

Combining low order network modelling with incompressible flame LES for thermoacoustic instability in an industrial gas turbine combustor

Yu Xia^{a,*}, Aimee S. Morgans^a, William P. Jones^a, Ghenadie Bulat^b

^a*Department of Mechanical Engineering, Imperial College London, London SW7 2AZ, UK*

^b*Siemens Industrial Turbomachinery Ltd., Waterside South, Lincoln LN5 7FD, UK*

Abstract

Ultra low NO_x emissions from gas turbine combustors can be achieved using lean premixed combustion. However, this makes the combustor highly susceptible to thermoacoustic instability, which arises due to a two-way coupling between acoustic waves and unsteady heat release from the flame, and can cause fatigue failure of the combustor hardware. Predicting thermoacoustic instabilities is extremely challenging due to the range of length scales involved, from tiny chemical reaction scales to long acoustic wavelengths. It is for this reason that low order thermoacoustic network models are attractive, modelling the acoustic waves using linear theory. The combustor geometry is simplified into a network of connected simple modules, with the linear acoustic wave strengths tracked across module boundaries. The flame region is assumed to be ‘acoustically compact’, meaning that the flame can be represented as a thin sheet [1]. The unsteady heat release rate of the thin flame is assumed to respond weakly nonlinearly to upstream acoustic forcing. This means its response frequency matches the forcing frequency, but with a gain and phase change that depend on forcing amplitude as well as frequency. The resulting frequency response is known as a Flame Describing Function (FDF). In this work, the FDF is obtained via incompressible LES, which assumes that the flame responds primarily to hydrodynamic flow disturbances. The use of incompressible simulations allows much larger time steps, hence computational speed up, while the use of LES allows the large scale unsteady flow features to be captured accurately. Two incompressible LES codes, BOFFIN [2] and OpenFOAM [3], are tested, incorporating a complex (15-step [4]) and a simple (4-step [5]) chemical reaction mechanism for methane respectively. By combining the FDF with the low order network modelling tool, OSCILOS [6], both the frequencies and growth rates of a combustor’s thermoacoustic modes can be predicted. The accuracy of above combined approach has been verified by measurements on a lab scale combustor [7]. In this work, this approach is extended to predict the thermoacoustic modes of a full-scale combustor [8] taken from a Siemens industrial gas turbine operated under 3 bar and 6 bar (see Fig. 1). Two low order network representations for the combustor geometry are built (see Fig. 2), and multiple acoustic forcing cases involving two forcing amplitudes (0.1 and 0.2) and seven forcing frequencies (200-1500 Hz) are applied at the combustor entrance. The responding flame heat release rates are numerically simulated and processed with fast Fourier transform to form a weakly non-linear FDF (see Fig. 3a). By incorporating the FDF into OSCILOS, all the thermoacoustic modes under 3 bar pressure are predicted to have negative growth rates and be stable, in agreement with the experiments. The predicted modal frequencies are also in good agreement with the measurements (see Fig. 3b), giving confidence in this coupled approach for real industrial combustors.

Keywords: Thermoacoustic instability, incompressible LES, flame describing function (FDF), OSCILOS, BOFFIN

References

- [1] F. E. Marble, S. M. Candel, *Proc. Combust. Inst.* 17 (1) (1979) 761–769.
- [2] W. P. Jones, F. di Mare, A. J. Marquis. *LES-BOFFIN: Users Guide*. London, UK. 2012.
- [3] H. G. Weller, G. Tabor, H. Jasak, C. Fureby, *Computers in physics* 12 (6) (1998) 620–631.

*Corresponding author
Email address: yu.xia13@imperial.ac.uk (Yu Xia)

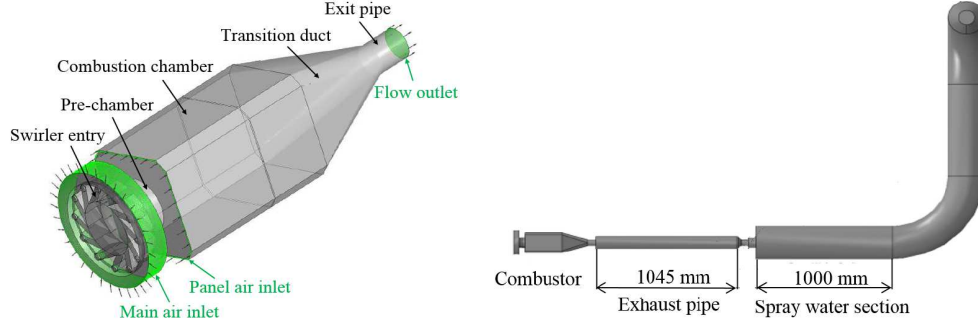


Figure 1: (Left) the original combustor from Siemens SGT-100 gas turbine; (right) the schematic of high pressure test facility built in German Aerospace Centre (DLR)

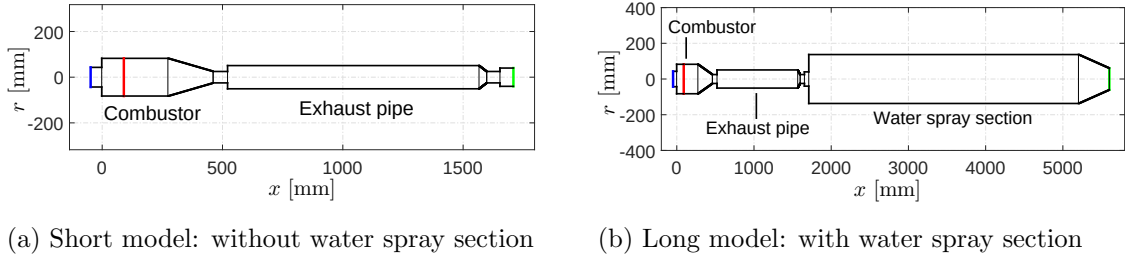


Figure 2: Two low order network models of the DLR test facility (blue line: closed inlet; green line: open outlet; red line: compact flame sheet).

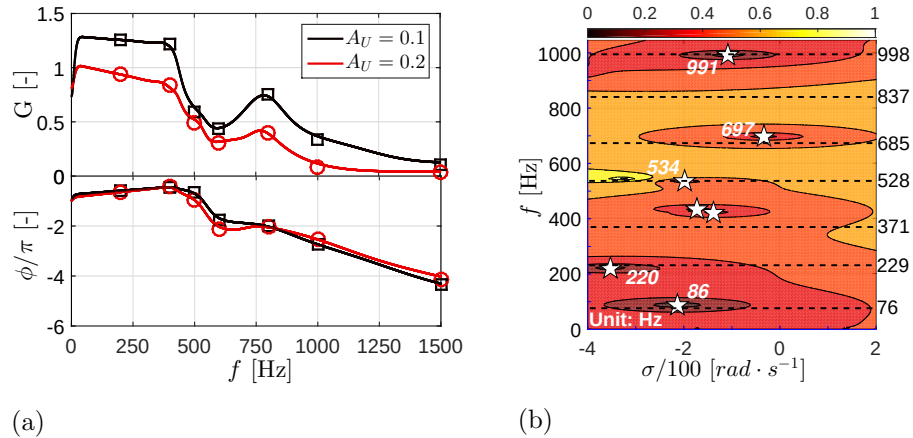


Figure 3: (a) FDF from BOFFIN LES, with polynomial fitting for forcing amplitude $A_U = 0.1$ (black) and 0.2 (red) at 3 bar pressure; (b) contour map of the complex s -plane with modal frequency f versus growth rate σ . The predicted thermoacoustic modes of ‘Short model’ under forcing amplitude of 0.1 are marked by white stars at the minima, while frequencies of the corresponding measured modes are indicated by black dashed lines.

- [4] G. Bulat, W. P. Jones, A. J. Marquis, *Combust. Flame* 161 (7) (2014) 1804–1825.
- [5] A. Abou-Taouk, B. Farcy, P. Domingo, L. Vervisch, S. Sadasivuni, L.-E. Eriksson, *Combustion Science and Technology* 2202 (July) (2015) 150729213950008.
- [6] J. Li, D. Yang, C. Luzzato, A. S. Morgans, *Oscilos: the open source combustion instability low order simulator technical report*, technical report, Imperial College London, 2015.
- [7] X. Han, J. Li, A. S. Morgans, *Combust. Flame* 162 (10) (2015) 3632–3647.
- [8] U. Stopper, W. Meier, R. Sadanandan, M. Stöhr, M. Aigner, G. Bulat, *Combust. Flame* 160 (10) (2013) 2103–2118.