. Large-eddy simulation and experimental study of heat transfer, nitric oxide emissions and combustion instability in a swirled turbulent high-pressure burner. *J. Fluid Mech.*, **570**:17-46, 2007.
- A. Sengissen, J. F. Van Kampen, R. Huls, G. Stoffels, J. B. W. Kok, and T. Poinso. LES and experimental studies of cold and reacting flows in a swirled partially premixed burner with and without fuel modulation. *Combust. Flame*, **150**:40-53, 2007.
- G. Staffelbach, L.Y.M. Gicquel, G. Boudier, and T. Poinso. Large eddy simulation of self-excited azimuthal modes in annular combustors. *Proc. Combust. Inst.*, **32**:2909-2916, 2009.
- P. Wolf, G. Staffelbach, R. Balakrishnan, A. Roux, and T. Poinso. Azimuthal instabilities in annular combustion chambers. In NASA Ames/Stanford Univ. Center for Turbulence Research, *Proc. of the Summer Program*, pages 259-269, 2010.