Core Noise –
Where do we come from, where are we going?

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Overview

• Motivation and core noise sources

• Historical overview on
  • direct combustion noise research
  • indirect noise modeling
  • indirect noise experiments

• The RECORD project
  • concept and main achievements

• Conclusions, outlook and main challenges
Background and Motivation

- Increasing relevance of noise sources in the core engine ("core noise")
- Particular interest in the interaction of combustion chamber and turbine with respect to noise generation and transmission.
- Especially for turboshaft engines core noise phenomena play a major role.
Core Noise Sources

Burner  Combustion Chamber  Turbine

Fluctuations in heat release

Entropy waves (hot and cold spots)

Flow

Vorticity inhomogeneities
History direct combustion acoustics 1 (mostly open flames)

1973:
- Combustion noise clearly measurable in jet flames
- More dominating for low jet velocities
- Different dependence on jet velocity than pure jet noise (Air Jet Noise)


Figure 4. Jet Noise, Combustion and Air Jet plus Pilot Flame Noise at Various Flow Velocities.
History direct combustion acoustics 2 (mostly open flames)

2003:

• Combustion noise (of jet flames) depends on jet diameter, jet velocity, fuel and equivalence ratio

• It seem to exist a scalable spectral function (similarity spectrum)


History direct combustion acoustics 3 (mostly open flames)

2005:

- Spectral combustion noise function can be described by flame property parameters (turbulence spectrum, spatial coherence, time relation chemistry-turbulence)

\[
P_{ac,t}(f) = \frac{1}{4\pi \rho_0 c_0} \left( \frac{\gamma - 1}{c_0^2} \right)^2 \int (2\pi f)^2 \left( \frac{3}{2} \kappa E_q(\kappa) \frac{2\pi}{2\pi f} \right)^2 V_{coh} \, dV
\]


History direct combustion acoustics 4 (mostly open flames)

2005:
• Coupling of incompressible (LES) flow simulations (→ source terms) with Computational Aero-Acoustics (CAA) solver (→ acoustic propagation)

Figure 2. Contours of the source term \(-\frac{c^2}{\rho} \frac{\partial p}{\partial t}\) in the plane \(z/D = 0\).

Figure 8. Comparison of the CAA results with experimental data. Radial intensity spectra are shown.


History direct combustion acoustics 5 (mostly open flames)

2010:

- Coupling of steady flow simulation (RANS) with statistically based Random Particle Mesh (RPM) method

The way to pressure, vorticity, and entropy waves

- conservation equations of mass, momentum, and energy:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0
\]

\[
\rho \left( \frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} \right) + \frac{\partial p}{\partial x_i} = 0
\]

\[
\rho \left( \frac{\partial e}{\partial t} + u_i \frac{\partial e}{\partial x_i} \right) = -\frac{\partial p u_i}{\partial x_i}
\]

- assumptions:
  - no body forces
  - no thermal flux
  - no heat sources
  - inviscid flow
The way to pressure, vorticity, and entropy waves

- conservation equations of mass, momentum, and energy:

\[
\frac{\partial^2 p'}{\partial t^2} + 2U \frac{\partial^2 p'}{\partial x_1 \partial t} + U^2 \frac{\partial^2 p'}{\partial x_1^2} - c^2 \frac{\partial^2 p'}{\partial x_1^2} = 0
\]

(acoustic) pressure waves:

vorticity “waves”:

\[
\frac{\partial \omega_i'}{\partial t} + U \frac{\partial \omega_i'}{\partial x_1} = 0
\]

entropy “waves”:

\[
\frac{\partial s'}{\partial t} + U \frac{\partial s'}{\partial x_1} = 0
\]

- assumptions:
  - no body forces
  - no thermal flux
  - no heat sources
  - inviscid flow
  - linearization for small perturbations
  - spatially constant and isentropic mean flow

This explains the choice of acoustic, vorticity and entropy waves.
Spatially non-constant mean $U=f(x_1)$ (e.g. in a nozzle):

**Convective acoustic wave equation:**

\[
- c^2 \overline{\rho} \frac{d}{dx_1} \left( \frac{1}{\overline{\rho c^2}} \right) \frac{\partial p'}{\partial t} - c^2 \overline{U} \frac{d}{dx_1} \left( \frac{\overline{U}}{\overline{\rho c^2}} \right) \frac{\partial p'}{\partial x_1} - c^2 \overline{\rho} \frac{d}{dx_1} \left( \frac{\overline{U}}{\overline{\rho}} \frac{d\overline{\rho}}{dx_1} \right) \\
- c^2 \overline{\rho} \frac{\partial}{\partial x_1} \left( \frac{\overline{\rho'}}{\overline{\rho}} \frac{d\overline{U}}{dx_1} \right) - c^2 \overline{\rho} \frac{\partial}{\partial x_1} \left( \frac{\overline{u_1'}}{\overline{\rho}} \frac{d\overline{\rho}}{dx_1} \right) - c^2 \frac{d\overline{U}}{dx_1} \frac{\partial \overline{\rho'}}{\partial t} \\
+ c^2 \overline{\rho} \frac{d\overline{\rho}}{dx_1} \frac{\partial \overline{u_1'}}{\partial x_1} + c^2 \overline{\rho} \frac{d\overline{U}}{dx_1} \frac{\partial \overline{u_1'}}{\partial x_1} + c^2 \frac{d\overline{U}}{dx_1} \frac{d}{dx_1} \left( \overline{\rho U} \right) \\
+ c^2 \frac{\partial}{\partial x_1} \left( \overline{\rho u_1'} \frac{d\overline{U}}{dx_1} \right) + c^2 \frac{\partial}{\partial x_1} \left( \overline{\rho' U} \frac{d\overline{U}}{dx_1} \right) + c^2 \frac{d^2 \overline{\rho}}{dx_1^2}
\]

Strong coupling of the differential equations → generation of entropy and vortex noise
History indirect noise modeling 1

- **Lighthill (1952):** “excess jet noise” caused by density inhomogeneities in a free jet
- **Chu and Kovasznay (1958):** Analysis the interaction of entropy, vorticity and acoustic modes of perturbation.
- **Morfey (1973):** First analytical investigations of noise generation by accelerated or decelerated entropy waves. Following an analytical estimation by Morfey the excess jet noise scales with the sixth power of the jet velocity.
- **Howe (1975):** Formulation of the noise generation in inhomogeneous and non-isentropic flows with an acoustic wave operator.
- **Ffowcs Williams and Howe (1975):** Analytical solution for sound generation of spherical pellet-like entropy fluctuations in a nozzle flow applying the Green function (limited to low Mach number flows)
- **Lu (1977):** One-dimensional analytical model for the prediction of entropy noise based on correlation quantities of temperature, pressure and velocity fluctuations (also limited to low Mach number flows).
History indirect noise modeling 2

• **Marble and Candel (1977):** One-dimensional theory for compact elements describing the noise generation by entropy waves in nozzle and diffuser flows at higher Mach numbers.

• **Cumpsty and Marble (1977):** Application of this one-dimensional theory on a quasi two-dimensional, unreeled turbine stage: in axial direction infinite thin discontinuity plane where the static pressure as well as the amplitude and direction of the flow velocity is changed. One result of these investigations was a strong increase of entropy noise generation with an increase of the pressure drop over a turbine stage.

• **Cumpsty (1979):** Comparison of directly generated noise to entropy noise in a simplified turbine stage. As a result of this analytic estimation was the indirect entropy noise dominating the direct combustion noise. Good agreement of total sound power of several aero-engines to prediction method especially for operating conditions with low jet noise contribution.
History indirect noise experiments

• **E.E. Zukoski, J.M. Auerbach (1976) and M.S. Bohn (1976/77):** Experiments with *electrically induced entropy waves* in an accelerated duct flow; very low temperature fluctuation of approx. 1 K, limited data acquisition possibilities.

• **Muthukrishnan et al. (1978):** Separation of the different combustion noises sources on a aero-engine combustor test rig by means of **coherence analysis** of different sensor signals; dominating broadband entropy noise contribution to the total noise spectrum.

• **Guedel and Farrando (1986):** Similar experiments on a **helicopter engine** using a three-signal coherence technique.

• **Martinez (2006):** Detection of **combustion related noise** (direct and indirect) by microphone-array measurements on a GE aeroengine (CF34-10E) in an open air test.

• **Harper-Bourne et al. (2008):** **Cross-correlations** between rumble probe and microphone signals; **direct combustion noise** was dominant at low frequencies **below 100 Hz** while the **entropy noise** peaks at 200 Hz and appears to dominate the combustor noise **at high frequencies.**
Objectives of RECORD

- Improvement and validation and benchmark of core noise modeling methods concerning:
  - Direct Combustion Noise
  - Indirect Combustion Noise
  - Transmitted Direct and Indirect Combustion Noise through carefully specified experimental test cases.
RECORD partners

• Project Coordinator
  • Friedrich Bake, German Aerospace Center (DLR; DE)

• Partners
  • GE AVIO SRL (GE AVIO; IT)
  • CAVE s.r.l officine meccaniche (CAVE; IT)
  • Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (CERFACS; FR)
  • Centre National de la Recherche Scientifique (CNRS; FR)
  • Free Field Technologies (FFT; BE)
  • Industria de Turbo Propulsores (ITP; ES)
  • Universidad Politécnica de Madrid (UPM; ES)
  • Office National d'Etudes et de Recherches Aérospatiales (ONERA; FR)
  • Politecnico di Milano - Dipartimento di Energia (PoliMi; IT)
  • Rolls-Royce Deutschland (RRD; DE)
  • Rolls-Royce plc (RRUK; UK)
  • Sandu M. Constantin PF (SMCPFA ; RO)
  • Snecma (SN; FR)
  • Turbomeca (TM; FR)
  • Technische Universität Darmstadt (TUD; DE)
  • Technische Universität München (TUM; DE)
  • University of Cambridge (UCAM; UK)
  • Università degli Studi di Firenze (UniFi; IT)

• Project duration: January 2013 – December 2015
Concept

RECORD

builds bridges

Combustion chamber

Turbine

Low order simulations

Semi-empirical models

Analytical models

Time averaged simulations and statistical methods

Incompressible high fidelity simulations and acoustic solvers

Full compressible high fidelity simulations
Methodology and Work Plan of RECORD

WP5: Coordination and Project Management

WP6 T6.1: Technical Coordination and Specifications

WP1: Nozzle Flow Test Case
- T1.1: Experimental Tests
- T1.2: Compressible Simulation
- T1.3: Low Order Modelling
- T1.4: Data Appraisal

WP1 WP2-Leader: CE CNRS

WP2: Combustor Test Case
- T2.1: Experimental Tests
- T2.2: Compressible Simulation
- T2.3: Hybrid Approach
- T2.4: RANS / Statistical Methods
- T2.5: Low Order Modelling
- T2.6: Data Appraisal

WP3: Turbine Test Case
- T3.1: Experimental Tests
- T3.2: Numerical Methods
- T3.3: Low Order Modelling
- T3.4: Data Appraisal

WP4: Exploitation to Full Scale
- T4.1: Analytical Methods
- T4.2: Numerical Methods

WP5: Coordination and Project Management

WP6 T6.2: Assessment

- Wave Generator / Modulator (for entropy or vortical waves)
- Convergent-divergent Nozzle
- Microphones
- Anechoic End Flow
- Loudspeaker (for acoustic wave generation)

Full-scale Test Data

WP1-Leader: CERFACS
WP2-Leader: CNRS
WP3-Leader: DLR
WP4-Leader: TM

> MUSAF III Colloquium 2016 • Core Noise > Friedrich Bake > 27.09.2016, Toulouse, France
WP1 – Nozzle Test Case: EWG

Heat pulse generation

Heat pulse and corresponding acoustic pressure

Temperature Perturbation $\Delta T [K]$

- Vibrometer
- Thermocouple

Time [s]

0.1 0.15 0.2 0.25

$T [^\circ C]$

0 10 20 30 40

$p' [\text{Pa}]$

0 10 20 30 40 50 60 70

Chart 20

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WP1 – Nozzle Test Case: VWG

Settling Chamber

Microphones

Convergent-divergent nozzle

Anechoic end

Variable tube section

Vorticity Wave Generator module

Sound pressure [Pa]

Direct sound

Vortex sound

Δx_{VWG-nozzle}

Axial flow direction

Tube flow

Swirling flow

Permanent added mass flow

Mass flow injected via valve

0.1 0.12 0.14 0.16 0.18 0.2

0 20 40 60 80

0 -20 -40 -60 -80 -100 -120

Microphone 2; Δx_{VWG-nozzle} = 100 mm

Microphone 2; Δx_{VWG-nozzle} = 200 mm

Microphone 2; Δx_{VWG-nozzle} = 250 mm
WP1 – Nozzle Test Case: HAT

Generation of entropy fluctuations by injection of cold air into hot mean flow

=> Analysis of entropy noise amplitude for different excitation cases
WP1 – Nozzle Test Case: LES and Low order modelling (EWG)

\[ R_{in} = -1 \]

\[ R_{out} = \frac{-1}{1 + i\frac{\omega}{160}} \]

![Graph showing measured and calculated pressure fluctuations](chart)

**Chart 23**

- **CERFACS**
- **UCAM**
WP1 – Nozzle Test Case: Summary

- **Test case data accomplished** (EWG, VWG, HAT) and distributed to partners.

- **Low order modeling** and **numerical simulation** verified, validated and compared.

- **Importance of indirect noise** confirmed both by experimental and simulation results.
WP2 – Combustor Test Case: Experiment

![Diagram of Combustor Test Case]

3 operating points:

- [Diagram of Combustor Chamber with labels and measurements]

- [Graph showing Power Spectral Density (PSD) vs. Frequency]

- [Legend for direct, indirect, and combustion noise]
WP2 – Combustor Test Case: HF-LES

Time = 0.2286 s

Isosurface of T=1000 K colored by axial velocity

Pressure spectrum

Temperature spectrum
WP2 – Combustor Test Case: RANS + stat. methods

1. Mean flow simulation in time domain
   - Based on compressible RANS along with k-ε closure model and finite-rate one-step chemistry
   - Inlet, Mixing duct, Combustor, outlet, convergent-divergent nozzle
   - Parameters: \( A_i, C, K_{ij} \)

2. Spectral source model postprocessor
   - Heat release rate, \( k, \epsilon \)
   - Source term \( f \)

3. Acoustic boundary conditions and Flame Transfer Function (FTF)
   - Nozzle reflection coefficient obtained from LNSEs, network models or simple numerical FDM schemes
   - Simple \( n-\tau-\sigma \) FTF model estimated from RANS simulation

4. Acoustic simulation in frequency domain and validation
   - Based on a set of linear transport equations: Linearized Navier-Stokes equations (LNSE) or Linearized Euler equations (LEE)
   - Rayleigh wave model
   - Feeding line impedance
   - Impedance model
   - Frequency \( \omega \) dependent excitation of LNSE by source term \( f \)
   - Evaluation of pressure spectra and comparison with experimental measurements

\[ \dot{\omega} \dot{q} + A_i \frac{\partial \dot{q}}{\partial x_i} + C \dot{q} = \frac{\partial}{\partial x_i} \left( K_{ij} \frac{\partial \dot{q}}{\partial x_j} \right) + f \]
WP2 – Combustor Test Case: Summary

- **Experimental database** for combustion noise analysis in turbulent swirling combustor

- Comparison between modeling methods with **four levels of fidelity** (high fidelity massive LES computations to fast engineering tools based on low-order models)

- **Temporally resolved flame dynamics** (pressure, velocity fields) for direct noise analysis and temperature measurements / entropy fluctuation for indirect noise analysis

- Combustion chamber not fully adapted to indirect combustion noise study due to **high levels of direct noise** contributions
WP3 - Turbine Test Case: Test rig

- Test rig with representative HP-turbine stage (stator-rotor)
WP3 - Turbine Test Case: Acoustic instrumentation

- Test rig with representative HP-turbine stage (stator-rotor)
- Acoustic measurement setup / microphone arrays
WP3 - Turbine Test Case: Perturbation forcing

- Test rig with representative HP-turbine stage (stator-rotor)
- Acoustic measurement setup / microphone arrays
- Perturbation injection system
WP3 - Turbine Test Case: Experimental results

- Generated sound power is proportional to the squared temperature amplitude of the perturbation.
- The slope is depending on the operating condition (= the maximum Mach number in the stator passage).
WP3 - Turbine Test Case: Reflection and Transmission

Sound Power per mode from modal amplitudes

\[
P^\pm_m = \frac{(p^\pm_m)^2 k^\pm_m}{\rho c k_0} \left( \frac{1 - M^2}{1 + (k^\pm_m/k_0) M} \right)^2 A
\]

Reflection R^+ and Transmission T^+ for all modes

\[
R^+ = P^-_{1,all} / P^+_{1,all}; T^+ = P^+_2,all / P^+_1,all
\]

Reflection R^+_m and Transmission T^+_m per mode

\[
R^+_m = (P^-_m)_1 / (P^+_m)_1; T^+_m = (P^+_m)_2 / (P^+_m)_1
\]

Note: No radial modes present/considered  \( n=0 \)
WP3 - Turbine Test Case: Comparison with Low Order Model (LOM) and Harmonic Balance Method

**Reflection:**
General trend is reproduced very accurately
“Wavy” behavior LOM, only few points for HB

**Transmission:**
General trend is reproduced very accurately
WP3 - Turbine Test Case: Comparison with LOM and HB for $m=\pm 1$ (OP1)

Reflection

Transmission

Reflection Coeff. (%) vs. Frequency (Hz)

Transmission Coeff. (%) vs. Frequency (Hz)

- exp DLR
- num DLR
- lom UCAM

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WP3 – Turbine Test Case: Summary

• Experimental, numerical and analytical investigation of indirect combustion noise by prescription of well controlled harmonic perturbations at the HP turbine inlet

• Absorption of acoustic waves within the turbine stage can exceed 50% (observed experimentally and numerically)

• Entropy noise power scales with the power two of the entropy perturbation (qualitatively conform to theory by Marble and Candel)

• Here low contribution of steady hot streaks to turbine interaction tones despite a temperature ratio of about 50%
WP4 – Exploitation to Full Scale:

**UCAM / RRUUK**

- Comparison in jet pipe

- With no hypothesis on entropy diffusion, indirect combustion noise is largely dominant, and much larger than experimental values.

- 2 scenarios are considered about entropy attenuation: no s’ after NGV, or 95% s’ at combustor outlet. In both cases, good agreement is found.
Sound pressure spectrum at turbine exit of turboshaft engine

- Computed combustion noise is mostly dominated by Indirect Noise
- Good agreement is found with experimental broadband noise
Good agreement has been met between calculated and experimental data. Direct noise is dominant inside the combustor.
WP4 – Exploitation to Full Scale: CERFACS / SN

- Full engine with far field instrumentation

**Compressible LES (AVBP)**  
**Propagation through the Turbine (CHORUS)**  
**Far field propagation (AVSP-f or ACTRAN)**

**C O N O C H A I N**

- Comparisons in the far field

**Measurements Calculations**

Δ 5dB
WP4 – Exploitation to Full Scale: Summary

- **Prediction chains** for core noise defined and implemented.
- Comparison to **full scale engine** noise data to some degree successful.
- Evaluation concerning **ratio of contributing noise sources** reveals strong dependence on individual engine cases.
Conclusions of RECORD

- All test cases within RECORD successfully performed.
- RECORD...
  - established **new reference data** for worldwide code benchmarking by providing very valuable test data
  - enabled huge progress in **unsteady quantities identification** in combustion-turbine systems.
  - shows **good comparisons** of models with **full-scale engine data**, even if the models need further validation on academic test cases.
  - revealed the **challenges and needs** for well-defined **test cases** serving for phenomenological understanding and method validation covering conditions **closer to real engine applications**

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\(^1\): RECORD - Research on Core Noise Reduction: http://www.xnoise.eu/about-x-noise/projects/generation-2-projects/record/
Outlook and main challenges

• To be regarded **combined** (not longer separated):
\[ \text{combustion acoustics} = \text{combustion instabilities} + \text{combustion noise} \]
  (tonal)        (broadband)

• need for **closer collaboration** in research and scientific training between (at least) three scientific communities:
  - combustion
  - aeroacoustics
  - turbomachinery aerodynamics

• upcoming combustion acoustics **prediction tools** for industrial development purpose require inclusion of **higher fidelity effects** but with limited increase of computational effort → further development of theoretical models
Outlook and main challenges

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