1

Thermoacoustic Oscillations

The Wolf:	I'm Winston Wolf. I solve problems.
Jimmie:	Good, we got one.

From "Pulp Fiction", by Quentin Tarantino

1.1 Abatement of Emissions: Solutions and Problems

Modern premixed gas turbines have to comply with continually more stringent emission regulations (NO_x, CO etc.), and traditional methods of reducing NO_x (water and steam injection) cannot reach those extremely low levels required. Therefore, the equivalence ratio (or mixture ratio, defined as the ratio of fuel/air used to stoichiometric fuel/air ratio) is reduced, which brings the combustion into a regime called "dry lean". This means that the combustors operate with excess air to cool down the combustion temperature. The Zeldovich mechanism states that the formation of NO_x is exponentially dependent on temperature, which shows the benefits of lean combustion.

However, this regime makes the combustor prone to thermoacoustic instabilities, blowout, and flashbacks. The flame becomes much more sensitive to disturbances of pressure, velocity, and equivalence ratio. Thus, the flame anchoring and fronts are perturbed; shear layers and recirculation zones are altered. The acoustic damping of the combustion chamber is reduced, because of lacking dilution air downstream.

If the heat release and pressure fluctuations are properly phased, the flame feeds energy into the acoustic field. This in turn influences the flame and closes a (potentially) unstable feedback cycle, called thermoacoustic instability or oscillations.

Combustion instabilities are the most common form of thermoacoustic instabilities, where energy is transferred from a heat source to a fluid causing oscillatory fluctuations in heat release and pressure.

This phenomenon occurs in lean premixed low emission gas turbines, jet engines, afterburners, liquid-fueled rocket motors as well as domestic burners. Practitioners call the resulting noise "rumble", "growl", "howl", and "humming".

Four modes of unstable combustion can be distinguished:

- bulk: also known as Helmholtz mode or called “buzz”. In this case, the pressure varies only temporally but not spatially, the important parameter is the volume of the combustor. Unstable frequencies of less than several hundred Hz.
- longitudinal: also called “rumble”. It is strongly dependent on the acoustic length of the combustor. Unstable frequencies of several hundred Hz but less than 1 kHz.
- circumferential: this mode depends on the circumference of the annular combustor with several burners.
- transverse: also called “screech”, occurs mostly in afterburners.

The ensuing unsteady heat release and pressure oscillations lead to excessive vibrations resulting in mechanical failure, high levels of acoustic noise, high burn rates, and possible component melting [8, 198, 79]. In addition, higher heat transfer rates to the walls and increased emissions of pollutants such as unburnt hydrocarbons or oxides of nitrogen are observed. The pressure oscillations constitute between 1 and 10% of the mean operating pressure, and since today’s combustors work with pressures up to 35 MPa, these fluctuations are of considerable amplitudes [239, 49]. However, pressure oscillations are desired in certain devices such as ramjet engines and pulsed combustors.

A number of passive and active strategies have been employed in the past to mitigate these problems. The installation of dampers, baffles, and vortex generators is aimed at increasing damping and disrupting the phasing between heat release and pressure. On the other hand, active control algorithms monitor the pressure or another performance signal and take action accordingly, through an actuator such as a loudspeaker or auxiliary fuel injection.

The term “instabilities” is often used interchangeably with “oscillations”, as it is often difficult to determine whether the system is (linearly) unstable and saturated, or just lightly damped and noise driven. This slight abuse of notation should not cause any confusion.

1.2 Instability Mechanisms

At the core of thermoacoustic instabilities lies the coupling between the unsteady components of pressure and heat release rate. Atomization and vaporization play important roles for liquid-fueled combustors.

The often stated Rayleigh's criterion is as follows [256]: "If heat be periodically communicated to, and abstracted from, a mass of air vibrating in a cylinder bounded by a piston, the effect produced will depend upon the phase of the vibration at which the transfer of heat takes place. If heat be given to the air at the moment of greatest condensation or to be taken from it at the moment of greatest rarefaction, the vibration is encouraged. On the other hand, if heat be given at the moment of greatest rarefaction, or abstracted at the moment of greatest condensation, the vibration is discouraged". Mathematically stated, it is given by Eq. 1.1, from [79], with the pressure, density, heat-release rate per unit volume, particle velocity, speed of sound, and ratio of specific heat capacities denoted by $p, \rho, q, \mathbf{u}, c$ and γ, respectively. Mean and fluctuating values are denoted by an overbar and by a prime, respectively.

$$\frac{\partial}{\partial t}\int_V \Big(\underbrace{\frac{1}{2}\overline{\rho}\mathbf{u}^2}_{kinetic} + \underbrace{\frac{1}{2}\frac{p'^2}{\overline{\rho c}^2}}_{potential}\Big)dV = \int_V \underbrace{\frac{\gamma-1}{\overline{\rho c}^2}p'q}_{Rayleigh}\,dV - \int_S \underbrace{(p'\mathbf{u})}_{surface}\,d\mathbf{S} \tag{1.1}$$

The first two terms denote the kinetic and potential energies, and the first term on the right-hand side is Rayleigh's integral. It can be seen that if p' and q are in phase, the integral is positive. Finally, the last term describes the surface loss terms.

Thermoacoustic instabilities may be caused by fluctuations in the air supply to the burner, by aerodynamic (intrinsic) instabilities or by perturbations in the fuel supply, where the pressure waves interact with the fuel nozzle [120, 198, 49]. These equivalence ratio perturbations happen when a positive pressure excursion produces a decrease of the fuel supply at a later instant. Local extinction and re-ignition within the flame may be due to maldistributions in the fuel distribution. Large-scale structures such as vortices are also involved.

The periodic heat released by the flame gives rise to pressure fluctuations, which are reflected back to the flame. If they are coupled such that Rayleigh's criterion is fulfilled, this process is sustained. The flame may wrinkle and increase its surface area, and change its position.

Interestingly, this mechanism can also be reversed and used to build a thermoacoustic refrigerator [266, 167, 183, 297, 296]. A thermoacoustic Stirling heat engine is proposed in [16], and used in [252] to drive a pulse tube cooler (PTC), which reaches 80 K ($-193\,^\circ$C). Such devices contain no moving mechanical parts, no environmentally hazardous substances, and reach high efficiencies. Potential applications are in space exploration (Space Shuttle mission STS-42 in 1992) and liquifying natural gas[1]. A "SoundsCool" freezer from ThermoAcoustics Corp. cools "Sweet & Sonic" ice cream at Ben & Jerry's in New York City, using a loudspeaker emitting 195 dB of sound [32].

1.2.1 Premixed Swirl-Stabilized Burners

The ETH combustor works in premix operation, so that fuel feed line dynamics and equivalence ratio fluctuations are of minor importance.

The installed lab-scale ALSTOM EV (EnVironmental) burner is discussed [222]. It has the unique property of flame stabilization in free space near the burner outlet utilizing the sudden breakdown of a swirling flow, called vortex breakdown.

Vortex shedding for dump combustors is studied in [274]. The shear layer develops instability waves in its initial region. When the amplified waves reach a certain energy level, they roll up into vortices. In the early phase of the vortex development, with the unburnt mixture on one side of an interface and the hot combustion products on the other side, mixing and burning are limited. When the vortex roll-up process is followed by interaction between vortices and/or side walls, a large interface between the air/fuel mixture and hot products develops, leading to fine-scale turbulence enhancement and sudden heat release. The associated acoustic velocity fluctuations then trigger the next cycle of vortex shedding [49].

Unsteady flame dynamics in a lean premixed swirl-stabilized combustor are addressed in [129, 128]. A central toroidal recirculation zone is established in the wake of the center body under the effects of the swirling flow (vortex breakdown). As a result of the sudden increase in combustor area, a corner recirculation zone is also formed downstream of the backward-facing step.

The flame can be anchored in the center or in both the center and outer recirculation zone. This depends on the flame speed, which is influenced by the preheat temperature and the equivalence ratio. Hysteresis is related to the heating of the combustor walls.

Large-scale vortex structures can influence the turbulent flame speed and the flame area [159].

More on the role of coherent large-scale structures can be found in [276, 231, 129, 226, 273, 244, 198, 153, 193, 82].

[1] And, just like in the Middle Age: "to give a small quantity of Beer &c. a moderate degree of coolness" [10].

1.3 Approaches to the Problem

Combustion instabilities became a serious issue in liquid-fueled rocket engines before and during World War II. However, the installation and cooling of pressure transducers was difficult. The first theoretical considerations were done in the 1950's on liquid-fueled rocket motors [65, 264], and the development of the F-1 engine for the Apollo space vehicle increased the efforts, see [214, 67] for a review. Active control of thermoacoustic oscillations was first applied to for Rijke tubes in the 1980's [37, 35, 300, 194, 34, 93]. Due to new environmental standards requiring more stringent emission levels both for aircraft and land-based gas turbines, the interest in modeling and active control grew steadily [181].

1.3.1 Passive Control

A number of passive ways to suppress instabilities exists [28, 84, 8]. They can be classified into two categories:

1. Reduction of the coupling between heat release and acoustics. Therefore, less energy is fed into the unstable acoustic modes by

    - changing flame anchoring point
    - affecting vortex shedding [234]
    - changing acoustic boundary condition
    - changing fuel line dynamics
    - changing fuel injection pattern [198]

2. Increase of (acoustic) energy losses in the combustor is achieved by

    - installing baffles
    - acoustic dampers
    - geometric changes of the combustion chamber

Reducing the coherence of large-scale vortices and generating axial vorticity is another passive approach [234, 228, 88, 240, 274]. This may be accomplished by extending the fuel injecting lance so that the vortices break down [222], or to install distributed vortex generators [234]. Changing the burner shape is also an option [225].

1.3.2 Active Control

Active control methods are becoming more promising with the introduction of new sensor, actuator, and computing technology.

Active control methods are advantageous because they can [8]:

- reduce pressure oscillations
- reduce pollutants (NO_x)
- increase combustion intensity
- operate combustors beyond their natural flammability limits
- be applied in a wider frequency band than passive control
- cope with changing operating conditions
- allow design changes, for example shorter combustors

Available sensors are piezoelectric and moving coil microphones to detect pressure fluctuations; photodiodes and OH/CH chemiluminescence to measure heat release rates. Radiometers measure CO and CO_2; NO_x can be determined, and Laser velocimetry and Schlieren photographs show the flame shape.

Actuators introduce perturbations in acoustic pressure, velocity, vorticity, fuel or air mass flow, or heat release. Mostly used are fuel stream oscillation devices and speakers; oscillating center bodies, moving flaps or airfoils, single or several stream-wise or cross-stream jets, swirl generators or heating elements are reported, too [8]. (Secondary) fuel injection uses small fractions of power generated in the system, whereas mechanical methods which use loudspeakers or moving bodies are less feasible due to the high energy density in the combustor [147, 105].

An active control algorithm has been applied to a Siemens-Westinghouse heavy-duty V94.3A 267 MW gas turbine in January of 1999. Two circumferential modes in a 24 burner configuration are controlled with secondary fuel injectors using a phase-shift strategy [181, 283].

Summary

This chapter has given an introduction to and classification of thermoacoustic instabilities. It explained mechanisms that are particular to swirl-stabilized burners, and laid out both passive and active control strategies.

2

Literature Review

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2.1 Reported Control Concepts

In general, it is difficult to compare the achievements of the different controllers directly against each other, since the range of combustor setups used varies by a great degree (liquid, gaseous, laminar, swirl-, dump-, bluff body-stabilized, different power ratings). Moreover, various sensors and actuators are used (microphones and photomultipliers, loudspeakers and fuel injectors being the most common).

One more important distinction has to be made. Most of the researchers class their combustor behavior as "unstable" and as being in a limit cycle, except in [47, 20, 59, 48], which are rated as lightly damped. The reduction of the noise in an unstable combustor can usually be seen at all frequencies [263], and may be very large. Reducing the sound pressure is thus a task of stabilizing a plant. Conversely, making a stable combustor more silent is a problem of noise suppression.

The easiest and ubiquitous control strategy is **phase-shift** or **Gain-Delay** control [38, 154, 283], where the sensor signal is multiplied with a gain and delayed by a certain amount and sent to the actuator. This controller is easy to implement and often gives satisfactory results. Manual tuning is usually employed.

Subharmonic fuel injection is tried in [135, 140, 52]. Although it is found to work for some particular conditions, it can be conjectured that the flame is just locally enriched (yielding a different global equivalence ratio) and thus stabilized.

In an early paper [154], a swept-sine signal is used to find the transfer function of a combustor equipped with on/off fuel valves in a stable condition. The parameters of a second-order system are then adjusted so that an unstable plant can be described. In the Nyquist plot, the parameters of a phase-shift controller are found such that the closed-loop plant is stabilized. A similar approach is followed in [59, 20], but here a stable system is fitted.

The **Least-Mean-Square** error method (LMS) and its derivations (x-LMS, u-LMS, leaky) have been used with mixed success—feedback loop instabilities and algorithm divergence occur [139, 33, 299, 4, 204, 11]. Furthermore, there are no theorems that guarantee global stability. An improvement is shown in [92, 90].

A so-called **Self-Tuning Regulator** (STR) [93, 90, 263, 262, 91] only needs knowledge of the time delay, and shows some robustness against changing operating conditions. In two semester theses [201, 265], it is concluded that for a combustor which is already stable, the STR does not offer advantages over a model-based controller. In particular, numerical problems may arise.

Loudspeakers controlling vortex shedding and cross-flow jets are implemented as actuators in [216, 215]. Optimization using a downhill-simplex algorithm is performed on the frequency of the loudspeaker control signal and the cross-flow strength. Note that this yields a *static* control system, not one with pressure feedback. The tradeoff between acquiring repeatable cost functions and short convergence times is highlighted.

In [19, 147], adaptive algorithms are presented. But only simulations are carried out in [147], and only the control phase is updated in [19]. Noise is identified as a problem, and questions about algorithm instability are raised.

A Rijke tube is controlled in [36] with loudspeakers and a neural network, which requires an identification procedure beforehand.

The fuel flow through different injection locations along the burner is optimized with an evolutionary algorithm in [237].

A range of **lead/lag** controllers are optimized with an evolutionary algorithm in [238, 275]. The influence of the noise is realized, the problem with resulting long evaluation times discussed, and a two-step evaluation proposed (short and long). The maximum number of iterations is fixed to 200.

A loudspeaker is used to control an unstable 1 kW rig in [7]. With an analytical model, an **LQG/LTR** and an $\mathcal{H}_\infty$ **controller** are designed. A linear model valid for the limit cycle of the unstable 114 kW swirl combustor is identified in [206]. About 8% of the total fuel are modulated with on/off injectors, using an LQG/LTR approach. The results are compared with a fixed gain/ variable delay phase-shift controller, which performs worse for one condition but just as well in a one-mode dominated case.

Only simulation studies with an $\mathcal{H}_\infty$ **controller** are reported in [126, 57]. A loudspeaker is used as actuator together with an on/off fuel injector operated open-loop at 400 Hz in a swirl-stabilized 125 kW spray combustor [48]. A stable network model valid between 100–300 Hz is identified and used to design an **LQG/LTR** and $\mathcal{H}_\infty$ **controller**. Small delays are added during the experiments to obtain maximum attenuation. Only the phase is varied for the phase-shift controller. It turns out that LQG/LTR works best, followed by $\mathcal{H}_\infty$ and phase-shift.

Fuel is modulated in a swirl-stabilized premix combustor [47]. It is identified as a stable but lightly damped noise-driven network model. Two kinds of $\mathcal{H}_\infty$ controllers are tried, and found to work better than phase-shift. However, pollutant emissions can rise for some conditions.

2.2 Work of Various Research Groups

The work of various research groups is presented here, along with more references to publications.

ALSTOM (Switzerland), Ltd, Baden, Switzerland

The structure of instabilities is examined in [229, 230, 228, 233, 275], coherent structures are explained in more detail in [231]. The model of a burner and flame is laid out in [248, 29, 239, 276]. The network model is presented in [279, 223, 277, 278, 236]. A phase-shift controller is implemented in [229, 230, 228, 232, 224]. An evolutionary algorithm working on controller parameters is discussed in [238], while the injection pattern is influenced with such an algorithm in [237, 235]. An $\mathcal{H}_\infty$ controller is shown in [47, 278, 112]. Passive approaches are evaluated in [88, 240, 222, 225, 226, 227], and further in [234, 26, 28, 27]. The ALSTOM EV burner is discussed in [222]. Power Plant CO_2 emissions are treated in [190, 113].

Massachusetts Institute of Technology, Cambridge, USA

Good overviews are given in [8, 9]. This group presents a model based on the acoustic equation with a one- or two-mode Galerkin expansion [8, 5, 6, 121, 99, 119, 118, 110]. A model for a laminar premixed flame similar to a $n-\tau$ model is presented in [98, 6, 220, 221]. Stability of the combustor depends on the position of the flame (Rayleigh's criterion), the first mode is stable and the second unstable. This model is stabilized with a self-tuning phase-lead controller and compared to an LMS algorithm [4, 91]. LQG/LTR and $\mathcal{H}_\infty$ are used in [7, 220, 206], and open-loop control is discussed in [251].

Cambridge University, Cambridge, UK

An excellent review on feedback control of combustion oscillations is [79]. A general overview of the problem is [77], and of the acoustics [80]. A flame model similar to the $n-\tau$ model and further experiments are described in [153, 39]. Yet more modeling is found in [74, 75, 76, 78, 308, 42, 290, 14, 289, 18], passive approaches are considered