Applied Energy 181 (2016) 399–407

Contents lists available at ScienceDirect

Applied Energy

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

Theoretical and experimental demonstration of minimizing self-excited thermoacoustic oscillations by applying anti-sound technique

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HIGHLIGHTS

- Minimizing self-sustained thermoacoustic oscillations is theoretically and experimentally studied.
- LMS-based online identification algorithm is applied to achieve robust control.
- Noise effect is theoretically studied by adding Gaussian noise to a van der Pol oscillator.
- Off-design performance is experimentally evaluated by varying fuel flow rate.
- 45 dB sound pressure level reduction is experimentally achieved.

ARTICLE INFO

Article history:
Received 14 June 2016
Received in revised form 12 August 2016
Accepted 13 August 2016

Keywords:
Thermoacoustic oscillation
Combustion instability
System identification
Heat-to-sound conversion
Feedback control

ABSTRACT

The coupling between unsteady heat release and acoustic perturbations can lead to self-sustained thermoacoustic oscillations, also known as combustion instability. When such combustion instability occurs, the pressure oscillations may become so intense that they can cause engine structural damage and costly mission failure. Thus there is a need to develop a real-time monitoring and control approach, which enables engine systems to be operated stably. In this work, an online monitoring and optimization algorithm is developed to stabilize unstable thermoacoustic systems, which are characterized by nonlinear limit cycle oscillations. It is based on least mean square method (LMS). The performance of the optimization algorithm is evaluated first on a Van der Pol oscillator. It can produce nonlinear limit cycle oscillations, which is similar to pressure oscillation as frequently observed in gas turbine engines. It is shown that implementing the control strategy leads to the oscillations quickly decayed. To further validate the control strategy, experimental study is conducted on a Rijke tube. It is found that approximately 45 dB sound pressure reduction is achieved by actuating a loudspeaker. In addition, the control approach is demonstrated to be able to track and prevent the onset of new limit cycle thermoacoustic oscillations resulting from the changes of fuel flow rate. The present work opens up a new applicable approach to stabilize engine system in terms of minimizing thermoacoustic oscillations.

1. Introduction

Combustors play a critical role in determining the performance of aero-engines and gas turbines and other propulsion systems. However many combustion systems are susceptible to self-excited thermoacoustic instabilities [1,2], especially under lean combustion condition [3,4]. They are characterized by large-amplitude pressure oscillations [5,6]. Such oscillations are wanted in thermoacoustic engines/prime movers [6,7] or cooling systems [8,9]. However, they are undesirable in aerospace and power generation industries. When thermoacoustic instabilities occur, premixed or diffusion flame may be blow out and the working life of practical engines may be seriously reduced due to structural vibrations and overheating [10]. Therefore it is important to understand the physics and to develop control approaches to mitigate these self-sustained thermoacoustic oscillations [11,12] in designing energy-efficient and stably operated combustors.

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http://dx.doi.org/10.1016/j.apenergy.2016.08.069

Nomenclature

a_k, A^t	FIR filter coefficients
$D(n)$	external noise entering the system
$e(n)$	error output
$fx(n)$	estimate from secondary propagation path
$\widehat{H}(n)$	adaptive LMS filter
$H(n)$	ordinary LMS filter
L	total length of the tube (m)
M	Length of the samples used in the LMS method
n	Sample number at current time step
p	Pressure oscillation
t	time (s)
t^*	normalized time
x	Van der Pol parameter
x(n)	Input signal
y(n)	Real output signal
$\hat{y}$(n)	Estimate output signal
$\tilde{y}$	FIR filter output signal
$Ys(n)$	signal from secondary propagation path

Greek letters

μ	Coefficient involved in Van der Pol oscillator
ω	Frequency of pressure oscillations

Subscripts

n	sampling time
k	$k = 0$ to M, where $M = L - 1$ and L is filter length

Superscripts

$'$	first order derivative
$''$	second order derivative
$*$	normalized term
$\hat{}$	estimation
$\sim$	FIR filter estimation

Abbreviations

LMS	least mean square
FIR	Finite Impulse Response
IIR	Infinite Impulse Response
ANC	active noise control, active noise cancellation
SPL	sound pressure level

The main cause of self-sustained thermoacoustic oscillations [13,14] are due to the energy transferred from unsteady heat source to acoustic waves [15,16]. Unsteady heat release from a heat source is an efficient sound source [17,18], which produces acoustic disturbances. These acoustic disturbances propagate along the combustor and are reflected back due to the change of the boundary condition. Under certain conditions, the acoustic disturbances can further perturb the heat release rate and result in a 'constructive' feedback loop between heat release and acoustic waves [19,20]. This will lead to small-amplitude flow disturbances growing quickly into limit cycle oscillations [21,22]. Rayleigh's criterion is widely used to characterize the generation mechanism of thermoacoustic instability [23]. It states that if unsteady heat release and pressure disturbances are in-phase, thermoacoustic instability occurs and combustion system will be unstable [24]. However, if the heat-release rate and pressure disturbances are out of phase, flow disturbances decay. And the combustion system is stable.

In order to mitigate such thermoacoustic instabilities, the coupling between unsteady heat release and the acoustic perturbations must somehow be broken. Active [25,26] or passive [27,28] control techniques can be applied to achieve this. Passive control approaches [29,30] involves modifying the fuel injection system [29], changing the geometry of the combustion system or attaching acoustic dampers [31,32]. The main advantages of passive control approaches include that (1) the lack of moving component [33], (2) low maintenance cost [34] and (3) high durability [35]. Generally, implementing passive control approaches does not involve any risk to destabilize a stable combustor. However, modifying the combustion system can be costly and time consuming, while acoustic dampers cannot respond to changes in operating conditions due to the absence of a dynamic control system. These drawbacks limit the usage of passive control approaches to engine systems.

Conventional passive control approaches are aimed to dissipate acoustical energy without utilizing it. Recently attempts [36,37] are made to apply some energy conversion devices to combustors susceptible to self-sustained thermoacoustic oscillations [38,39]. In this way, the acoustical energy is converted into electricity for energy harvesting purpose. The study on heat-to-sound energy conversion recently became more and more popular. Various energy conversion techniques are developed and tested, for example, piezoelectric [36,37] and thermoelectric [38] power generators applied on a Rijke-Zhao system [39] with a premixed laminar flame confined. Promising results are obtained. And these energy conversion techniques may have great potential to be apply to a combustion system with a diffusion flame [40,41].

Active control approaches are generally applied in closed-loop configuration [20,21] by using a dynamic actuator such as a loudspeaker. Such configuration is also known as feedback control. In feedback control configuration, the controller drives the actuator in response to a sensor's measurement [23,42]. Annaswamy et al. developed and tested a self-tuning controller to stabilize an unstable combustor. Comparison is then made between a fixed phase-lead controller and the self-tuning one. Neumeier et al. [23] developed an FFT-like online algorithm to stabilize an unstable premixed turbulent combustor. The algorithm can determine the amplitude, frequency and phase of the pressure oscillations in real time. Yi and Gutmark [42] developed a similar observer-based adaptive control algorithm. And it's performance is evaluated in a modelled Cambridge combustor by stabilizing two unstable modes. One of the typical feedback control strategy is based on an infinite impulse response filter [20], whose coefficient is optimized by using least mean square algorithm (LMS). Numerical implementation of X-filtered LMS algorithm on a modelled combustor can reduce the pressure oscillations by about 15% [21]. In practice, the condition of the combustion system needs to be monitored in real-time. If there are small-amplitude oscillations or no limit cycle, then it is not necessary to activate the controller and actuator. Thus real-time monitoring and control of a combustion system is necessary for achieving safe operations. This partially motivated the present work. In addition previous studies did not experimentally validate the LMS control algorithm. Lack of such investigations partially motivated the present work.

In this work, real-time monitoring and minimizing thermoacoustic instabilities are theoretically and experimentally studied.