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Simultaneous identification of transfer functions and combustion noise of a turbulent flame

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ABSTRACT

The Large Eddy Simulation/System Identification (LES/SI) approach allows to deduce a flame transfer function (FTF) from LES of turbulent reacting flow: Time series of fluctuations of reference velocity and global heat release rate resulting from broad-band excitation of a simulated turbulent flame are post-processed via SI techniques to derive a low order model of the flame dynamics, from which the FTF is readily deduced. The current work investigates an extension of the established LES/SI approach: In addition to estimation of the FTF, a low order model for the combustion noise source is deduced from the same time series data. By incorporating such a noise model into a linear thermoacoustic model, it is possible to predict the overall level as well as the spectral distribution of sound pressure in confined combustion systems that do not exhibit self-excited thermoacoustic instability. A variety of model structures for estimation of a noise model are tested in the present study. The suitability and quality of these model structures are compared against each other, their sensitivity regarding certain time series properties is studied. The influence of time series length, signal-to-noise ratio as well as acoustic reflection coefficient of the boundary conditions on the identification are examined. It is shown that the Box-Jenkins model structure is superior to simpler approaches for the simultaneous identification of models that describe the FTF as well as the combustion noise source. Subsequent to the question of the most adequate model structure, the choice of optimal model order is addressed, as in particular the optimal parametrization of the noise model is not obvious. Akaike's Information Criterion and a model residual analysis are applied to draw qualitative and quantitative conclusions on the most suitable model order. All investigations are based on a surrogate data model, which allows a Monte Carlo study across a large parameter space with modest computationally effort. The conducted study constitutes a solid basis for the application of advanced SI techniques to actual LES data.

1. Introduction

In various industrial applications, e.g. gas turbines for power generation or propulsion, combustion noise is an undesirable, but unavoidable by-product of turbulent combustion. In aeronautical engines combustion noise may dominate the sound emissions within a certain frequency range [1]. Besides being harmful for those continuously exposed to noise emissions, elevated combustion noise levels may even trigger thermoacoustic instabilities [2], which should be avoided at any cost. Consequently, combustion noise is a subject of past as well as on-going research.

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Nomenclature

Latin letters

a_i, b_i, c_i, d_i, f_i	model coefficients
A, B, C, D, F	polynomial filters
$\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D}$	state-space matrices
c	speed of sound
f	char. wave downstream
g	char. wave upstream
G	plant model
H	noise model
J	cost function
$\mathbf{K}$	correlation vector
l	length scale
n_a, n_b, n_c, n_d, n_f	polynomial model order
N	number of time series samples
p'	acoustic pressure fluctuation
P_{xx}	power spectral density
q	time shift operator
$\dot{Q}'$	heat release rate fluctuation
R	reflection coefficient
$\mathbf{R}$	weighting matrix
Δt	sampling interval
t	time
u'	acoustic velocity fluctuation
$\mathbf{x}$	state vector

Greek letters

α	cross-section ratio
$\gamma_{\epsilon\epsilon}$	auto-correlation of ϵ
$\gamma_{\epsilon u}$	cross-correlation of ϵ with input
Δ	noise model error
ϵ	model residual
$\boldsymbol{\theta}$	parameter vector
Θ	temperature ratio
λ	regularization parameter
ξ	specific acoustic impedance
ρ	density
τ	impulse response length
ω	angular frequency

Abbreviations

AIC	Akaike's Information Criterion
ARX	Autoregressive Exogenous Model
BJ	Box-Jenkins
FIR	Finite Impulse Response
FTF	Flame Transfer Function
LES	Large Eddy Simulation
nAIC	norm. Akaike's Information Criterion
PEM	Prediction Error Method
SNR	Signal-to-Noise Ratio
WHI	Wiener-Hopf Inversion

In any effort to reduce or limit sound emissions from turbulent combustion devices, two aspects are highly relevant: Firstly, a detailed understanding and characterization of the combustion noise source is essential. Secondly, an accurate and flexible prediction tool for estimating the spectral sound pressure distribution is needed in order to develop and assess suitable countermeasures. In this context 'flexible' means that changes in the geometry and acoustic reflection conditions of the setup, as well as changes in the noise source itself are quickly realizable. If this is the case, predictions of the spectral sound pressure distribution are possible across a large parameter space.

Over the last decades a multitude of studies were conducted to develop a deeper understanding of the generation of combustion noise and the noise source characteristics of a turbulent flame. Bragg [3] stated that a turbulent flame behaves like a set of monopole sources. Refining Bragg's theory and making use of Lighthill's analogy [4], Strahle [5] derived a formulation of the far field pressure for a region that encompasses a turbulent flame. This formulation related the fluctuations of acoustic pressure in the far field to those of unsteady heat release within the flame region. More recent work on the determination of the combustion noise source and its spectral distribution was conducted by Clavin and Siggia [6], who analytically predicted a spectral decay of combustion noise scaling as $f^{-2.5}$. Hirsch *et al.* [7] and Wäsle *et al.* [8] provided a quantitative closure for the spectral distribution of heat release in turbulent premixed combustion that is based on local, time-mean values of heat release rate, turbulent kinetic energy and turbulence lengthscale. The closure proposed by Hirsch *et al.* [7] and Wäsle *et al.* [8] was confirmed by Rajaram and Lieuwen [9], who measured the noise source spectra emitted from a turbulent open jet flame for a variety of operating conditions.

Once the noise source is characterized, the next step is to predict the spectral distribution of sound pressure levels. In this context, there is an essential difference between open and confined configurations. For open configurations the influence of the flame on the acoustics is strong, but not *vice versa*. In this scenario of '*one-way coupling*', the spectral distribution of sound pressure is strongly correlated to that of the combustion noise source. Only open configurations with pronounced intrinsic thermoacoustic feedback may reveal distinct peaks in their sound pressure spectrum [10].

For confined configurations, on the other hand, acoustic reflections at the confinement boundary can establish a '*two-way coupling*' between flame and acoustics [11–13]. The acoustic field of the enclosing cavity is excited by the broad-band combustion noise source and resonances at the acoustic eigenfrequencies may develop. This results in a spectral distribution of sound pressure that depends strongly on the acoustic properties of the enclosing cavity and may differ distinctly from the combustion noise source spectrum. Therefore, a correct description of the flame and the combustion noise source is not enough to predict the resulting spectral sound pressure distribution for confined configurations. An accurate acoustic characterization of the confinement cavity is crucially needed as well.

As almost every combustion device of applied interest is confined, the corresponding possible prediction approaches shall be further examined. Experimental measurements of a certain configuration represent the most straightforward approach. How-