Progress in Aerospace Sciences 97 (2018) 35–60

Contents lists available at ScienceDirect

Progress in Aerospace Sciences

journal homepage: www.elsevier.com/locate/paerosci

A review of active control approaches in stabilizing combustion systems in aerospace industry

Dan Zhao [a,*], Zhengli Lu [b], He Zhao [b], X.Y. Li [c], Bing Wang [d], Peijin Liu [e]

[a] Department of Mechanical Engineering, College of Engineering, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand
[b] School of Energy and Power Engineering, Jiangsu University of Science and Technology, Zhenjiang City, Mengxi Road 2, Jiangsu Province 212003, China
[c] School of Mechanical and Aerospace Engineering, College of Engineering, Nanyang Technological University, 639798, Singapore
[d] School of Aerospace Engineering, Tsinghua University, Beijing 100084, China
[e] Science and Technology on Combustion, Internal Flow and Thermo-Structure Laboratory, Northwestern Polytechnical University, Xi'an 710072, Shanxi Province, China

ARTICLE INFO

Keywords:
Active control
Engine system
Propulsion
Aeroacoustics
Combustion instability
Feedback control
Thermoacoustics

ABSTRACT

Self-sustained combustion instabilities are one of the most plaguing challenges and problems in lean-conditioned propulsion and land-based engine systems, such as rocket motors, gas turbines, industrial furnace and boilers, and turbo-jet thrust augmenters. Either passive or active control in open- or closed-loop configurations can be implemented to mitigate such instabilities. One of the classical disadvantages of passive control is that it is only implementable to a designed combustor over a limited frequency range and can not respond to the changes in operating conditions. Compared with passive control approaches, active control, especially in closed-loop configuration is more adaptive and has inherent capacity to be implemented in practice. The key components in closed-loop active control are 1) sensor, 2) controller (optimization algorithm) and 3) dynamic actuator. The present work is to outline the current status, technical challenges and development progress of the active control approaches (in open- or closed-loop configurations). A brief description of feedback control, adaptive control, model-based control and sliding mode control are provided first by introducing a simplified Rijke-type combustion system. The modelled combustion system provides an invaluable platform to evaluate the performance of these feedback controllers and a transient growth controller. The performance of these controllers are compared and discussed. An outline of theoretical, numerical and experimental investigations are then provided to overview the research and development progress made during the last 4 decades. Finally, potential, challenges and issues involved with the design, application and implementation of active combustion control strategies on a practical engine system are highlighted.

1. Introduction

One of the critical requirements for modern and future combustion system is to achieve low NO_x emissions and increased fuel efficiency [1]. For this, lean premixed pre-vaporized (LPP) combustion technology is widely applied in both land-based gas turbines [2,3] and aero-engines [4,5]. However, this technology is often associated with combustion instability. The instability are characterized by large amplitude pressure or velocity oscillations, corresponding to one or more eigenmodes of the combustor, which is typically acoustic resonant. Such instability has been frequently encountered in operated propulsion systems such as rocket motors [6], ramjet engines [7] and aero-engine afterburners [8–10], power generation systems such as industrial furnaces [11], boilers, heating systems and land-based gas turbines.

In general, such instability is undesirable and its occurrence is problematic, since they produce large-amplitude flow fluctuations. These oscillations can give rise to enhanced periodic heat transfer and thermal stresses to combustor walls, severe vibrations that interfere with control-system operation, thrust oscillations, oscillatory mechanical and thermal loads that lead to high- or low-cycle fatigue of engine components, even flame blow-off or flash-back. These periodic flow oscillations are highly detrimental to combustion/engine systems. Thus there is a strong need to understand the generation mechanism and to develop effective control approaches to stabilize combustion systems to avoid structural damage and costly mission failure.

On a laboratory-scale, combustion instabilities can occur in Rijke tube [12,13]. It is typically a simple open-ended vertical or horizontal tube with a heat source such as a flame or an electrical heater confined. The

* Corresponding author.
E-mail address: dan.zhao@canterbury.ac.nz (D. Zhao).

https://doi.org/10.1016/j.paerosci.2018.01.002
Received 30 April 2017; Received in revised form 23 January 2018; Accepted 24 January 2018
Available online 9 February 2018
0376-0421/

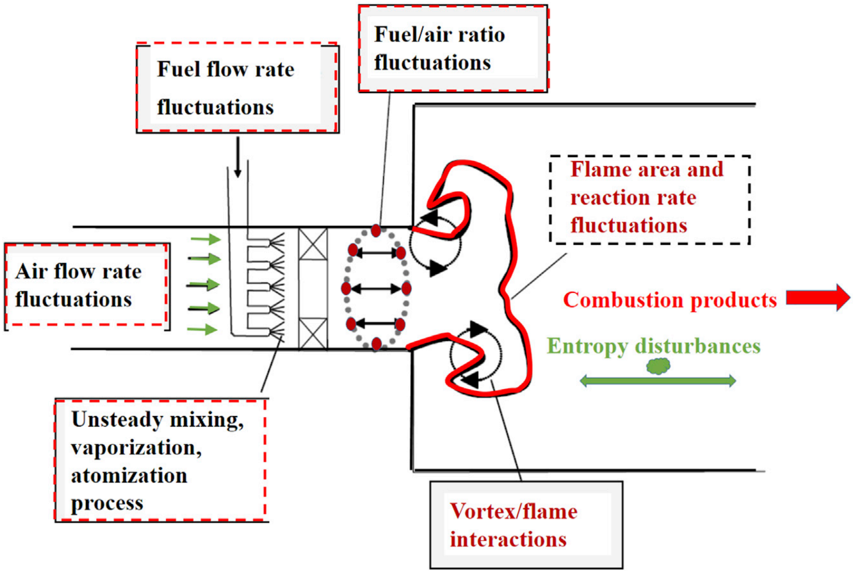

Fig. 1. Unsteady flow and flame processes that may cause combustion instability in gas turbine engines [29].

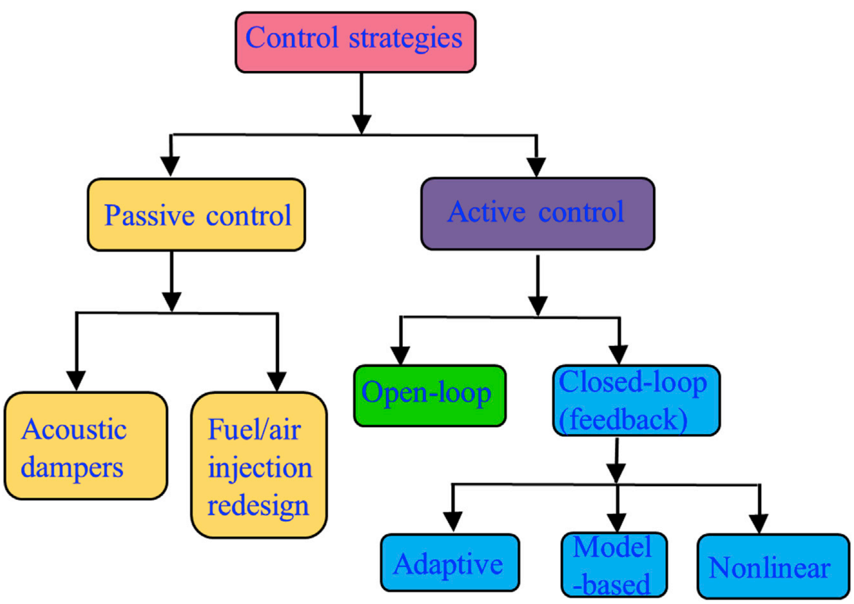

Fig. 2. Typical control approaches applied in combustion systems.

main requirements for producing combustion instability in Rijke tube are that 1) there must be an air flow through the tube (e.g. natural or force convection), 2) the boundary losses must not be excessive and 3) the heat source needs to be placed in the upstream stream half of the tube. A modified design of Rijke tube was proposed and tested for energy harvesting [14,15] and controller performance evaluation [16]. It is shaped like Y, having a mother tube (bottom stem). It splits into 2 or more bifurcating daughter tubes (i.e. upper branches). The lengths of the bifurcating branches are generally different. This provides a mechanism to produce 2 or more non-harmonic combustion-driven oscillation modes; its wavelength corresponds to the total length of each bifurcating branch and the bottom stem.

Considerable researches [17–19] have been conducted in industrial and academic research and development communities over the past few decades to elucidate the generation mechanism/processes, which contribute to these instabilities, aiming to develop effective control means to mitigate these instabilities. An overview of the physics and mechanisms of combustion instabilities and the methods for mitigating them is presented in the following sections.

1.1. Basic physics of combustion instabilities

Self-sustained combustion instabilities are typically generated by the dynamic interaction between unsteady heat release (including entropy fluctuations) and acoustic disturbances [17–19]. Under lean premixed conditions, a small variation of the flow rate of fuel or inlet air can cause unsteady heat release. Unsteady heat release is an efficient monopole-like sound source [20,21]. And acoustic waves are produced and propagate within the combustor. Partial of the acoustic waves are reflected back from the combustor boundaries to the flame/combustion zone, causing more unsteady heat release. Such feedback can lead to the acoustic oscillation successively intensified. This is what is well known as combustion instability. Eventually, some nonlinearity in the combustion system will ensure that the acoustic oscillation intensity is ‘saturated’. Thus it is the nature of the dynamic coupling between the acoustic disturbances and unsteady heat release that determines whether or not a