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

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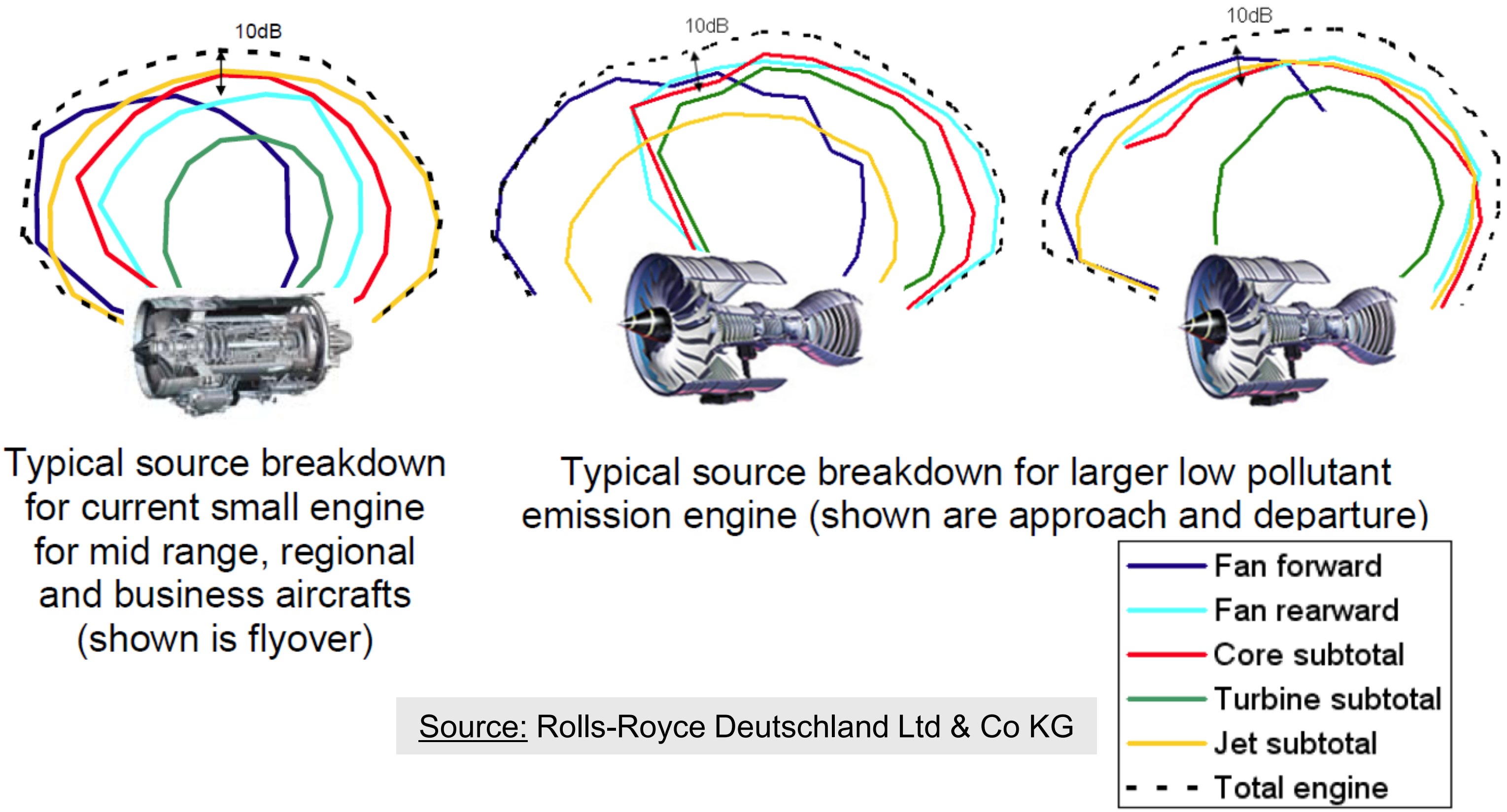
Background and Motivation



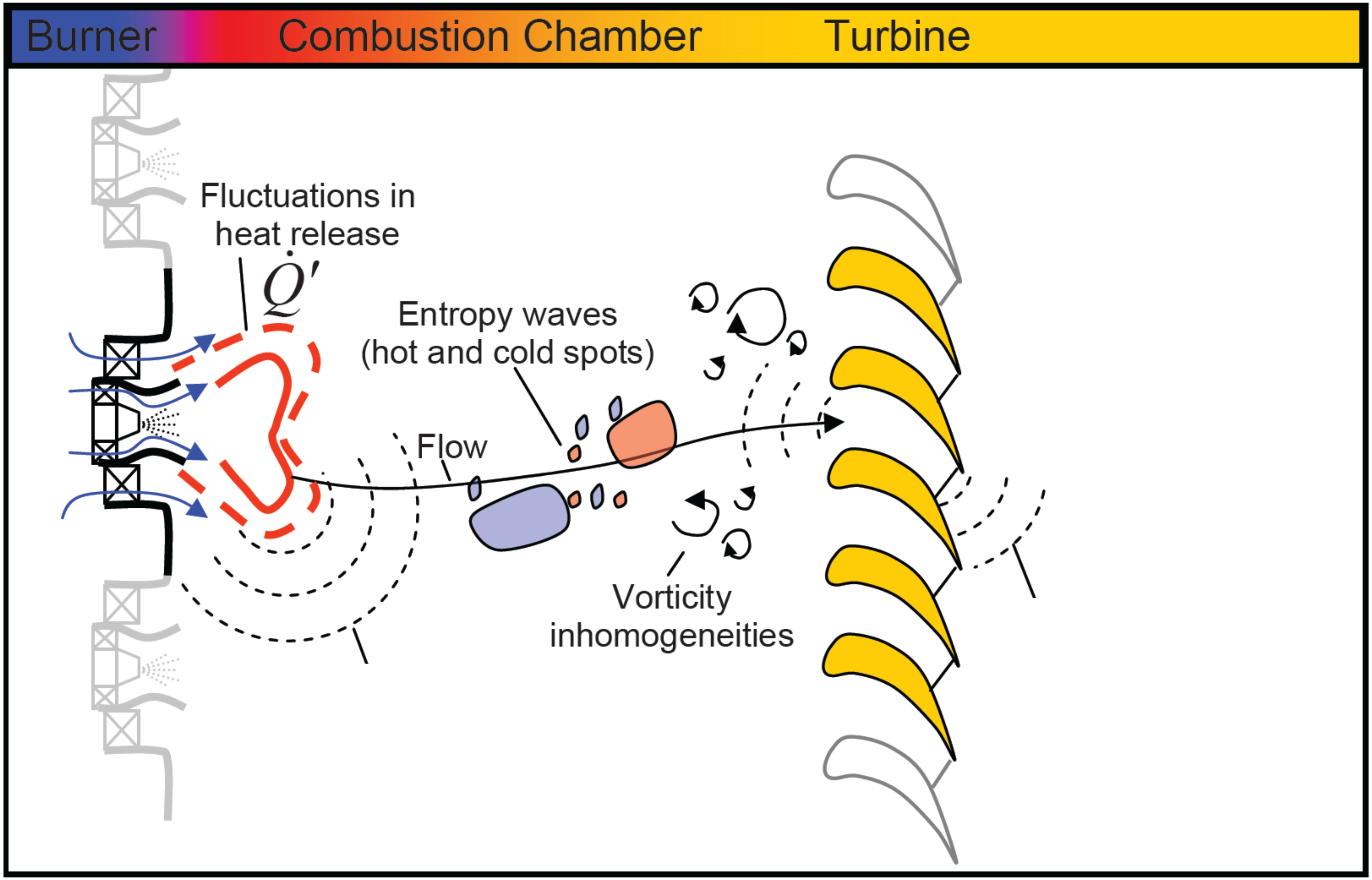
Typical source breakdown for current small engine for mid range, regional and business aircrafts (shown is flyover)

Typical source breakdown for larger low pollutant emission engine (shown are approach and departure)

Source: Rolls-Royce Deutschland Ltd & Co KG

- 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



History direct combustion acoustics 1 (mostly open flames)

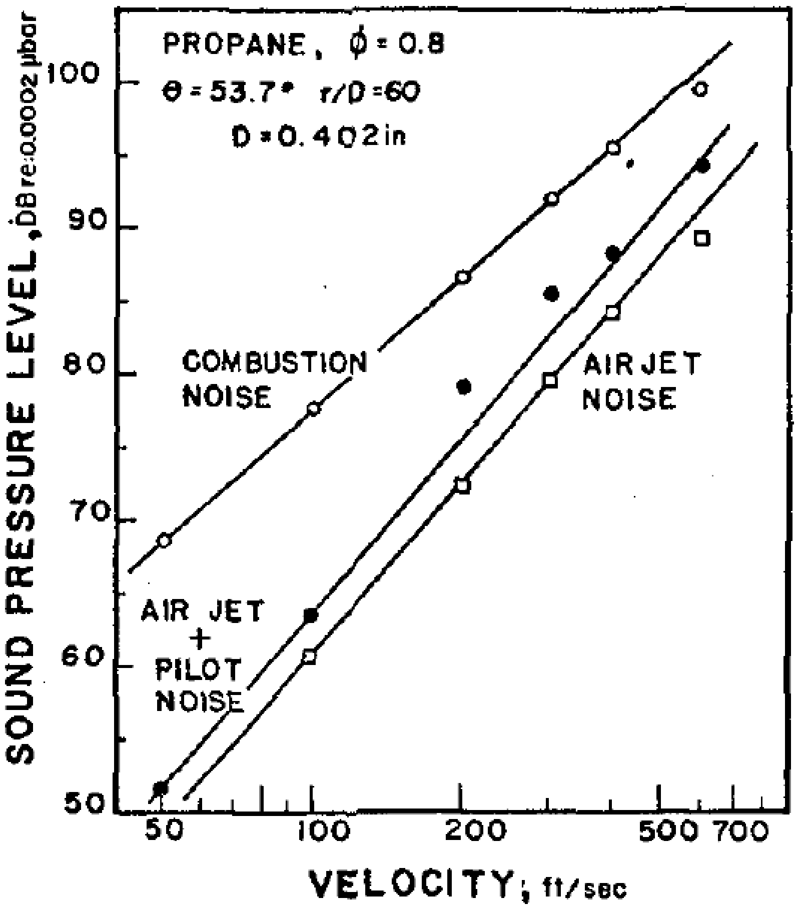


Figure 4. Jet Noise, Combustion and Air Jet plus Pilot Flame Noise at Various Flow Velocities.

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)

- Shivashankara, B.N., Strahl, W.C., and Handley, J.C., Combustion Noise Radiation by Open Turbulent Flames, AIAA Aeroacoustics Conference Seattle, Washington, AIAA 73-1025, October 15-17, 1973.

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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)

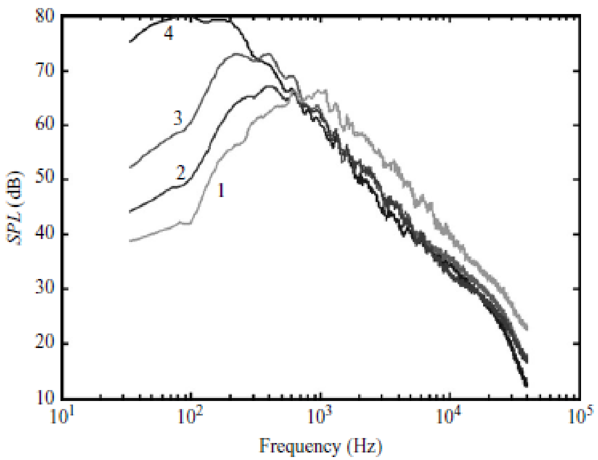


FIGURE 3. Four typical combustion noise spectra. Conditions are (1) $D = 6.4$ mm, $U_{ave} = 40.2$ m s^{-1}, Fuel = Acetylene, $\phi = 0.71$, $u'/U_{ave} = 0.8\%$, (2) $D = 10.9$ mm, $U_{ave} = 21.8$ m/s, Fuel = Acetylene, $\phi = 0.64$, $u'/U_{ave} = 1.5\%$, (3) $D = 17.3$ mm, $U_{ave} = 17.4$ m s^{-1}, Fuel = Propane, $\phi = 1.03$, $u'/U_{ave} = 11.5\%$, (4) $D = 34.8$ mm, $U_{ave} = 9.6$ m s^{-1}, Fuel = Natural Gas, $\phi = 0.95$, $u'/U_{ave} = 9.4\%$.

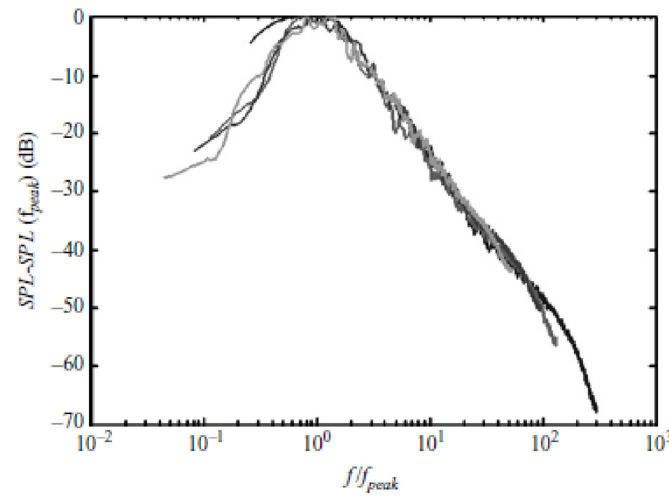


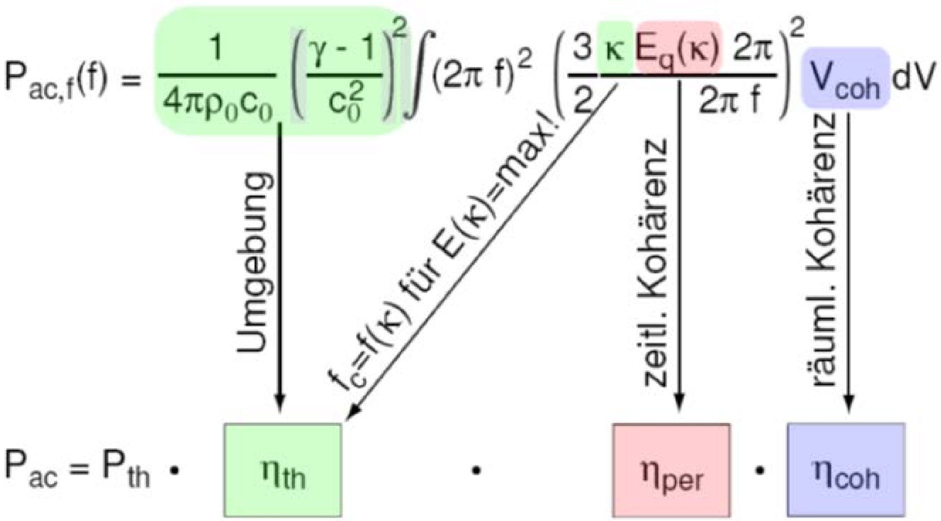
FIGURE 4. Same combustion spectra as shown figure 3, with normalized axes.

- Rajaram, R., Lieuwen, T., Parametric studies of acoustic radiation from premixed flames, Combust. Sci. Tech. 175, p. 2269-2298, 2003.
- Rajaram, R., Lieuwen, T., Acoustic radiation from turbulent premixed flames, J. Fluid Mech. 637, p. 357-385, 2009.
- Singh, K.K., Frankel, S.H., and Gore, J.P., Study of spectral noise emissions from standard turbulent nonpremixed flames. AIAA J. 42, p. 931-936, 2004.

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)



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

$$P_{ac} = P_{th} \cdot \eta_{th} \cdot \eta_{per} \cdot \eta_{coh}$$

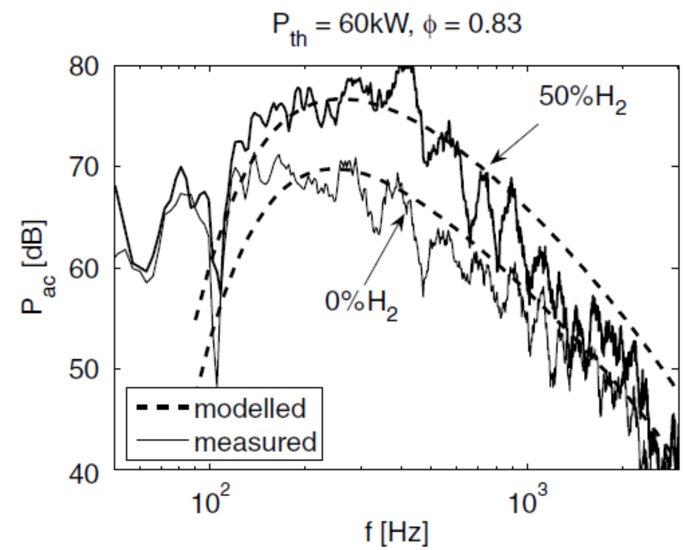


Fig. 5. Acoustic power spectra for $P_{th} = 60$ kW with 0% and 50% vol H_2.

- Winkler, A., Wäsle, J., and Sattelmayer, T., Experimental Investigations on the Acoustic Efficiency of Premixed Swirl Stabilized Flames, 11th AIAA/CEAS Aeroacoustics Conference (26th AIAA Aeroacoustics Conference), AIAA 2005-2908, 23-25 May 2005, Monterey, California.
- Hirsch, C., Wäsle, J., Winkler, A., and Sattelmayer, T., A spectral model for the sound pressure from turbulent premixed combustion, Proceedings of the Combustion Institute 31 (2007), p. 1435–1441.

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)

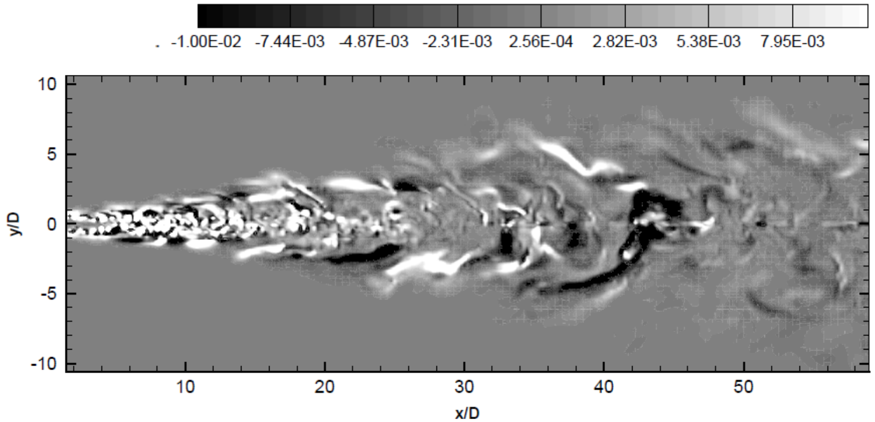


Figure 2. Contours of the source term $-\bar{c}^2 \frac{\overline{p}}{\rho} \frac{D\rho}{Dt}$ in the plane $z/D = 0$.

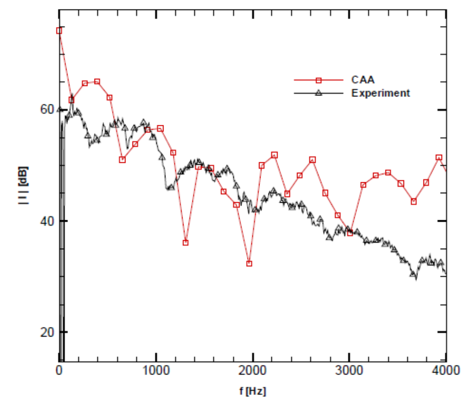


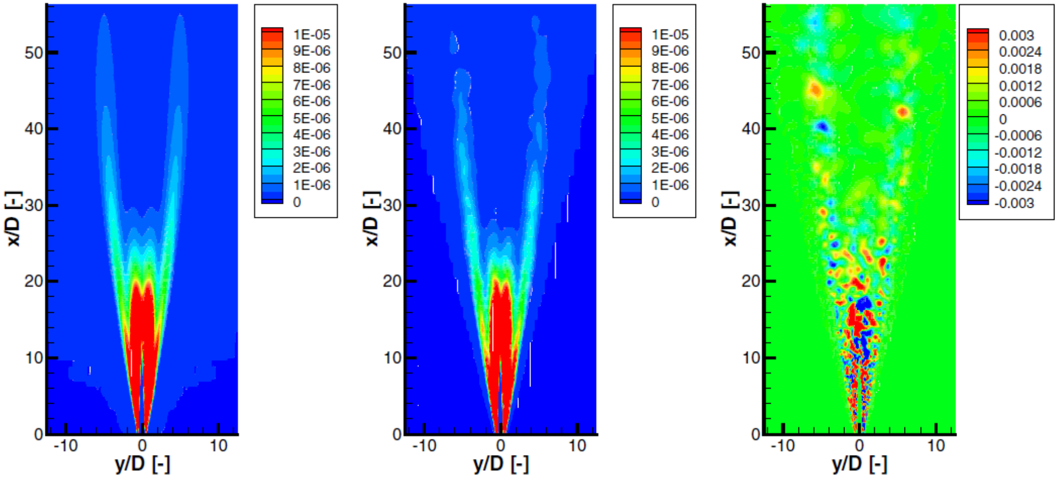
Figure 8. Comparison of the CAA results with experimental data. Radial intensity spectra are shown.

- Bui, T.P., Meinke, M., Schröder, W., Flemming, F., Sadiki, A., Janicka, J., A hybrid method for combustion noise based on LES and APE, 11th AIAA/CEAS Aeroacoustics Conference (26th AIAA Aeroacoustics Conference), AIAA 2005-3014, 23-25 May 2005, Monterey, California.
- Flemming, F., Sadiki, A., Janicka, J., Investigation of combustion noise using a LES/CAA hybrid approach, Proceedings of the Combustion Institute, 31 (2007) p. 3189–3196.
- Bui, T., Schröder, W., and Meinke, M., Numerical analysis of the acoustic field of reacting flows via acoustic perturbation equations. Computers & Fluids 37(9), (2008), p. 1157–1169.
- Bui, T.P., Ihme, M., Schröder, W., Pitsch, H., Analysis of different sound source formulations to simulate combustion generated noise using a hybrid LES/APE-RF method, Int. J. Aeroacoustics, 8, p. 95-124, 2009.

History direct combustion acoustics 5 (mostly open flames)

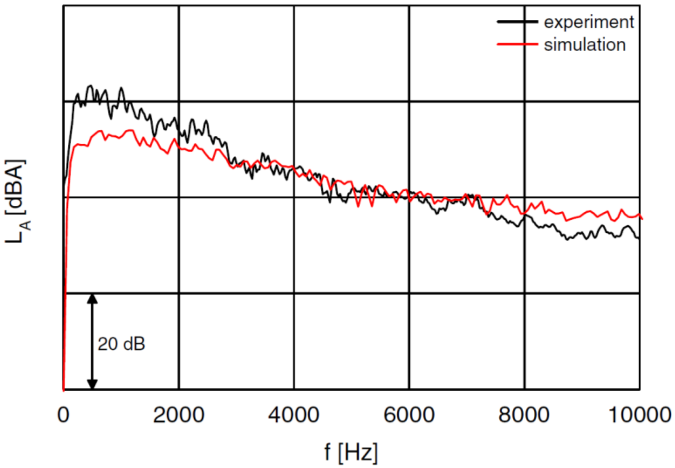
2010:

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



a) RANS b) RPM c) RPM sources

Fig. 4 RANS target source variance distribution, source variance distribution of the stochastic reconstruction by RPM, and an instantaneous RPM source distribution.



- Mühlbauer, B., Ewert, R., Kornow, O., and Noll, B., "Evaluation of the RPM Approach for the Simulation of Broadband Combustion Noise", AIAA Journal, Vol. 48, No. 7 (2010), pp. 1379-1390.

The way to pressure, vorticity, and entropy waves

- conservation equations of mass, momentum, and energy:

$$\frac{\partial \varrho}{\partial t} + \frac{\partial \varrho u_i}{\partial x_i} = 0$$

$$\varrho \left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} \right) + \frac{\partial p}{\partial x_i} = 0$$

$$\varrho \left(\frac{\partial e}{\partial t} + u_i \frac{\partial e}{\partial x_i} \right) = - \frac{\partial p u_i}{\partial x_i}$$

- assumptions:
  - no body forces
  - no thermal flux
  - no heat sources
  - inviscid flow

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The way to pressure, vorticity, and entropy waves

- conservation equations of mass, momentum, and energy:

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

(acoustic) pressure waves:

$$\frac{\partial^2 p'}{\partial t^2} + 2\overline{U}\frac{\partial^2 p'}{\partial x_1 \partial t} + \overline{U}^2 \frac{\partial^2 p'}{\partial x_1^2} - c^2 \frac{\partial^2 p'}{\partial x_i^2} = 0$$

vorticity "waves":

$$\frac{\partial \omega_i'}{\partial t} + \overline{U}\frac{\partial \omega_i'}{\partial x_1} = 0$$

entropy "waves":

$$\frac{\partial s'}{\partial t} + \overline{U}\frac{\partial s'}{\partial x_1} = 0$$

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:

$$\frac{\partial^2 p'}{\partial t^2} + 2\overline{U}\frac{\partial^2 p'}{\partial x_1 \partial t} + \overline{U}^2\frac{\partial^2 p'}{\partial x_1^2} - \frac{\partial^2 p'}{\partial x_\mathrm{i}^2} =$$

$$-c^2\overline{U}\overline{\varrho}\frac{\mathrm{d}}{\mathrm{d}x_1}\left(\frac{1}{\overline{\varrho}c^2}\right)\frac{\partial p'}{\partial t} - c^2\overline{U}\overline{\varrho}\frac{\mathrm{d}}{\mathrm{d}x_1}\left(\frac{\overline{U}}{\overline{\varrho}c^2}\right)\frac{\partial p'}{\partial x_1} - c^2\overline{U}\overline{\varrho}\frac{\mathrm{d}}{\mathrm{d}x_1}\left(\frac{\overline{U}}{\overline{\varrho}}\frac{\mathrm{d}\overline{\varrho}}{\mathrm{d}x_1}\right)$$

$$-c^2\overline{U}\overline{\varrho}\frac{\partial}{\partial x_1}\left(\frac{\varrho'}{\overline{\varrho}}\frac{\mathrm{d}\overline{U}}{\mathrm{d}x_1}\right) - c^2\overline{U}\overline{\varrho}\frac{\partial}{\partial x_1}\left(\frac{u_1'}{\overline{\varrho}}\frac{\mathrm{d}\overline{\varrho}}{\mathrm{d}x_1}\right) - c^2\frac{\mathrm{d}\overline{U}}{\mathrm{d}x_1}\frac{\partial \varrho'}{\partial t}$$

strong coupling of the differential equations → generation of entropy and vortex noise

$$+c^2\overline{U}\frac{\mathrm{d}\overline{\varrho}}{\mathrm{d}x_1}\frac{\partial u_1'}{\partial x_1} + c^2\overline{\varrho}\frac{\mathrm{d}\overline{U}}{\mathrm{d}x_1}\frac{\partial u_1'}{\partial x_1} + c^2\frac{\mathrm{d}\overline{U}}{\mathrm{d}x_1}\frac{\mathrm{d}}{\mathrm{d}x_1}\left(\overline{\varrho}\overline{U}\right)$$

$$+c^2\frac{\partial}{\partial x_1}\left(\overline{\varrho}u_1'\frac{\mathrm{d}\overline{U}}{\mathrm{d}x_1}\right) + c^2\frac{\partial}{\partial x_1}\left(\varrho'\overline{U}\frac{\mathrm{d}\overline{U}}{\mathrm{d}x_1}\right) + c^2\frac{\mathrm{d}^2\overline{p}}{\mathrm{d}x_1^2}$$

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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).

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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.**

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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.

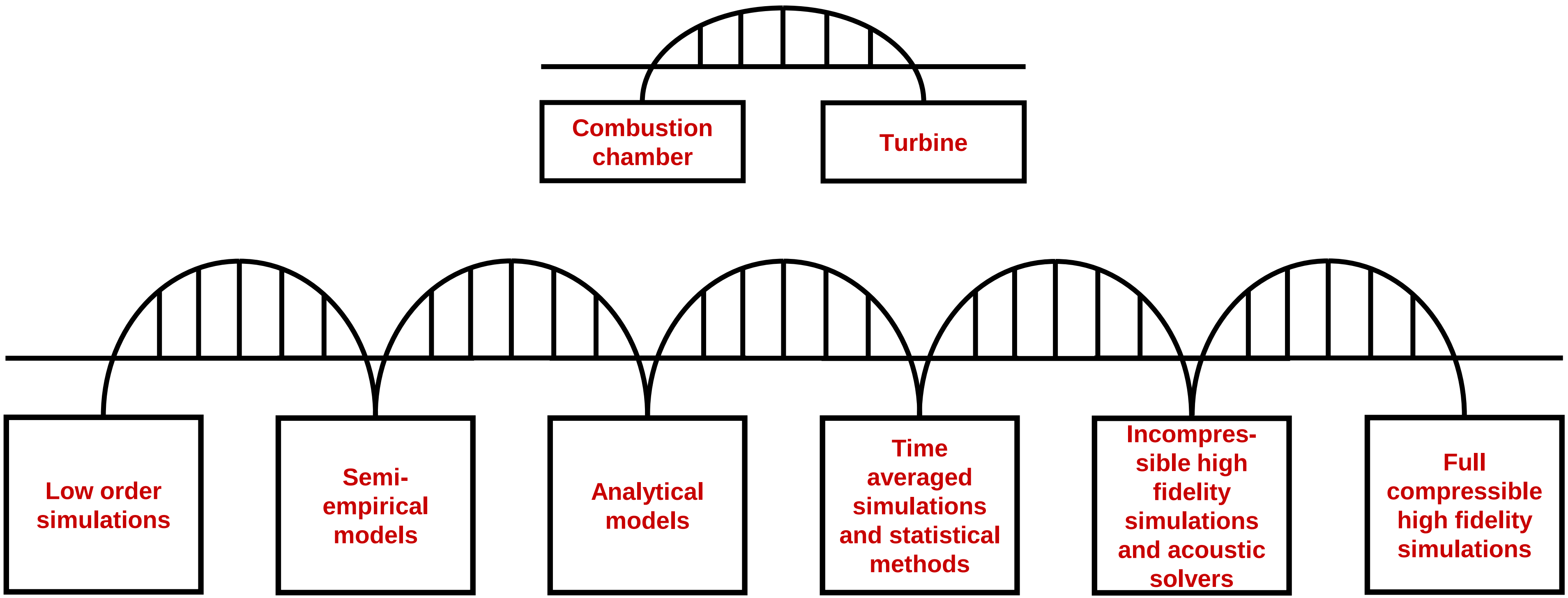
RECORD partners

- **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



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Methodology and Work Plan of RECORD

WP5: Coordination and Project Management

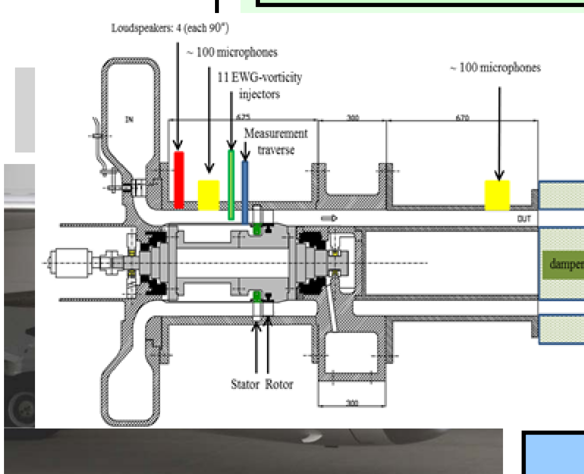
WP6 T6.1: Technical Coordination and Specifications

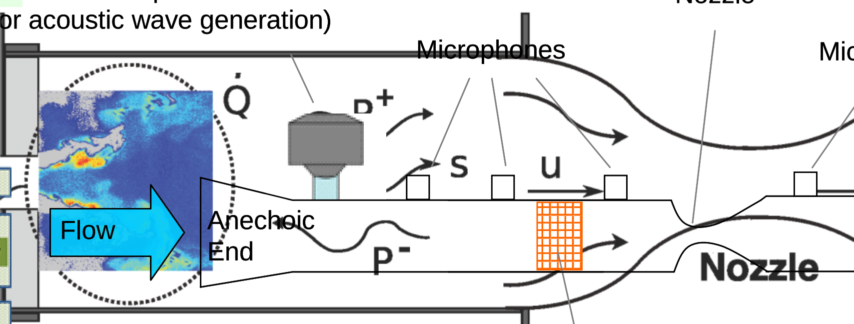
RECORD
Research on Core Noise Reduction

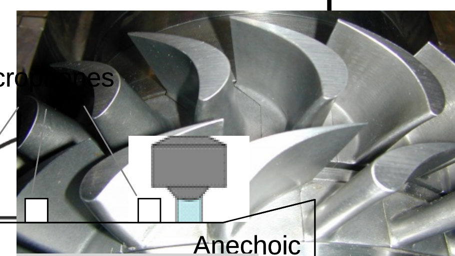
WP1:
Nozzle Flow Test Case

- **T1.1: Experimental Tests**
- **T1.2: Compressible Simulation**
- **T1.3: Low Order Modelling**
- **T1.4: Data Appraisal**

WP1 WP2-Leader:
CE CNRS







WP4-Leader:
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WP6 T6.2: Assessment

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WP1 – Nozzle Test Case: EWG

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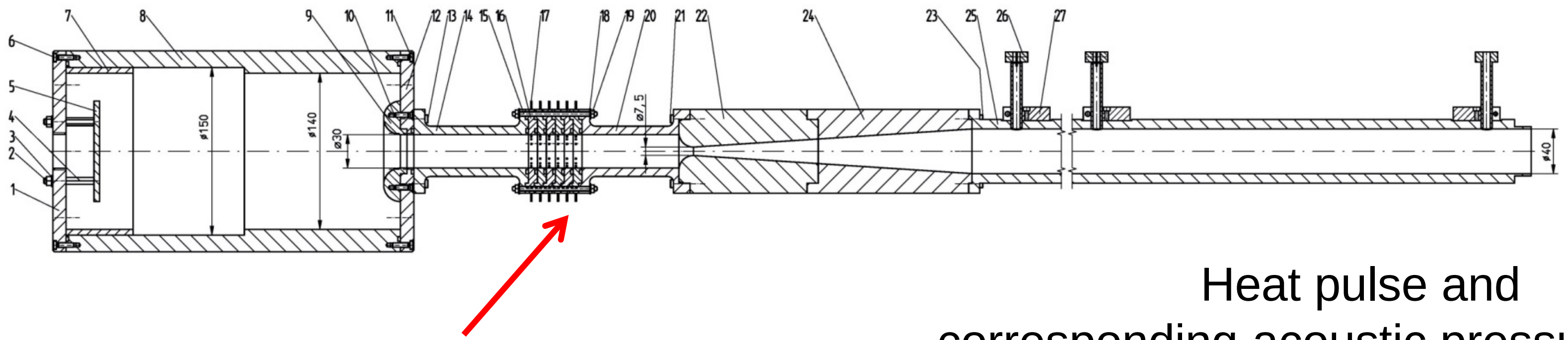
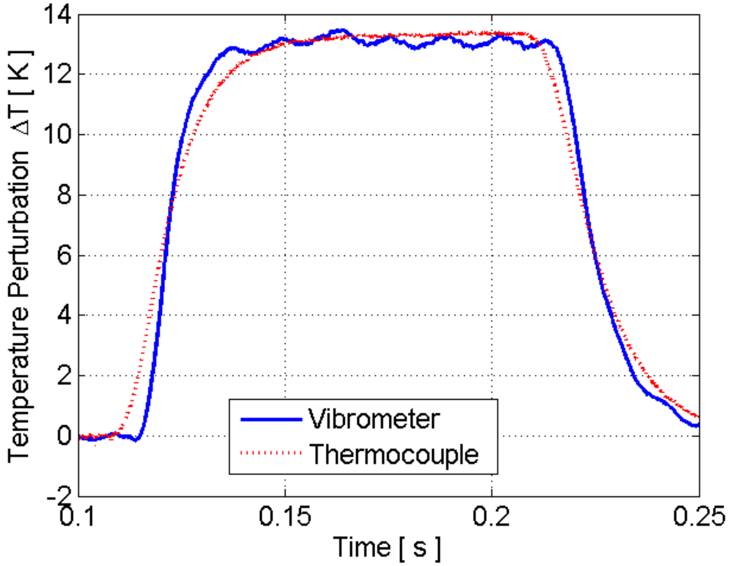
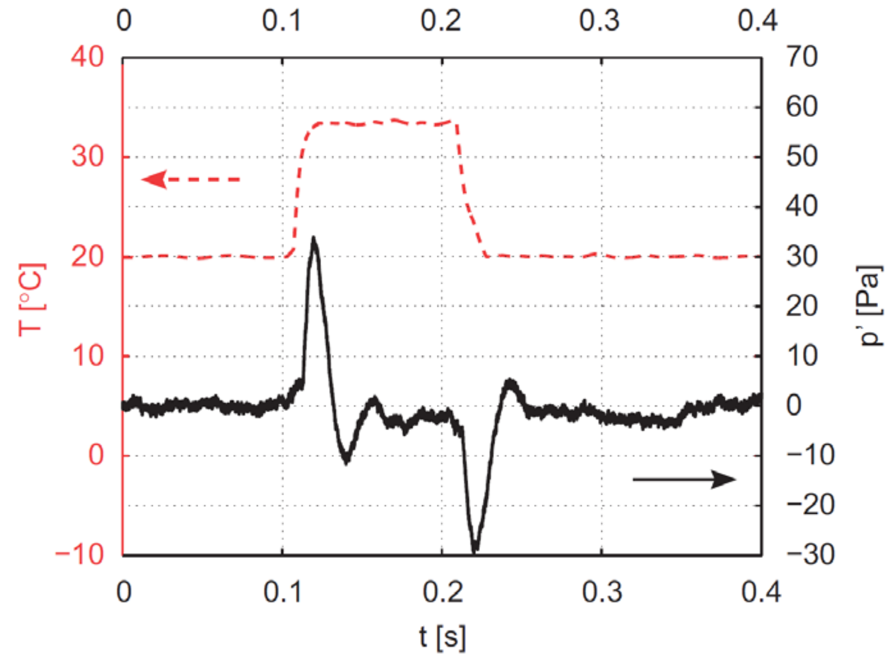


Heat pulse generation



Heat pulse and corresponding acoustic pressure



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WP1 – Nozzle Test Case: VWG

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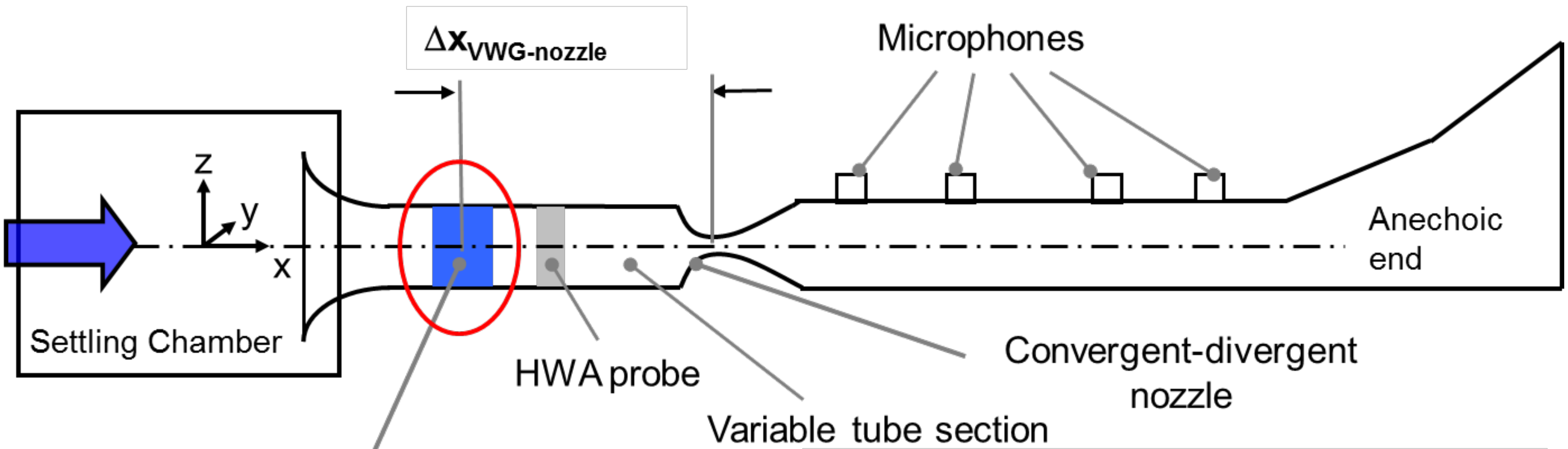

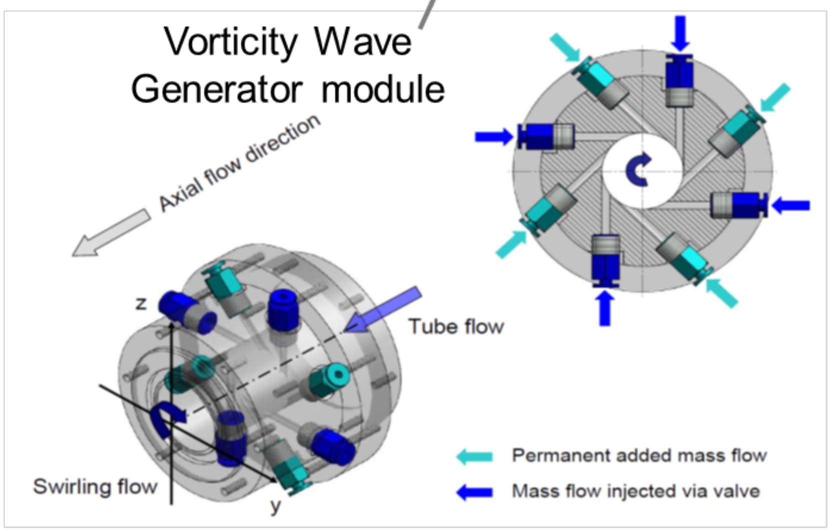

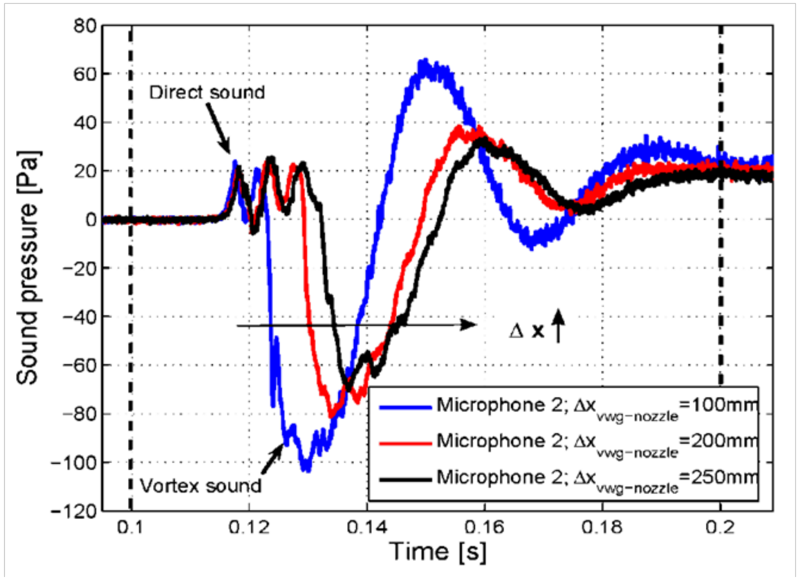

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WP1 – Nozzle Test Case: HAT

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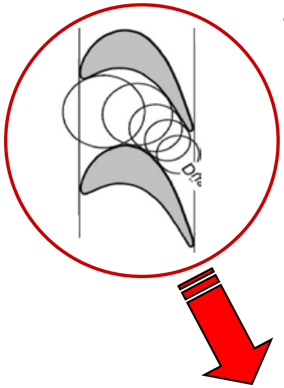
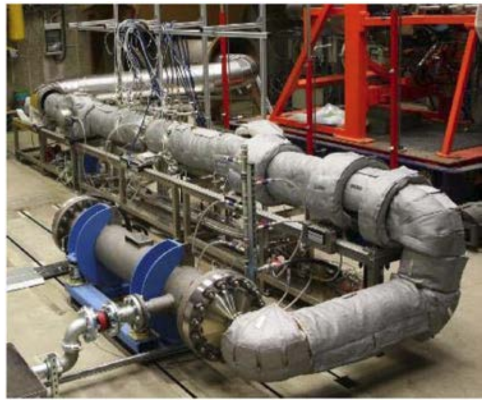
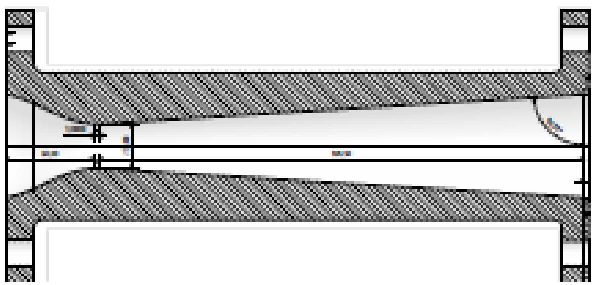
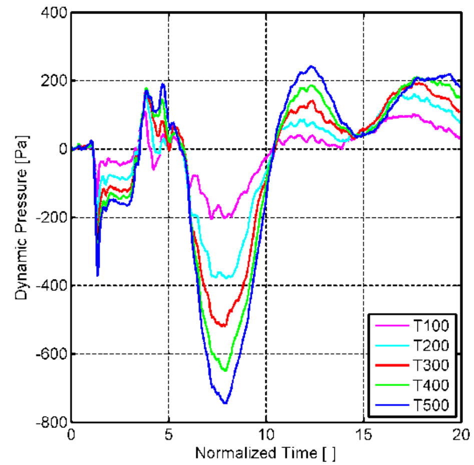
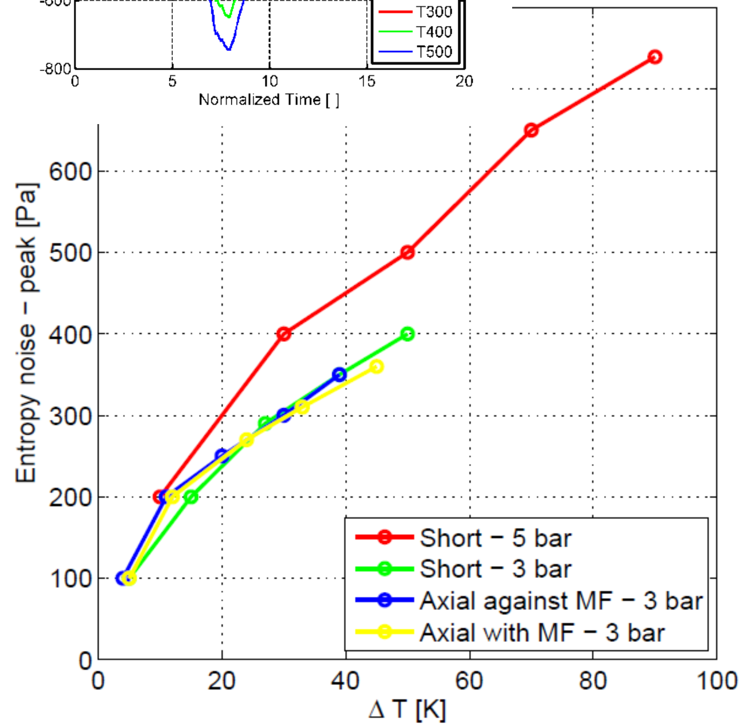


Turbine NGV









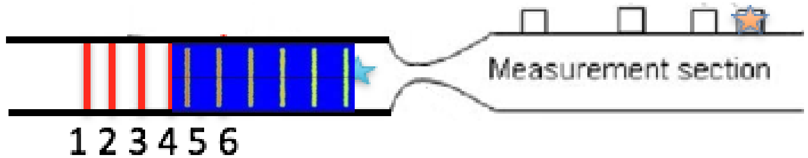
Generation of entropy fluctuations by injection of cold air into hot mean flow

=> Analysis of entropy noise amplitude for different excitation cases

WP1 – Nozzle Test Case: LES and Low order modelling (EWG)

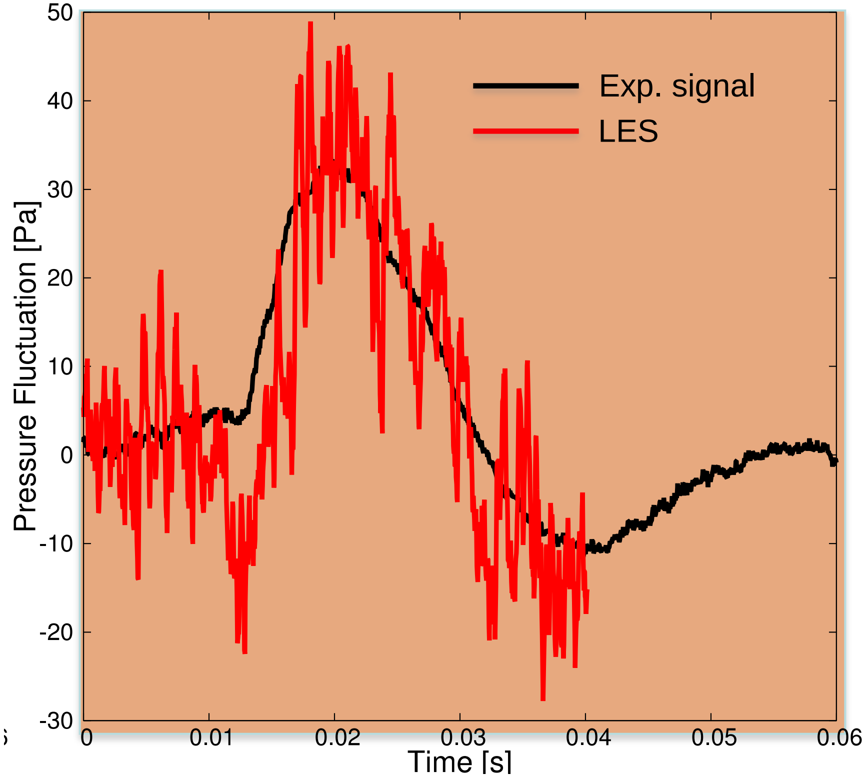
CERFACS UCAM

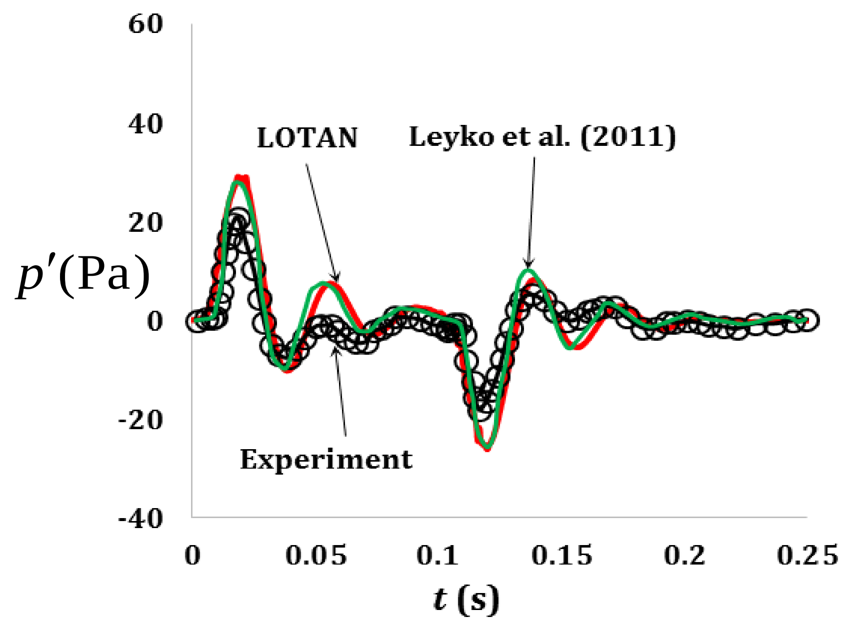
$R_{in} = -1$



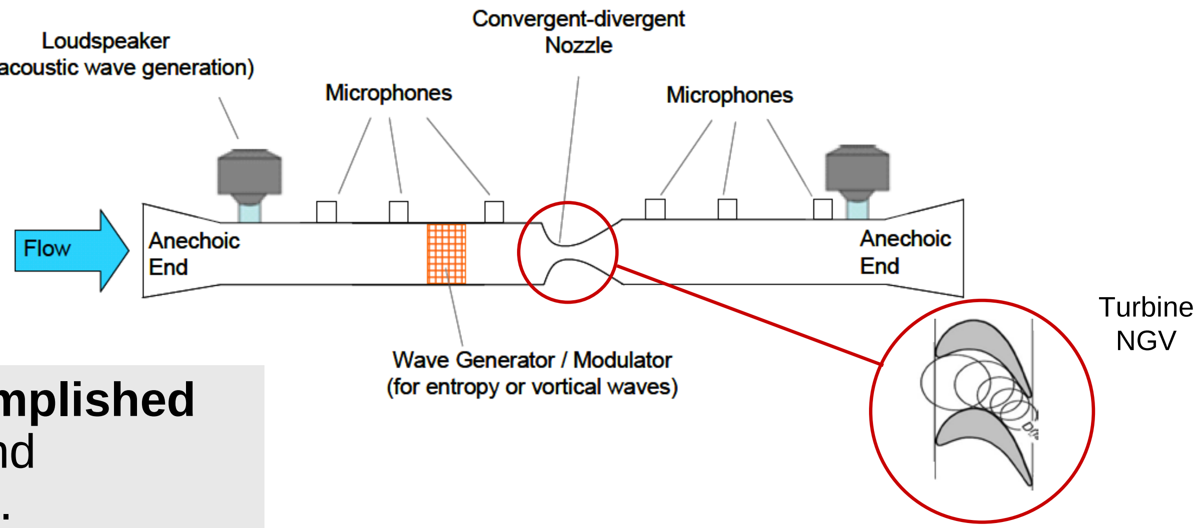
$$R_{out} = \frac{-1}{1 + i\frac{\omega}{160}}$$

Microphone 4





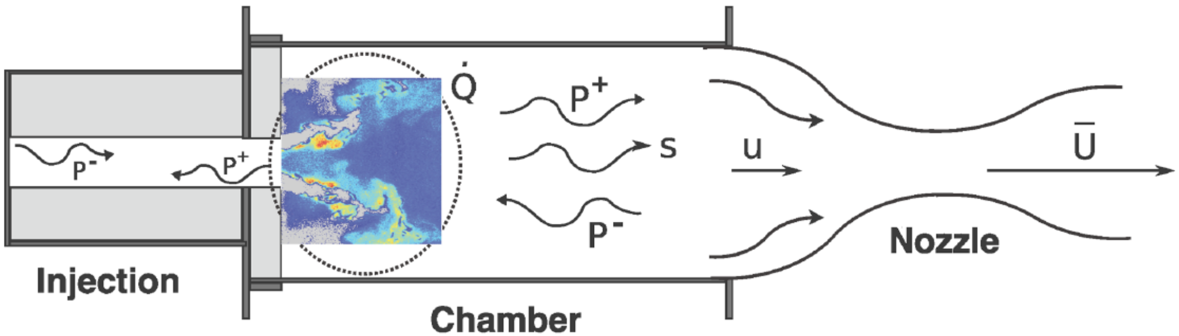
WP1 – Nozzle Test Case: Summary

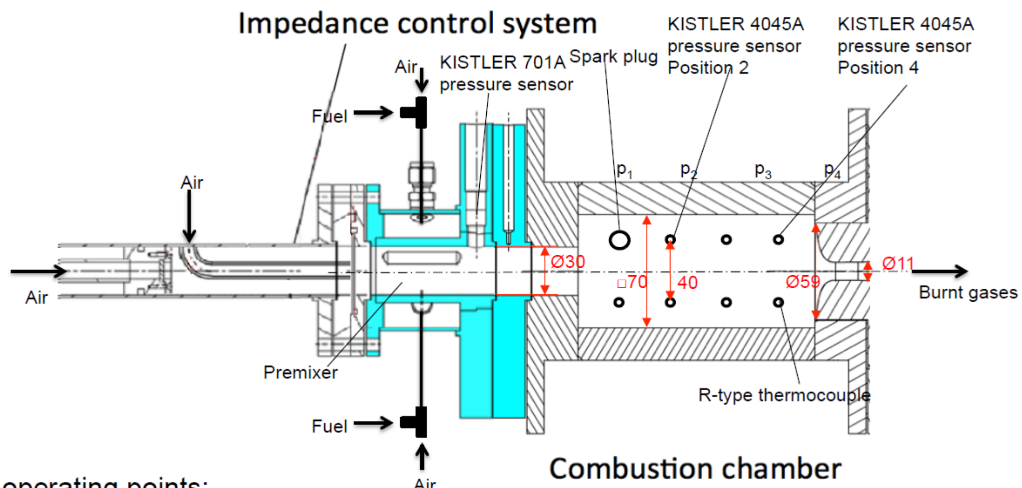


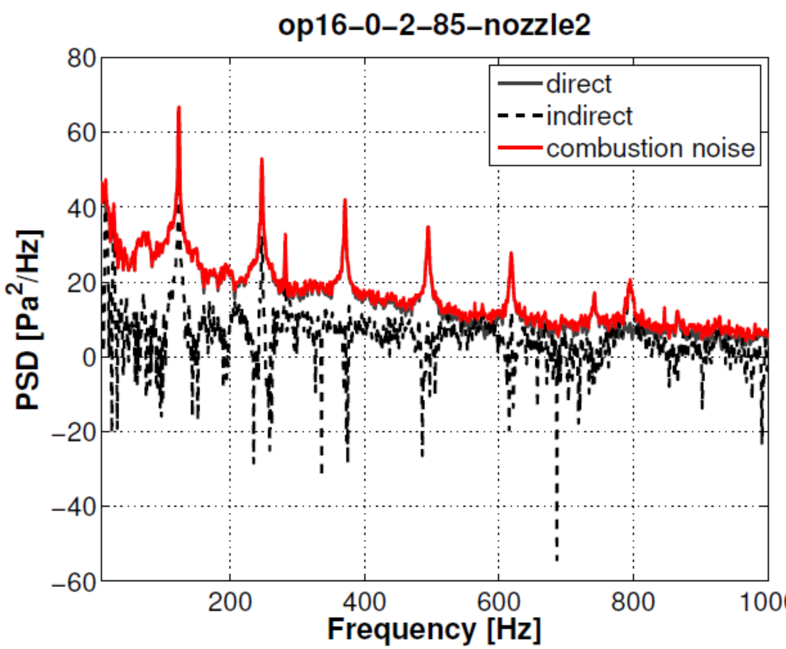
- **Test case data accomplished** (EWG, VWG, HAT) and distributed to partners.
- **Low order modeling** and **numerical simulation** verified, validated and compared.
- **Importance of indirect noise** confirmed both by experimental and simulation results.

WP2 – Combustor Test Case: Experiment

CNRS







3 operating points:

WP2 – Combustor Test Case: HF-LES

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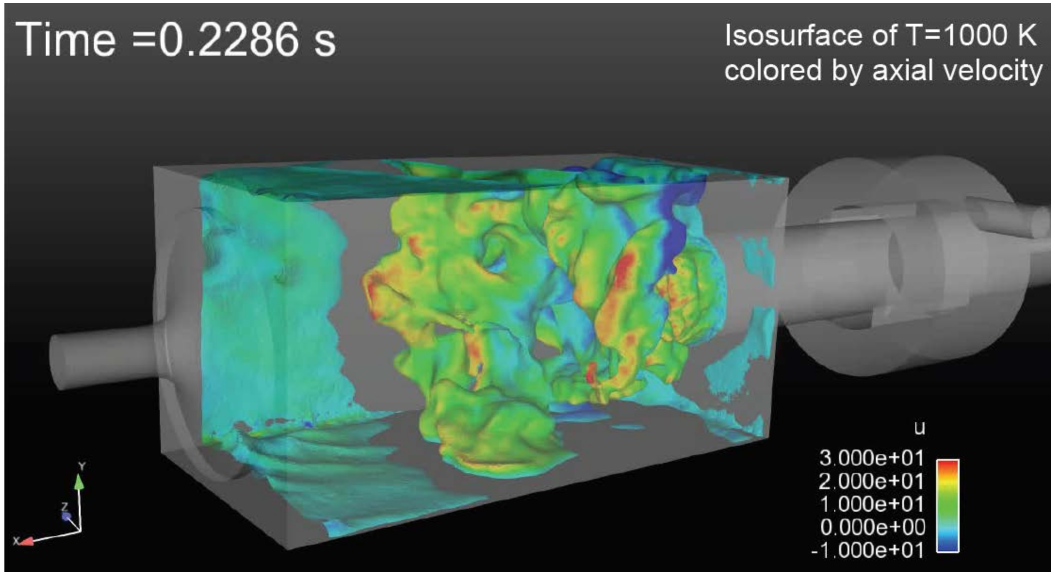
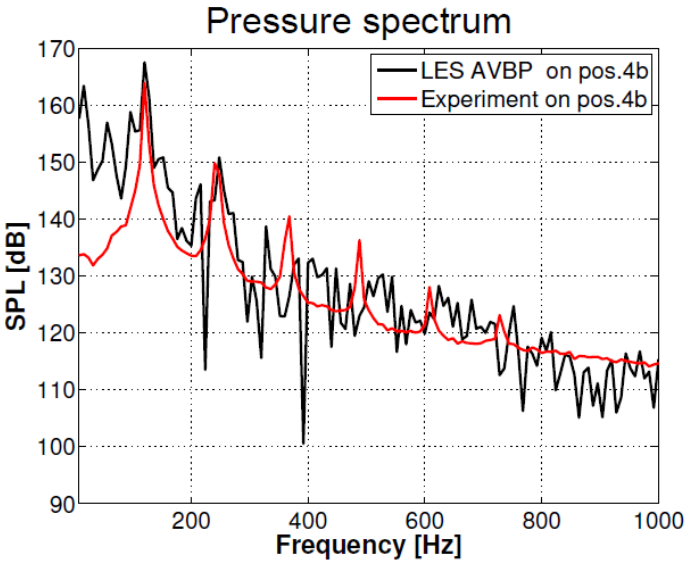
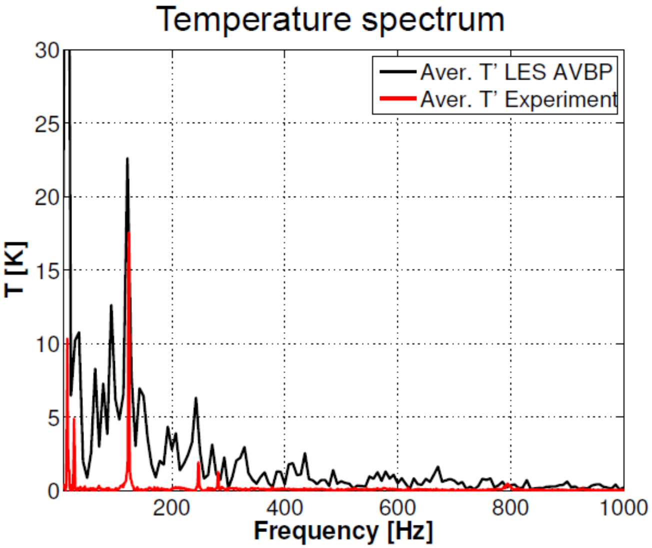
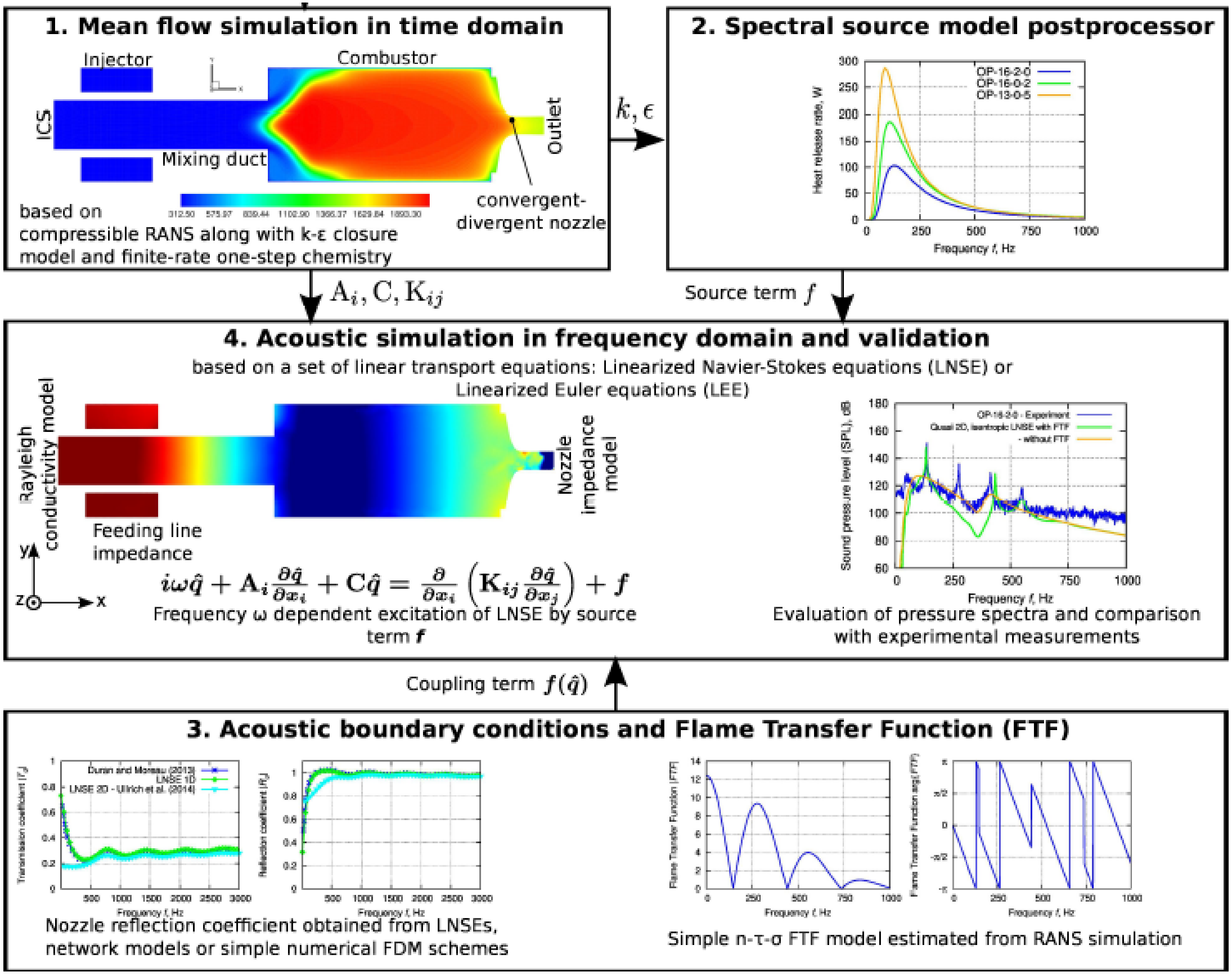






WP2 – Combustor Test Case: RANS + stat. methods

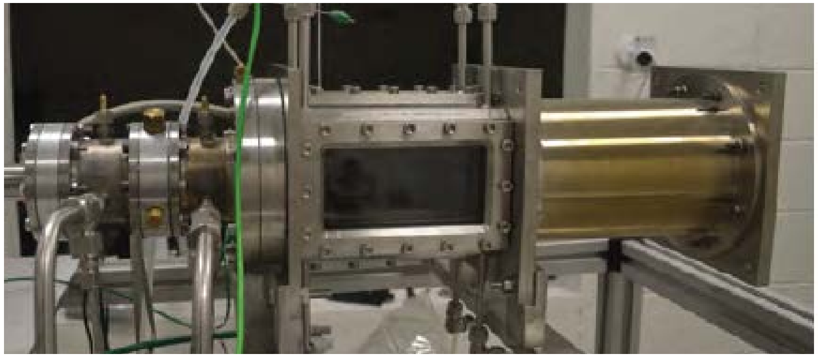
TUM



DLR

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



DLR

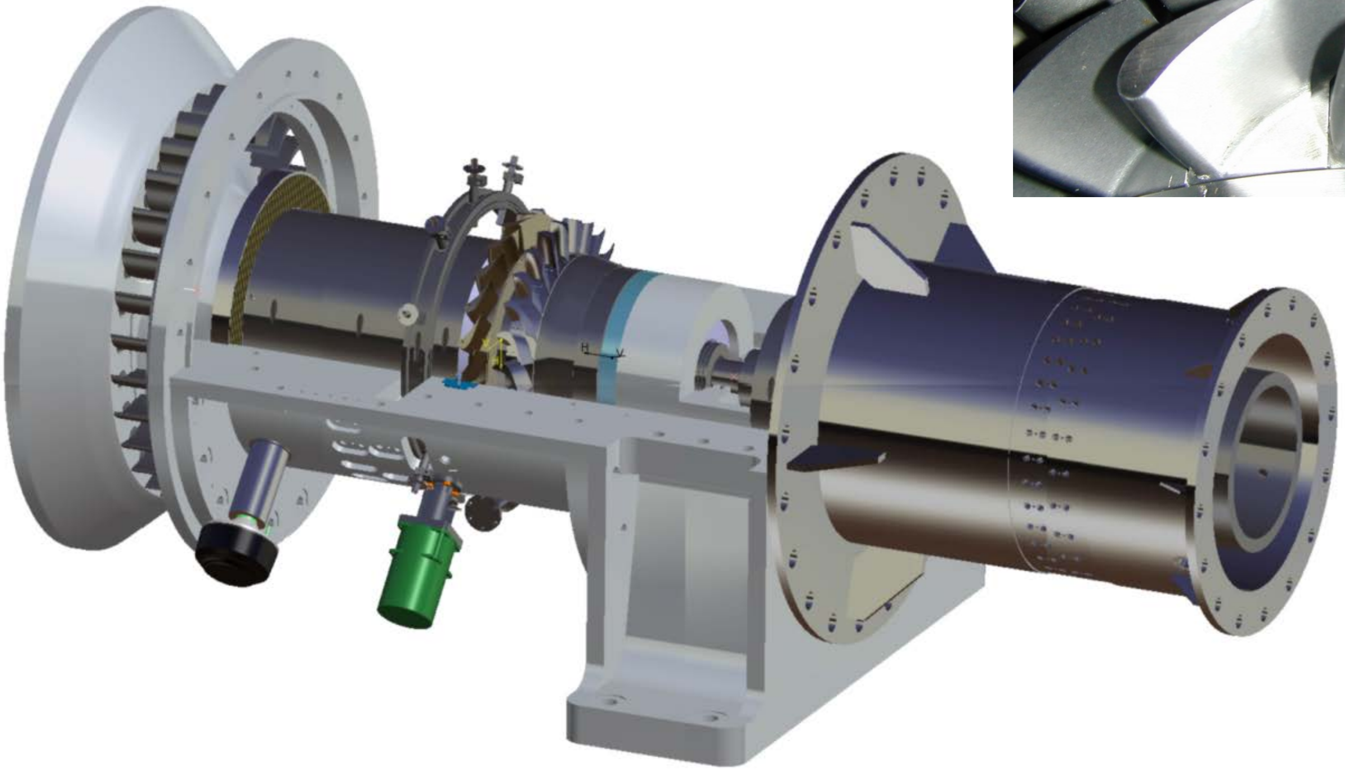
WP3 - Turbine Test Case: Test rig

PoliMi

- Test rig with representative HP-turbine stage (stator-rotor)

DIPARTIMENTO DI ENERGIA

POLITECNICO MILANO 1863

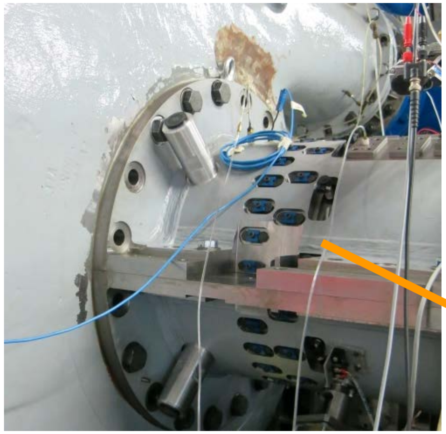


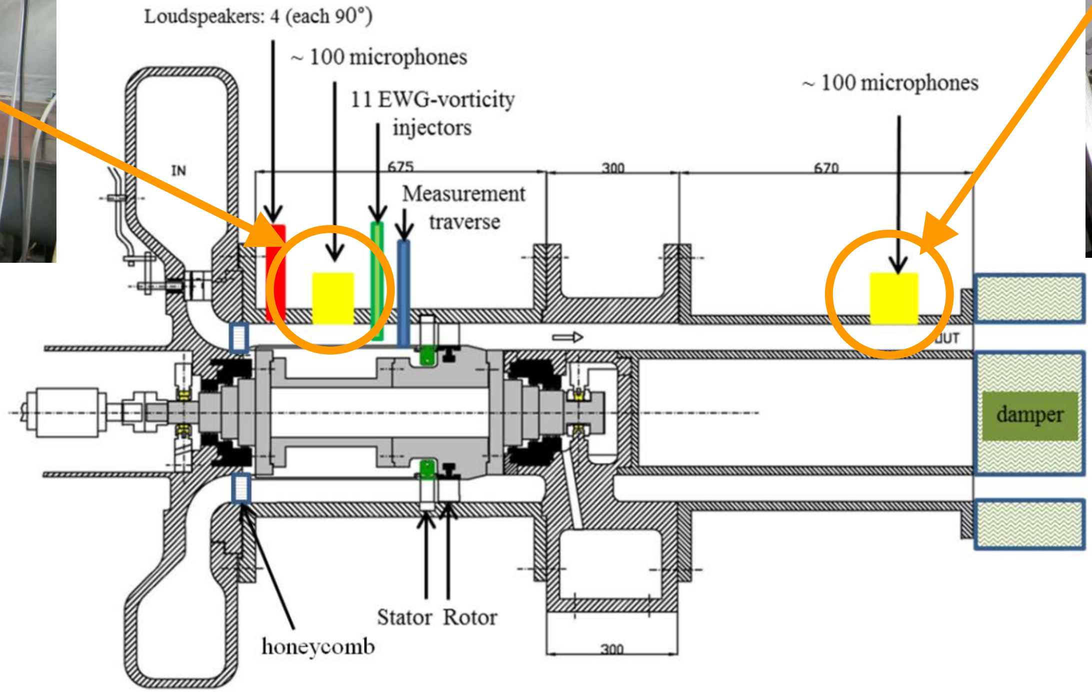
RECORD
Research on Core Noise Reduction

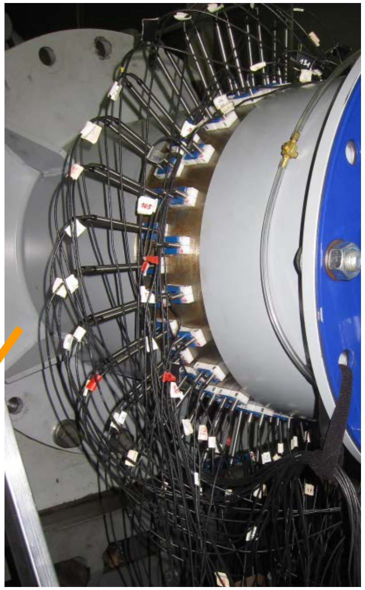
DLR

WP3 - Turbine Test Case: Acoustic instrumentation

- Test rig with representative HP-turbine stage (stator-rotor)✓
- Acoustic measurement setup / microphone arrays





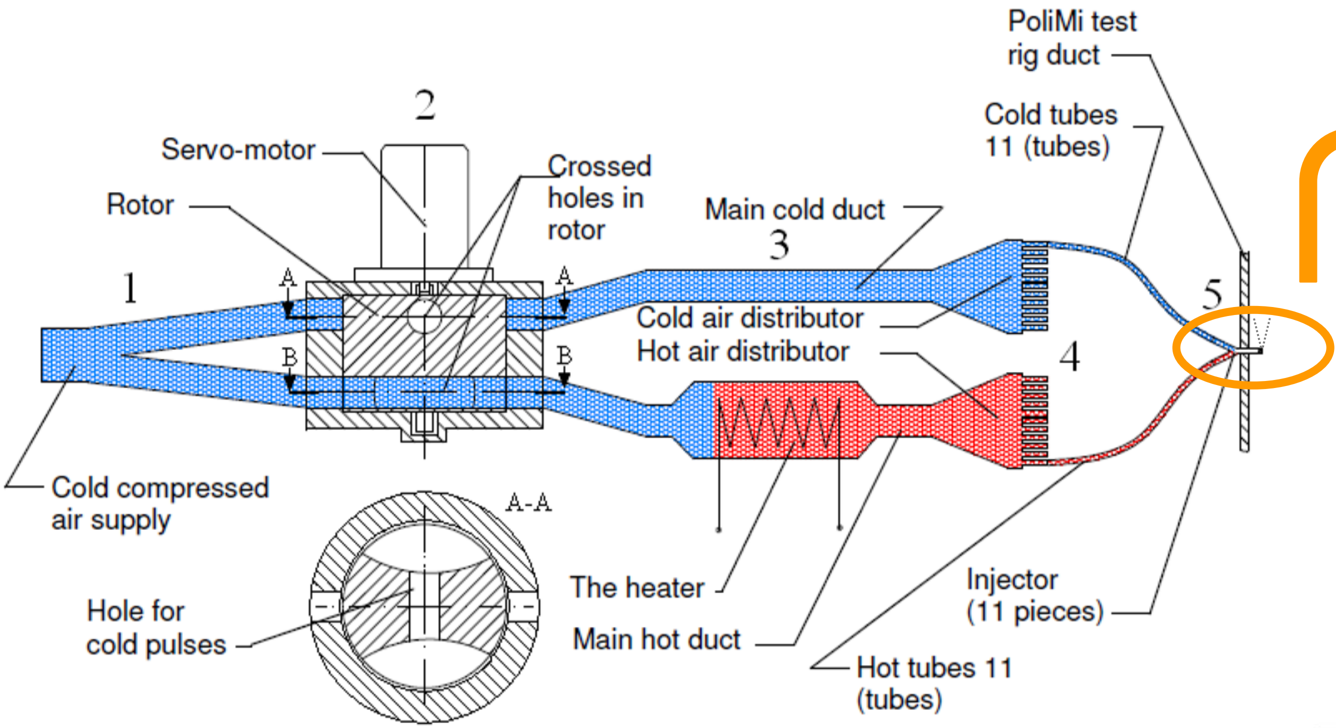


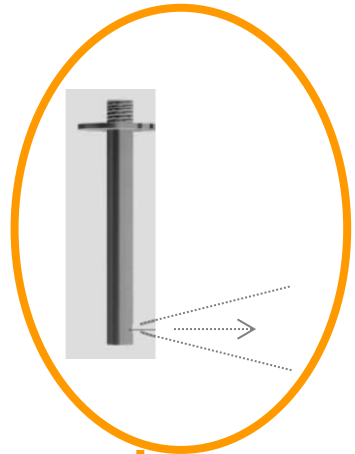
PoliMi
DLR

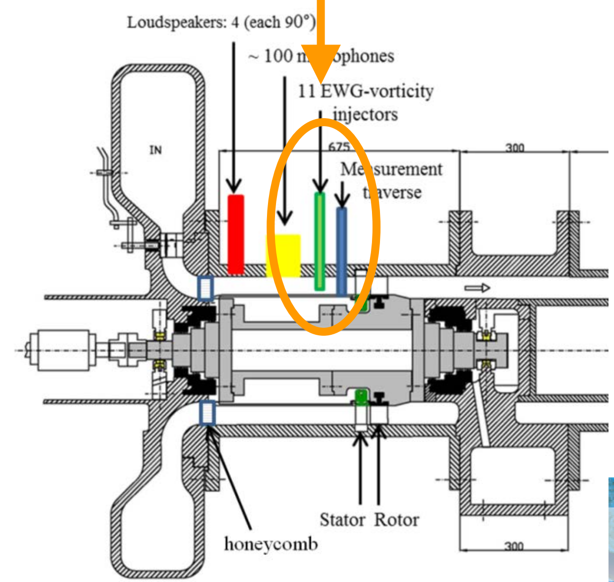
WP3 - Turbine Test Case: Perturbation forcing

- Test rig with representative HP-turbine stage (stator-rotor) ✓
- Acoustic measurement setup / microphone arrays ✓
- Perturbation injection system

SMCPFA
PoliMi

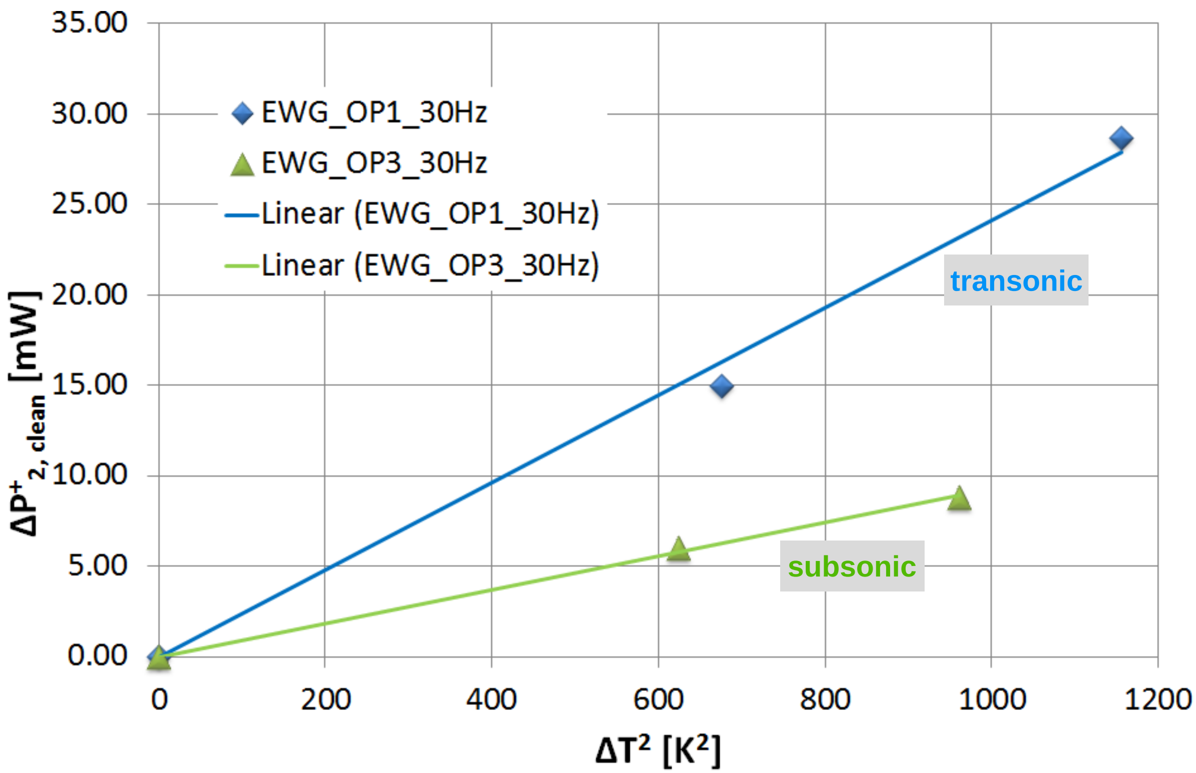






WP3 - Turbine Test Case: Experimental results

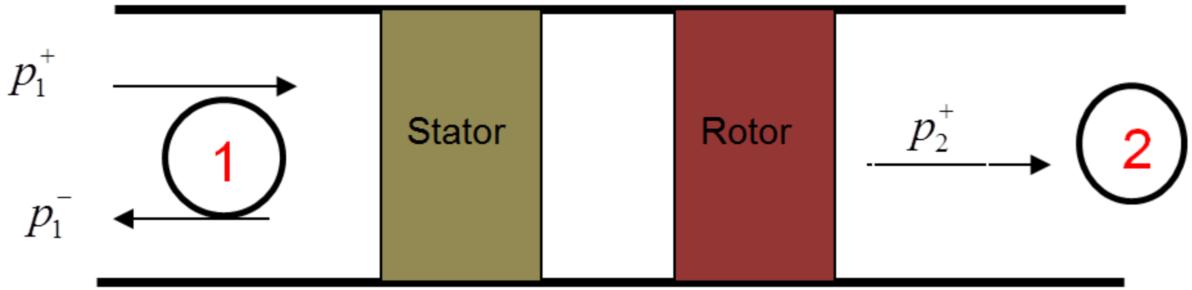
DLR



- 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

DLR



Note: **No radial modes** present/considered *n=0*

Sound Power per mode from modal amplitudes

$$P_m^{\pm} = \frac{(p_m^{\pm})^2}{\rho c} \frac{k_m^{\pm}}{k_0} \left(\frac{1 - \overline{M}^2}{1 \mp (k_m^{\pm}/k_0)\overline{M}} \right)^2 A$$

Reflection R^+ and Trans-mission T^+ for all modes

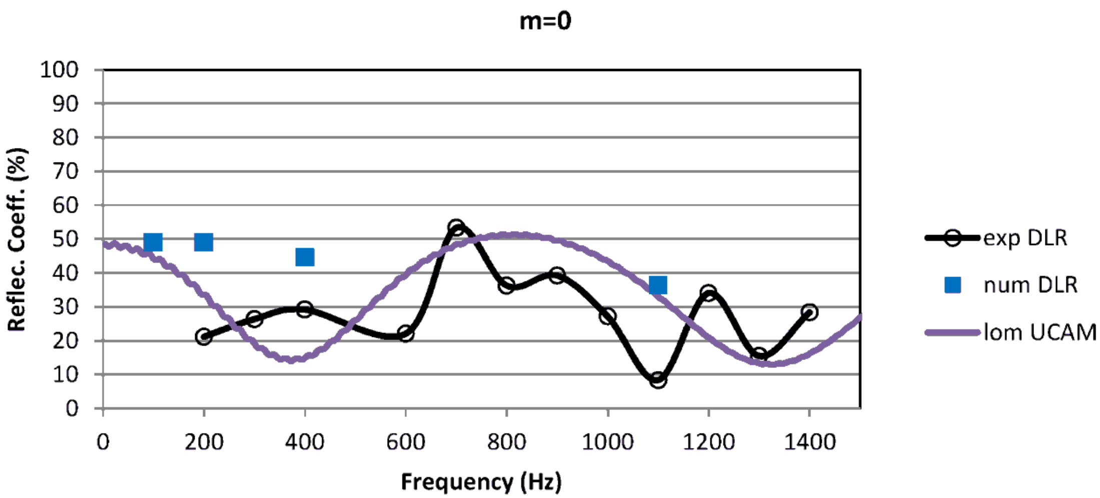
$$R^+ = P_{1,all}^- / P_{1,all}^+ ; \; T^+ = P_{2,all}^+ / P_{1,all}^+$$

Reflection R^+_m and Trans-mission T^+_m per mode

$$R_m^+ = (P_m^-)_1 / (P_m^+)_1 \quad T_m^+ = (P_m^+)_2 / (P_m^+)_1$$

WP3 - Turbine Test Case: Comparison with Low Order Model (LOM) and Harmonic Balance Method

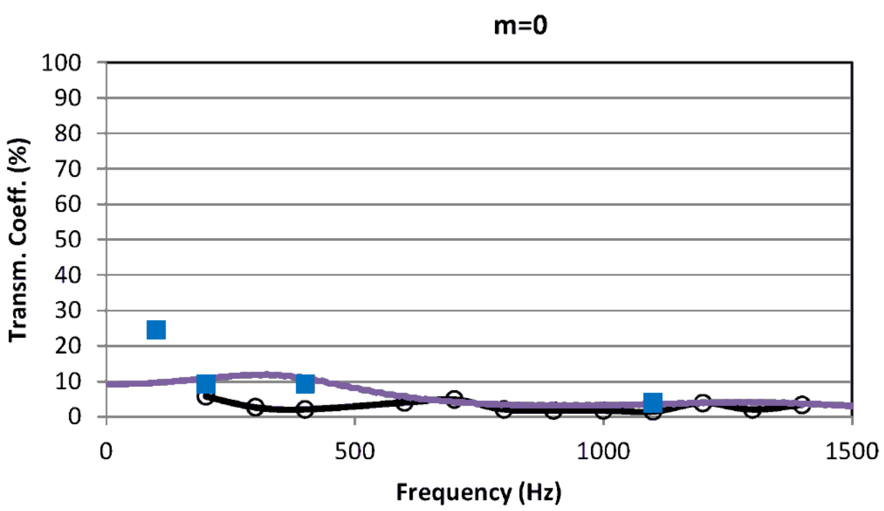
DLR
UCAM



Reflection:

General trend is reproduced very accurately

“Wavy” behavior LOM, only few points for HB



Transmission:

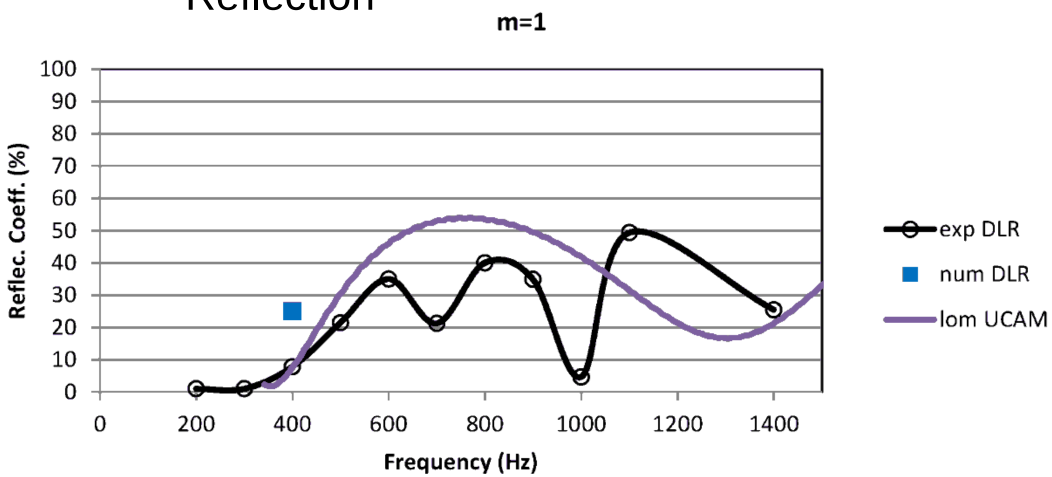
General trend is reproduced very accurately

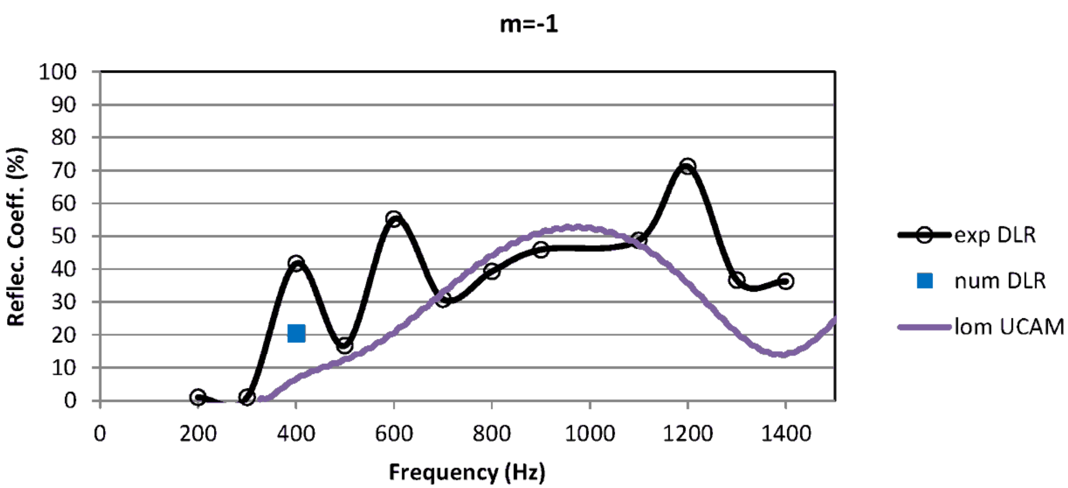
DLR

WP3 - Turbine Test Case: Comparison with LOM and HB for m=±1 (OP1)

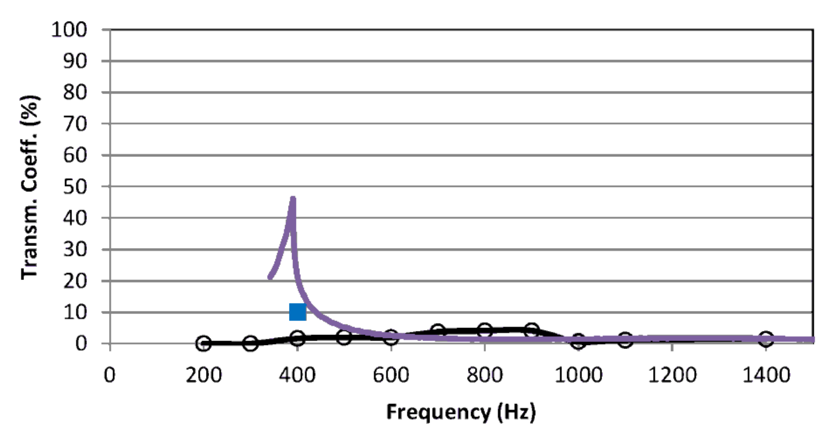
DLR
UCAM

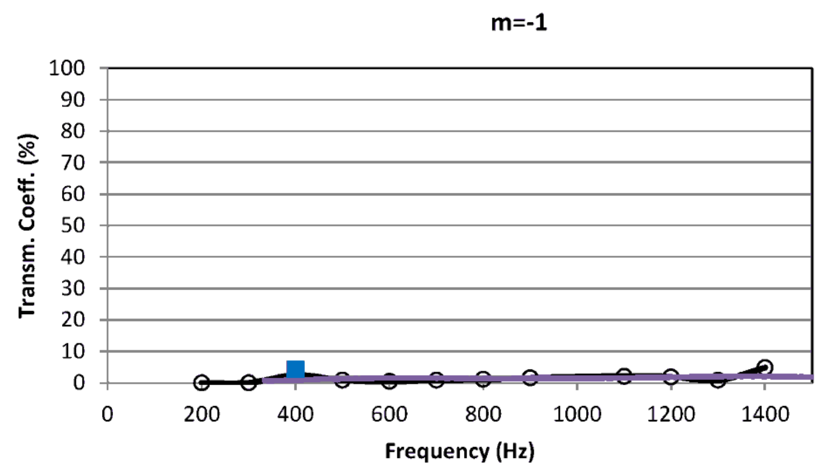
Reflection





Transmission

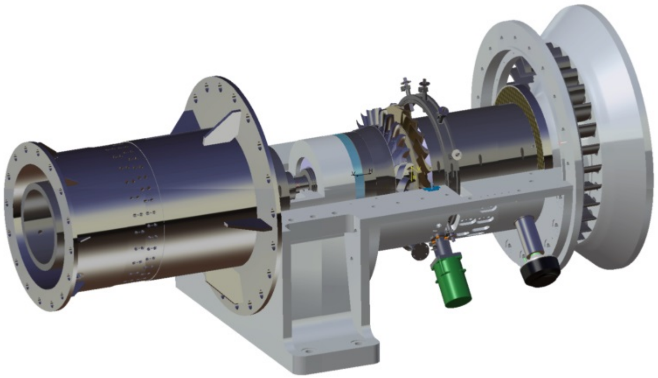




DLR

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%

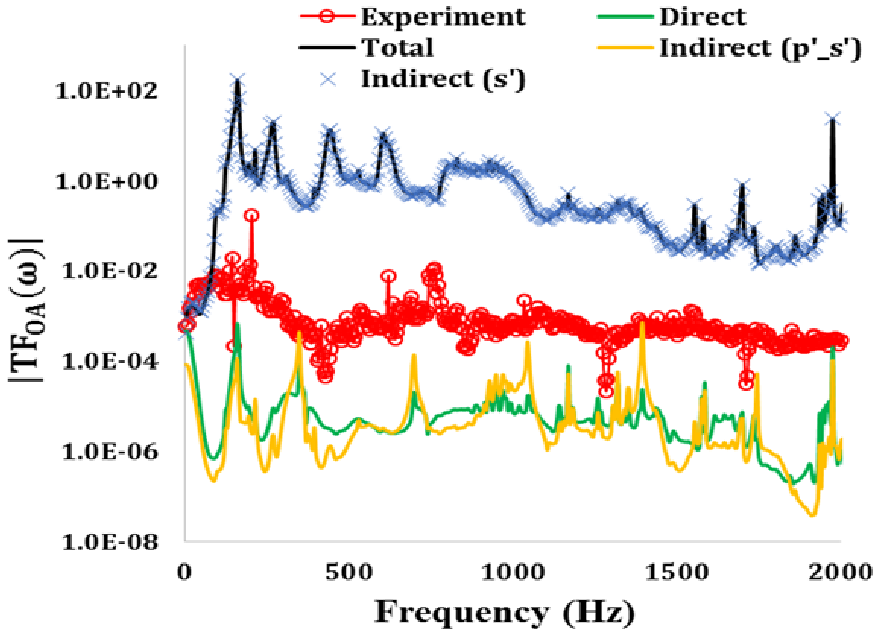


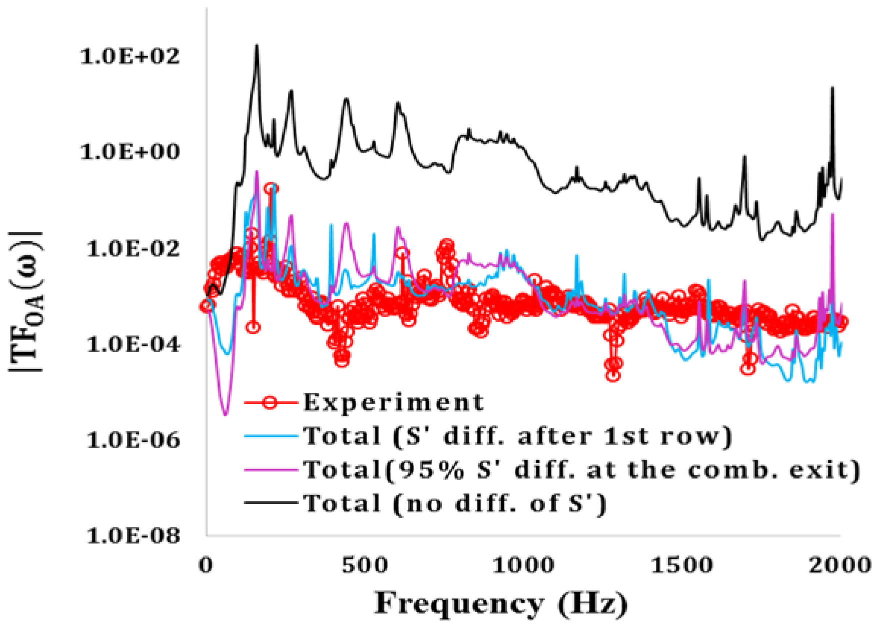
WP4 – Exploitation to Full Scale:

UCAM / RRUK

UCAM
RRUK

- Comparison in jet pipe





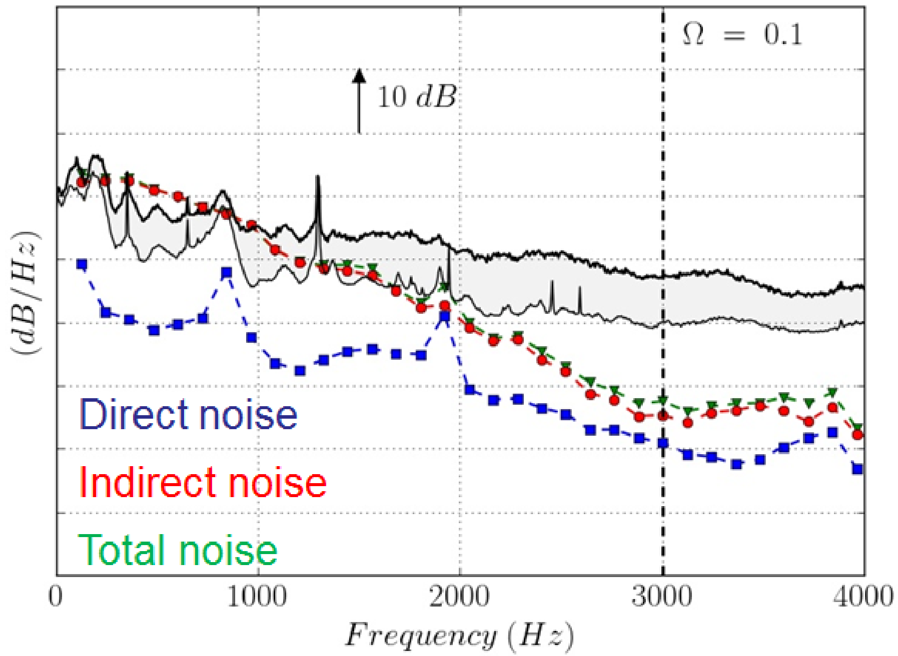
- With no hypothesis on entropy diffusion, indirect combustion noise is largely dominant, and much larger than experimental values
- 2 scenarios are considered about entropy attenuation : no s' after NGV, or 95% s' at combustor outlet. In both cases, good agreement is found.

WP4 – Exploitation to Full Scale:

CERFACS / TM

CERFACS
TM

Sound pressure spectrum at turbine exit of turboshaft engine

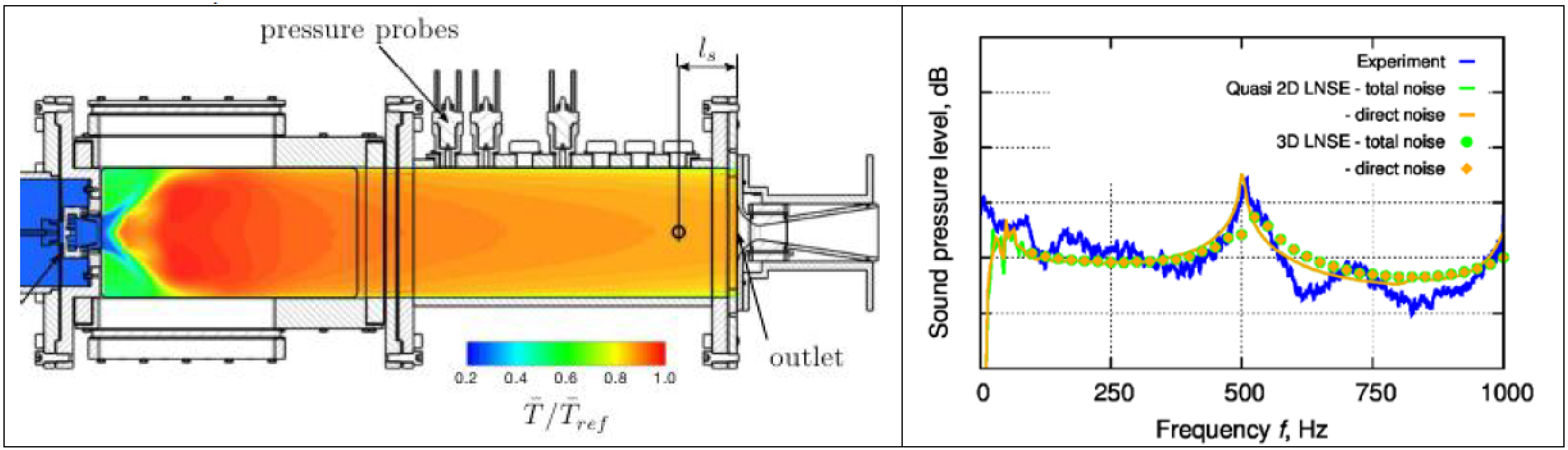


- Computed combustion noise is mostly dominated by Indirect Noise
- Good agreement is found with experimental broadband noise

WP4 – Exploitation to Full Scale:

TUM / GE-AVIO

TUM
GE AVIO

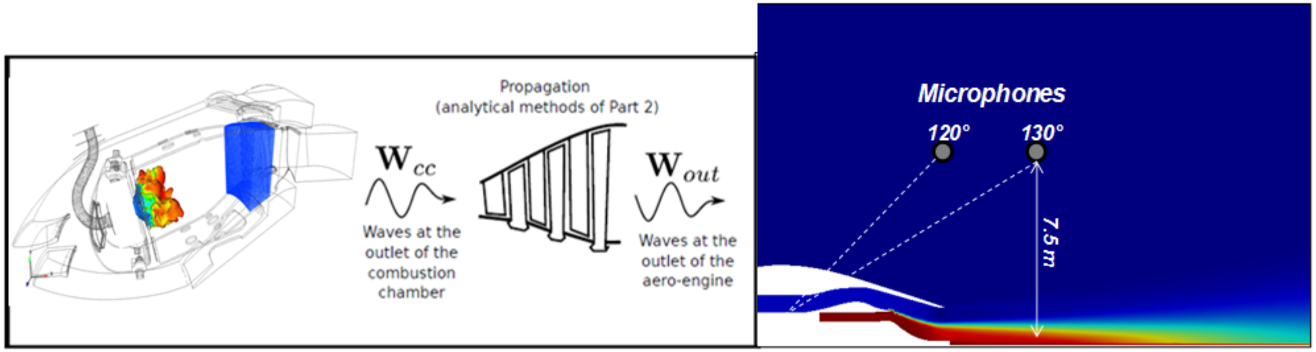


Good agreement has been met between calculated and experimental data. Direct noise is dominant inside the combustor.

WP4 – Exploitation to Full Scale: CERFACS / SN

CERFACS
SN

- Full engine with far field instrumentation



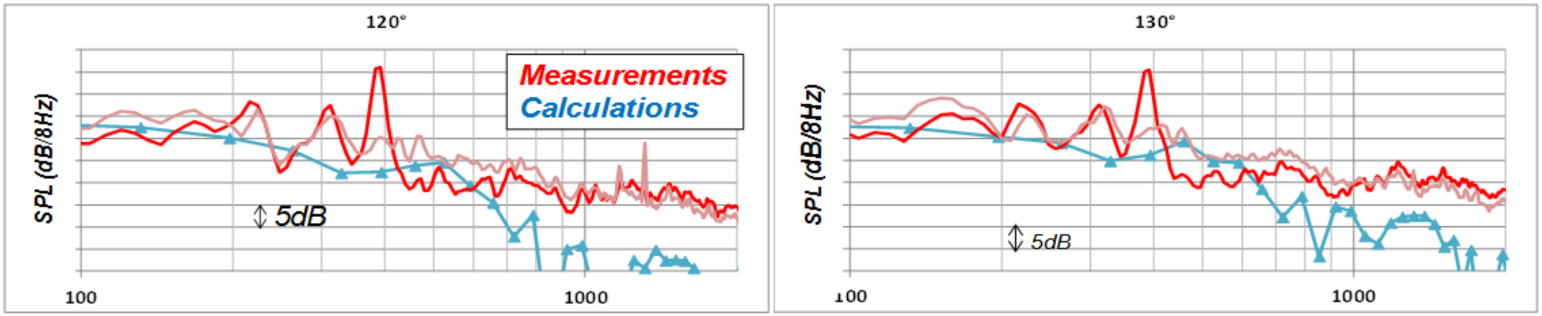
Compressible LES (AVBP)

Propagation through the Turbine (CHORUS)

Far field propagation (AVSP-f or ACTRAN)

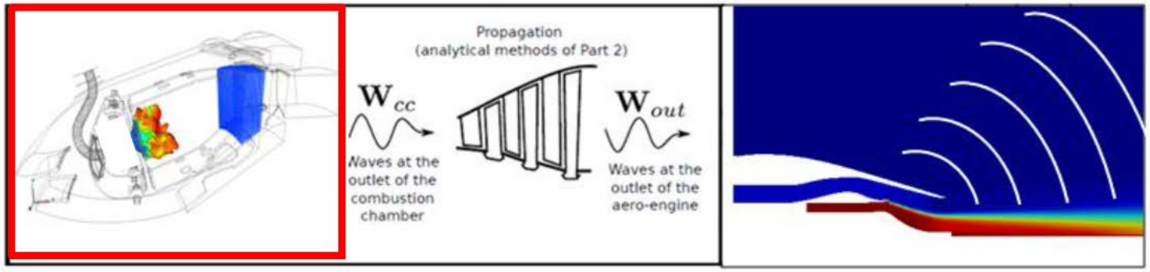
CONOCHAIN

- Comparisons in the far field



DLR

WP4 – Exploitation to Full Scale: Summary



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

- **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.

DLR

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 needs 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**

Acknowledgement: The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) within the EU-FP7 project RECORD[1] under grant agreement no. 312444.

[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):

combustion acoustics = **combustion instabilities** + **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

DLR

Outlook and main challenges

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combustion acoustics = **combustion instabilities** (tonal) + **combustion noise** (broadband)

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DLR