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Combining LES of combustion chamber and an actuator disk theory to predict combustion noise in a helicopter engine

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ABSTRACT

A method to predict combustion noise in real aero-engines using Large Eddy Simulations (LES) of the combustion chamber coupled with an analytical approach to model the acoustic transmission of acoustic and entropy noise through the turbine stages is described. The proposed strategy is tested by comparing predictions of the computed noise with experimental results obtained for a full helicopter engine with high frequency pressure sensors located in the chamber and in all turbine stages. First, an extensive experimental database is used to localize the acoustic sources responsible for the “core-noise” by a three-sensor technique constituting the reference data against which predictions will be assessed. Second, LES of the combustion chamber for two representative operating points are achieved and discussed. The waves leaving the combustion chamber are extracted from these simulations at the outlet of the chamber, and an analytical method based on actuator disk theory and compact assumptions gives noise levels at the various turbine stages using the waves amplitudes at the chamber outlet. Excellent agreement is found at low frequencies between simulations and engine measurements. These results also confirm the importance of indirect combustion noise (due to entropy waves) generated in a helicopter turboshaft engine for the first time.

1. Introduction

Dwindling oil reserves and ACARE 2050 targets on noise and pollution challenge aerospace industry to design increasingly efficient and silent aero-engines. To meet such new challenges, turbulent and lean partially premixed combustion has emerged in recent aeronautical engine combustion chambers but it triggers unwanted effects such as thermo-acoustic instabilities and noise generation. For several decades, combustion noise has been known as a major contributor to the broadband noise generated by aircraft engines also called “core noise”. Current understanding decomposes combustion noise into two main noise sources:

- Direct combustion noise corresponds to the generation of acoustic waves by turbulent combustion within the chamber.
- Indirect noise is the generation of downstream and upstream acoustic waves due to the acceleration of temperature inhomogeneities propagating through the turbine stages.

Indirect noise mechanisms were first described in [1–3], where one way coupling mechanisms between entropy spots and acoustic waves due to a velocity gradient in a quasi-one-dimensional nozzle was established. Using a compact assumption (characteristic length of the nozzle being negligible compared with the wavelength of the low-frequency combustion noise), linearized jump relations linking entropy and acoustic fluctuations are written through the nozzle. More recently, different analytical methods have been developed to remove the compact assumption in a quasi-one-dimensional case [4–6], taking into account arbitrary nozzle shapes [7] or shock waves. In the same manner, modeling of combustion-generated noise through turbine stages was addressed by Cumpsty and Marble [8] or Pickett [9], using the compact assumption and conservation laws between downstream and upstream sections of a turbine row. The low-frequency nature of combustion noise allowed considering only two-dimensional waves with no radial component. Thanks to this two-dimensional description, azimuthal modes, as well as flow deviation, could be considered. In practice, all these analytical methods and models must be validated using either numerical simulations or experimental databases.

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Nomenclature

A	characteristic tube section
c	mean local speed of sound
c_p	specific heat at constant pressure
G	cross-spectrum
h	enthalpy
H	linear transfer function
I	rothalpy
k	wave number
k_x	axial wave number
K	dimensionless wave number magnitude
$\mathbf{K}$	transfer matrix
L_p	characteristic tube length
l_c	axial chord length
L_i	axial distance between rows
M	Mach number
$\dot{m}$	mass flow rate
N_s	number of turbine blade rows
N	uncorrelated noise in the frequency domain
p	pressure
Pr	Prandtl number
r	specific gas constant
$\mathcal{R}$	radius
s	entropy
S	signal emitted by a source in the frequency domain
$\mathbf{S}$	phase-shift transfer matrix
T	temperature
$\mathbf{T}$	transfer matrix of a blade row in a waveform
U	rotational velocity
v	absolute azimuthal velocity
w	absolute velocity magnitude
w	wave
$\hat{\mathrm{w}}$	filtered wave
W	noise signal in the frequency domain
$\mathbf{W}$	wave vector
x	axial component
X	experimental signal in the frequency domain
α	azimuthal coordinate
ρ	density
γ	ratio of specific heats
ϵ	transfer matrix of a blade row for primitive variables
η	indirect to direct noise ratio
ω	pulsation
θ	flow deviation
ν	kinematic viscosity
υ	wave front angle
λ	wavelength
Ω	ratio of wavelength to axial blade chord
ζ	dimensionless difference between total enthalpy and rothalpy within a blade row
$_t$	total state
$_u$	upstream
$_d$	downstream
$'$	fluctuation
$+$	upstream
$-$	downstream
DLR	Deutsches Zentrum für Luft-und Raumfahrt
LES	Large Eddy Simulations
NASA	National Aeronautics and Space Administration
PSD	power spectral density

In realistic aeronautical engines, measurements of core-noise are a challenge because of the harsh conditions found in combustion chambers and turbines stages. In this context, analytical models for acoustic generation-transmission in turbines were primarily based on a database provided by NASA [10]. Recently, in the Seventh European Framework of Programme for research, the Turboshaft Engine Exhaust Noise Identification (TEENI) project was dedicated to the location of acoustic sources in a realistic helicopter engine covering the entire downstream section of a real engine from the combustion chamber to the exhaust with an identification of sources in a radiated acoustic field issued by real operating conditions. To this end, TEENI partners developed sets of sensors for measuring and analyzing unsteady quantities in a full-scale engine.

Currently, numerical simulations are potential alternatives to real test cases. Large-Eddy Simulation (LES) techniques, coupled with the increase of computing power, are mature methods to provide accurate compressible simulations of complex reacting turbulent flows. They have been successfully validated on academic and realistic burners, to retrieve mean statistical features, but also unsteady flow characteristics [11–15]. More precisely, LES is able to capture the strong interactions between turbulent structures and flames, which lead to acoustic wave generation. As such, it was used to study combustion instabilities within industrial and academic burners [16,17], demonstrating the efficiency of LES for combustion-generated noise. With such tools, Leyko [18] used an actuator disk theory [8] coupled with a LES of a turbulent reactive flow in an aero-engine to compute core-noise induced by a combustion chamber. Using also numerical simulations of a two-dimensional turbine stage, Leyko proved the ability of this analytical method to predict indirect combustion noise generated by entropy fluctuations, the direct combustion noise generated through a stator [18] or a rotor [19] and through a complete turbine stage [6]. In the same way, this actuator disk theory is investigated by comparing two-dimensional numerical simulations of a subsonic stator with an injection of entropy spots against analytical predictions [20] showing the validity of this theory for low-frequency cut-on acoustic modes. Indirect noise has been thoroughly studied by DLR in an experiment called Entropy Wave Generator [21,22] which has also been computed by many groups [23–25]. This experiment, however, is a single nozzle and misses many features of real engines so that, to date no actual industrial configuration has been tackled numerically or theoretically to assess the importance of combustion noise. In a first attempt to fill in this gap, the current study presents the TEENI data and a numerical tool to predict noise generated by a real helicopter engine. A complete description of the TEENI experimental setup and main results are presented in Section 2. Section 3 describes the hybrid method called CONOCHAIN coupling LES and analytical approach. LES results are detailed in Section 4.1. Finally, Section 4.2 discusses the validation of the CONOCHAIN tool by comparing predictions with full-scale test results.

2. TEENI: a full-scale experimental test

2.1. Experimental setup

The experimental system is a fully instrumented helicopter engine shown in Fig. 1. The harsh conditions, in terms of temperature and pressure especially in the combustion chamber, required dedicated original probe designs, developed by DLR (Berlin). Each pressure probe is a flush-mounted pin-hole apparatus with a remote microphone put perpendicular to a semi-infinite tube to limit standing wave effects [26]. To protect the microphone from hot combustion products, a cooling system injects a controlled air flow rate through the tube [27]. Temperature sensors are based on a

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