POLITECNICO DI MILANO

Development of boundary conditions for compressible LES simulation of ICE

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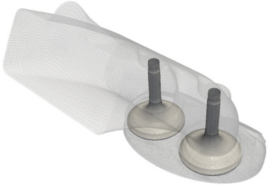
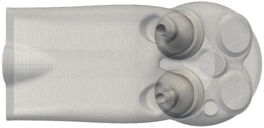
Introduction





LES applied to ICE can be used to simulate:

- Turbulent motion during gas exchange phase (swirl, tumble)
- Fuel mixing and combustion
- Cyclic combustion variability

However, there are some known problems...

- B.C. treatment in the LES code must be able to handle acoustic waves properly
- Unstructured meshes in real-world cylinder heads
- Large mesh size ($\simeq$ million of cells)

...and some lack of knowledge

- Subgrid models are developed for incompressible flows
- Numerical viscosity is comparable to ν_{sgs}

Roadmap

MOTIVATION: cold flow LES simulation on unstructured deforming meshes of complex cylinder heads.

In order to find a reliable methodology for LES, some steps must be done:

- Implementation of b.c. for LES in OpenFOAM® :
  - Turbulence synthetic inlet b.c.
  - NSCBC non-reflecting outlet b.c.
- Subgrid models:
  - one-equation model (in collaboration with **Dr. F. Brusiani**, University of Bologna)
  - dynamic Smagorinsky model with local coefficient values

Cold flow engine simulation:

- Piston-cylinder assembly with axis-centered valve
  - structured mesh
  - unstructured mesh
- Real engine-head geometry (unstructured mesh).

Validation on the real engine-head geometry will be performed against measurements employed at **Centro Ricerche Fiat** (Ing. G. Carpegna, Ing. G. Gazzilli) by hot-wire anemometry technique.

The LES4ICE ISCRA project

- The LES4ICE project (principal investigators: **F. Piscaglia**, **A. Montorfano**) has been selected among 136 submitted research proposals by the Italian SuperComputing Resource Allocation (ISCRA).
- The goal of the project is to **apply LES to simulate ICE by OpenFOAM®**
- Experimental measurements to validate simulation results are provided by Centro Ricerche FIAT

Computing resources (PLX cluster @ CINECA):

- 276 nodes
- RAM: 48 GByte/node DDR3 1333MHz
- 3312 cores (Xeon E5645 2.40GHz 12MB Cache 1333 MHz 80W)
- 528 GPU nVIDIA Tesla M2050
- 2 Remote Visualization Nodes (RVN): 2 nVidia Quadro Plex 2200 128GB RAM
- up to 1000 cores available for research/industrial projects

Outline

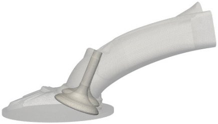
TODAY'S PRESENTATION:

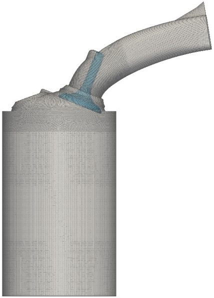
- *Implementation of a NSCBC-based Subsonic Non-Reflecting Outflow B.C. in OpenFOAM®*
  - Theory
  - The NSCBC strategy for Navier-Stokes equations
  - The Local One Dimensional Inviscid (LODI) relations
- Test problem: shock-tube
- Examples of industrial applications: multi-D non-linear acoustic simulation of silencers
  - Reverse flow chambers
  - Single-plug perforated muffler

BoF SESSION (Tuesday, July 12th, h. 10:00)

- LES simulation of ICE in OpenFOAM®
- Implementation and validation of an inflow for LES: synthetic turbulence inlet b.c.
- Validation of SGS models
- Current and future work

Boundary conditions for LES: non-reflecting outflow





Many numerical schemes can provide high-order precision and low numerical dissipation. The precision and the potential applications of these **schemes**, however, **are constrained by the quality of boundary conditions**.

- Unsteady simulations of compressible flows (LES or DNS) require an **accurate control of wave reflections** from the computational domain boundaries
- As LES and DNS algorithms strive **to minimize numerical viscosity, acoustic waves have to be controlled** by another mechanism such as better non-reflecting or absorbing boundary conditions
- Non-dissipative high-order schemes propagate numerical waves, in addition to acoustic waves
- Even in cases where physical waves are not able to propagate upstream from the outlet, numerical waves may do so and interact with the flow

NSCBC-based Subsonic Non-Reflecting Outflow B.C.

THEORY

- Variables at the outlet boundary are computed by solving the conservation equations as in the inner domain
- Wave propagation is assumed to be associated only with the **hyperbolic part of the Navier-Stokes equations**
- **Absence of reflection is enforced by correcting the amplitude of the ingoing characteristic** (wave reflected by the boundary).
- No extrapolation procedure for variables at the boundary is used

VALIDATION

- Shock Tube
- Non-linear acoustic simulation of silencers
- LES simulation of in-cylinder (current work)

OTHER INDUSTRIAL APPLICATIONS

- Aeroacoustics
- Compressible LES
- LES simulation of bluff bodies

NSCBC-based Subsonic Non-Reflecting Outflow B.C.

For each cell face at the boundary end, the governing equations written in a **local reference frame** (**ξ, η, ζ**) are:

Continuity:

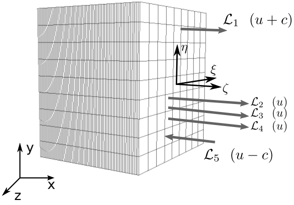
$$\frac{\partial \rho}{\partial t} + d_1 + \frac{\partial \rho u_2}{\partial \eta} + \frac{\partial \rho u_3}{\partial \zeta} = 0$$

Momentum:

$$\frac{\partial \rho u_1}{\partial t} + u_1 d_1 + \rho d_3 + \frac{\partial \rho u_1 u_2}{\partial \eta} + \frac{\partial \rho u_1 u_3}{\partial \zeta} = \frac{\partial \tau_{1j}}{\partial x_j}$$

$$\frac{\partial \rho u_2}{\partial t} + u_2 d_1 + \rho d_4 + \frac{\partial \rho u_2 u_2}{\partial \eta} + \frac{\partial \rho u_2 u_3}{\partial \zeta} = -\frac{\partial p}{\partial \eta} + \frac{\partial \tau_{2j}}{\partial x_j}$$

$$\frac{\partial \rho u_3}{\partial t} + u_3 d_1 + \rho d_5 + \frac{\partial \rho u_3 u_2}{\partial \eta} + \frac{\partial \rho u_3 u_3}{\partial \zeta} = -\frac{\partial p}{\partial \zeta} + \frac{\partial \tau_{3j}}{\partial x_j}$$



Each reference frame has its origin in the cell face center and the vector ζ is set as perpendicular to the cell face.

Energy:

$$\frac{\partial \rho E}{\partial t} + \frac{1}{2}(u_k \cdot u_k) d_1 + \frac{d_2}{\gamma - 1} + \rho u_1 d_3 + \rho u_2 d_4 + \rho u_3 d_5 + \frac{\partial[(\rho E + p) u_2]}{\partial \eta} + \frac{\partial[(\rho E + p) u_3]}{\partial \zeta} = -\nabla \cdot q + \frac{\partial \mu_j \tau_{ij}}{\partial x_i}$$

NSCBC approach for b.c.

The vector **d** given by characteristic analysis (Thompson) can be written as:

$$\boldsymbol{d} = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \\ d_5 \end{bmatrix} = \begin{bmatrix} \frac{\partial m_1}{\partial \xi} \\ \frac{\partial c^2 m_1}{\partial \xi} + u_1 \frac{\partial p}{\partial \xi} \\ u_1 \frac{\partial u_1}{\partial \xi} + \frac{1}{\rho} \frac{\partial p}{\partial \xi} \\ u_1 \frac{\partial u_2}{\partial \xi} \\ u_1 \frac{\partial u_3}{\partial \xi} \end{bmatrix} = \begin{bmatrix} \frac{1}{c^2} \left[L_2 + \frac{1}{2} \left(L_5 + L_1 \right) \right] \\ \frac{1}{2} \left(L_5 + L_1 \right) \\ \frac{1}{\rho c} \left(L_5 - L_1 \right) \\ L_3 \\ L_4 \end{bmatrix}$$

where:

$$\boldsymbol{L} = \begin{bmatrix} L_1 \\ L_2 \\ L_3 \\ L_4 \\ L_5 \end{bmatrix} = \begin{bmatrix} \lambda_1 \left(\frac{\partial p}{\partial \xi} - \rho c \frac{\partial u_1}{\partial \xi} \right) \\ \lambda_2 \left(c^2 \frac{\partial \rho}{\partial \xi} - \frac{\partial p}{\partial \xi} \right) \\ \lambda_3 \frac{\partial u_2}{\partial \xi} \\ \lambda_4 \frac{\partial u_3}{\partial \xi} \\ \lambda_5 \left(\frac{\partial p}{\partial \xi} + \rho c \frac{\partial u_1}{\partial \xi} \right) \end{bmatrix}$$

$$\lambda_1 = u_1 - c$$
$$\lambda_2 = \lambda_3 = \lambda_4 = u_1$$
$$\lambda_5 = u_1 + c$$

λ_i is the characteristic velocity associated to L_i

- L_i is the amplitude variation of the i_{th} characteristic wave crossing the boundary
- L_1 is the **incoming characteristic** reflected by the boundary

Subsonic non-reflecting outflow

- A perfectly subsonic non-reflecting outflow (L_1=0) might lead to an ill-posed problem (**mean pressure at the outlet would result to be undetermined**)
- **Corrections must be added** to the treatment of the b.c. to make the problem well posed. The amplitude of the incoming wave is then set as:

$$L_1 = K\left(p - p_\infty\right)$$

that in global coordinates becomes:

$$L_1 = \sigma \cdot \frac{|1 - \mathrm{M}^2|}{\sqrt{2} J \rho l}$$

  - M is the max. Mach number defined over the patch
  - σ is a constant leading the pressure drift. $0.1 < \sigma < \pi$ (Strickwerda)
  - l is a characteristic size of the domain
  - J is the Jacobian marix

The resulting formulation makes the b.c. **partially non-reflecting** and the **problem well-posed**.

Extension to local Cartesian coordinates

- For each cell face at the boundary end, a local reference frame (ξ, η, ζ) has been defined:

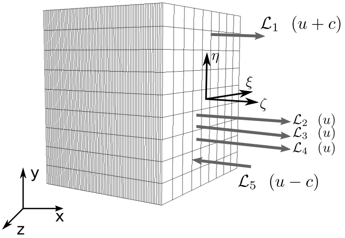
$$x = x(\xi, \eta, \zeta)$$
$$y = y(\xi, \eta, \zeta)$$
$$z = z(\xi, \eta, \zeta)$$

- Each reference frame has its origin in the cell face center and the vector ζ is set as perpendicular to the cell face.
- The governing equations for the **global reference frame** take the form:

$$\frac{\partial \boldsymbol{U}}{\partial t} + \frac{\partial \boldsymbol{F}_1}{\partial x} + \frac{\partial \boldsymbol{F}_2}{\partial y} + \frac{\partial \boldsymbol{F}_3}{\partial z} = -\boldsymbol{\nabla} p$$

where

$$\boldsymbol{U} = \frac{\hat{\boldsymbol{U}}}{J}$$
$$\frac{\partial \boldsymbol{F}_1}{\partial x} = \frac{\hat{\boldsymbol{F}}_1 x_\xi + \hat{\boldsymbol{F}}_2 x_\eta + \hat{\boldsymbol{F}}_3 x_\zeta}{\boldsymbol{J}}$$
$$\frac{\partial \boldsymbol{F}_2}{\partial y} = \frac{\hat{\boldsymbol{F}}_1 y_\xi + \hat{\boldsymbol{F}}_2 y_\eta + \hat{\boldsymbol{F}}_3 y_\zeta}{\boldsymbol{J}}$$
$$\frac{\partial \boldsymbol{F}_3}{\partial z} = \frac{\hat{\boldsymbol{F}}_1 z_\xi + \hat{\boldsymbol{F}}_2 z_\eta + \hat{\boldsymbol{F}}_3 z_\zeta}{\boldsymbol{J}}$$



Numerical solution

- Governing equations have been solved by a **multistage time stepping scheme** in $t^{n,k}$:

$$t^{n,k} \equiv t^n + k \cdot \delta t = t^n + \frac{k}{K}\Delta t \qquad k \in [1; K]$$

  where $t^{n,k}$ is a variable local fractional time-step.

- The method consists of the iteration of **two main steps**:

  1) Evaluation of backward spatial derivatives at t^n and of the fluxes at time $t^n + \frac{k}{K}\Delta t$; conservation equations are solved sequentially. The solution is first order in time.

  2) Fluxes and source terms calculated at the previous step are used to find the solution at time $t^n + \frac{k+1}{K}\Delta t$. The time accuracy of this method is of the second order at this stage.

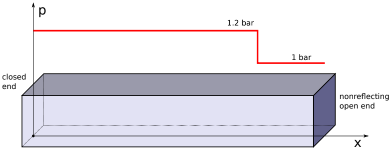
- The process is iterated until the solution at the new time $t^{n+1} \equiv t + \Delta t$ is calculated.

- The time stepping algorithm:
  - requires a **relatively small amount of memory storage**
  - it is **more stable and accurate** than an explicit method
  - it allows for **larger global time steps** in the simulation than a traditional explicit method

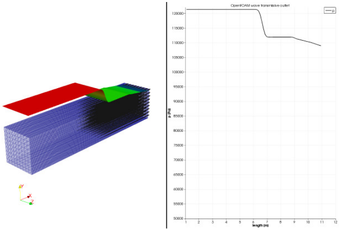
Non-Reflecting NSCBC vs `waveTransmissive`

SHOCK TUBE simulation:

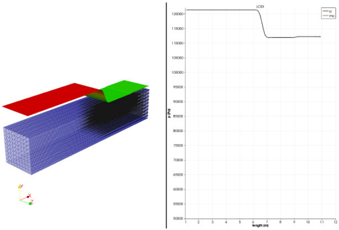
- 40500 hexahedral cells
- $p_{max} = 1.2$ bar
- $p_0 = 1.0$ bar, $T_0 = 293$ K



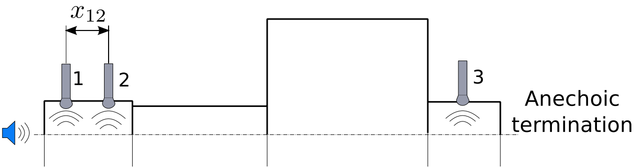
OpenFOAM wave transmissive BC



LODI nonreflecting BC



Validation: prediction of the acoustic performance of silencers



The acoustic performance of silencers is determined by the **Transmission Loss**:

$$\text{TL} = 10 \log_{10} \left(\frac{A_i}{A_o} \left| \frac{p_{in}}{p_{tr}} \right|^2 \right) \quad \text{[dB]}$$

Algorithms for **data postprocessing** based on the general hypotheses of the linear acoustics (**two-sensor method**) are used to measure the incident components of the pressure pulsation.

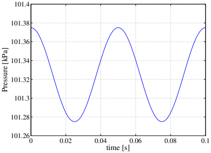
Simulation framework

- An **inlet b.c.** to model **different large-band acoustic sources** is needed
- Acoustic simulations of compressible flows require an **accurate control of wave reflections from the computational domain boundaries**. Acoustic waves are often modified by numerical dissipation
- the `waveTransmisive` b.c. in OpenFOAM® **is not perfectly non reflecting**; small acoustic waves are reflected to the inner domain on boundaries

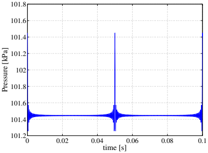
acousticSourceFvPatchField

A **boundary condition** `acousticSourceFvPatchField` **to model different types of acoustic sources** has been developed in the OpenFOAM® technology.

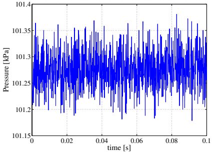
SINGLE SINUSOID



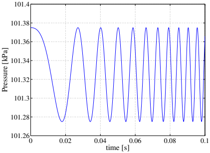
PULSE



WHITE NOISE



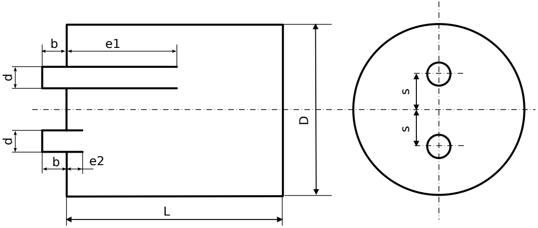
FREQUENCY SWEEP




```
inlet
{
type            acousticSourceTotalPressure;
sourceType      "whiteNoise";
U               U;
phi             phi;
rho             rho;
psi             none;
gamma           1.4;
refPressure     100000;
f0              10;
fn              2000;
step            10;
amplitude       50;
value           uniform 100000;
}
```

- **Different kind of time-varying perturbations** are applied at the inlet boundary patch
- Ad-hoc developed **run time controls** ensure correct case setup and avoid **aliasing** due to poor frequency resolution or to **non physical frequency signals**, distorting the spectrum in the chosen range (Oppenheim and Schaffer)

Case study: reverse-flow chambers

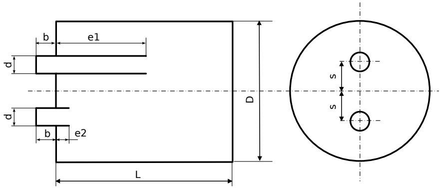


Silencer	l [mm]	w [mm]	d [mm]	b [mm]	e1 [mm]	e2 [mm]	s [mm]
RC-l1	494	197	50	17	17	17	50
RC-l2	494	197	50	17	257	17	50
RC-m	377	197	50	17	167	17	50
RC-s	127	197	50	17	17	17	50

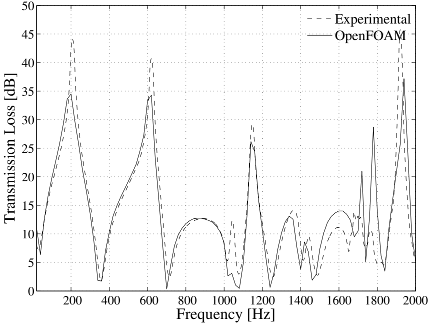
Case setup

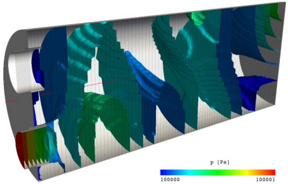
- **solver**: `sonicFoam`
- **temporal discretisation**: Crank-Nicholson scheme
- **differential operators**: standard finite volume discretisation of Gaussian integration
- **working fluid**: air
- **boundary conditions**:
  - inlet : pressure pulse with frequency content f∈[20;2000] Hz (step 20 Hz)
  - outlet: non-reflective NSCBC anechoic boundary condition
  - walls : adiabatic, no-slip condition
- **time step** limited by the CFL criterion (max. Courant=0.4). Max time-step: 10^{-6} s
- **perturbation period** $T = 1/\min(f_{min}, f_{step})$. Two periods were needed to reach full convergence in the simulation. Max time step used guarantees a sampling frequency that satisfies the Nyquist sampling law

Reverse-flow chambers: long chamber 1 (AVL)

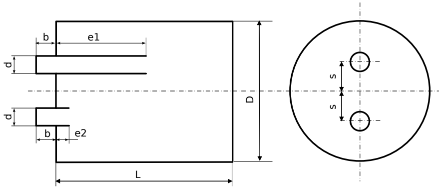


Silencer	l [mm]	w [mm]	d [mm]	b [mm]	e1 [mm]	e2 [mm]	s [mm]
RC-l1	494	197	50	17	17	17	50

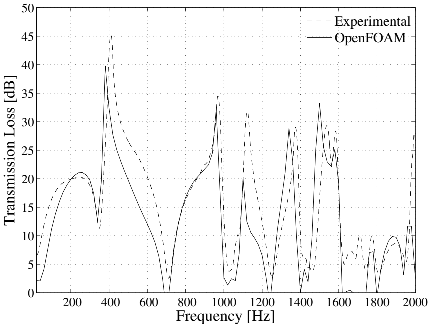


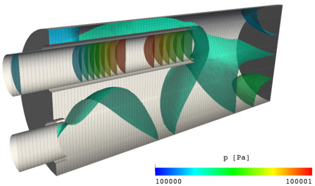


Reverse-flow chambers: long chamber 2 (AVL)

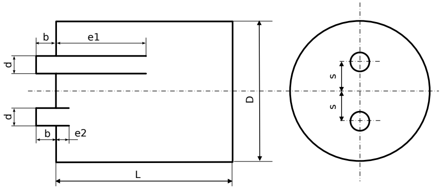


Silencer	l [mm]	w [mm]	d [mm]	b [mm]	e1 [mm]	e2 [mm]	s [mm]
RC-l2	494	197	50	17	257	17	50

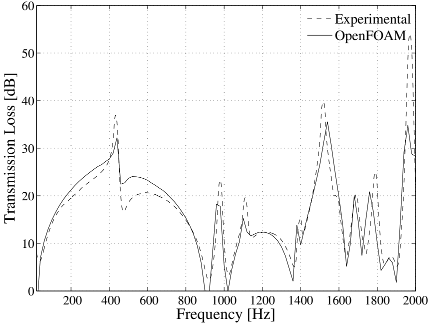


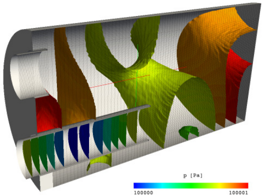


Reverse-flow chambers: mid chamber (AVL)

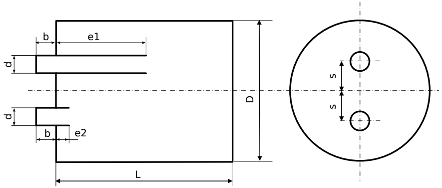


Silencer	l [mm]	w [mm]	d [mm]	b [mm]	e1 [mm]	e2 [mm]	s [mm]
RC-m	377	197	50	17	167	17	50

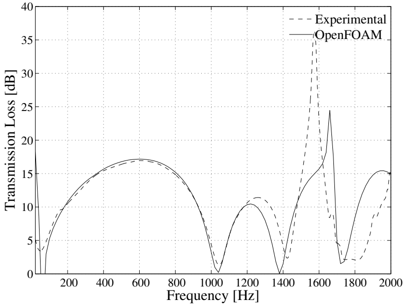


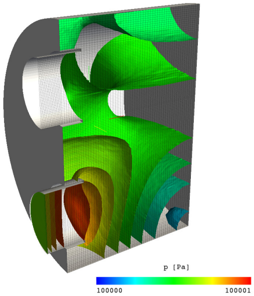


Reverse-flow chambers: short chamber (AVL)

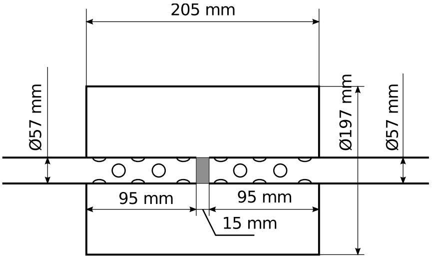


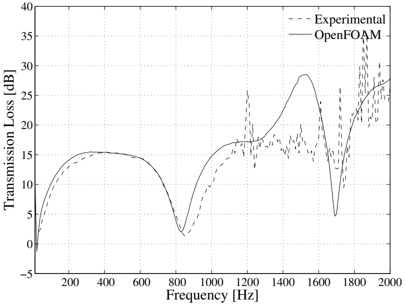
Silencer	l [mm]	w [mm]	d [mm]	b [mm]	e1 [mm]	e2 [mm]	s [mm]
RC-s	127	197	50	17	17	17	50





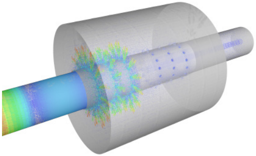
Single-plug perforated muffler (AVL)





Silencer	d [mm]	D [mm]	l_a [mm]	l_p [mm]	t_w [mm]	d_h [mm]	porosity [%]
P1	57	197	95	15	2	5	5

- porosity = 5%
- plug length = 95 mm
- chamber length= 205 mm
- zero mean flow



Conclusions

- NSCBC written in local coordinates for compressible subsonic Navier-Stokes equations
- **Non-reflecting condition for subsonic outflows** based on the NSCBC approach
- **Multistage time stepping scheme** for the semi-implicit solution of the NSCBC
  - faster convergence
  - allows for higher timesteps when coupled with a transient solver
  - improved robustness
- Validation on non-linear acoustics

Acknowledgments

Authors would like to aknowledge:

- Prof. L. Davidson, Prof. H. Nilsson	Chalmers University of Technology, Göteborg (Sweden)
- Dr. G. Carpegna, Ing. G. Gazzilli	Centro Ricerche Fiat, Orbassano (Italy)
- Dr. R. Fairbrother, Mr. A. Dolinar	AVL List GmbH, Graz (Austria)
- Dr. F. Brusiani	Università di Bologna (Italy)
- Ing. M. Fiocco	ICE PoliMi Group, Politecnico di Milano (Italy)
- Dr. C. Zannoni, Dr. I. Spisso	CINECA Bologna (Italy)

CPU time for LES simulation has been provided by:

- SNIC – Swedish National Infrastructure for Computing via Lunarc – Center for scientific and technical computing, Lund University (Sweden)
- CINECA – Consorzio Interuniversitario per l'Elaborazione e il Calcolo Automatico
- ISCRA – Italian Super-Computing Resource Allocation

Thanks for your attention!

Internal Combustion Engine
Group

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