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3D Numerical Analysis of the Unsteady Turbulent Swirling Flow in a Conical Diffuser using FLUENT and OpenFOAM

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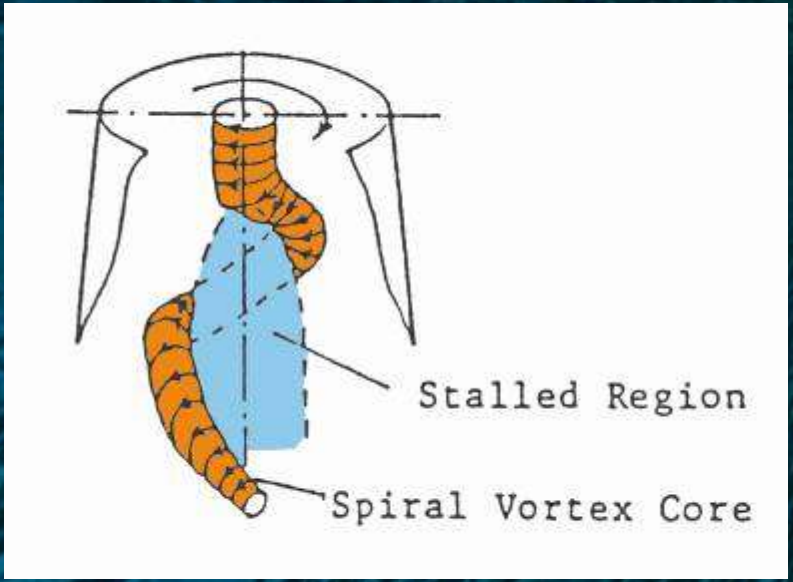
Introduction

- Decelerated swirling flow in hydraulic turbine draft tube cone ends in vortex breakdown (with associated severe unsteadiness and pressure fluctuations) when operating at partial discharge.
- The main cause of VB is the increase in swirl intensity downstream a fixed pitch runner as the discharge decreases, as a result of the mismatch between the swirl generated by wicked gates and the angular momentum extracted by the runner.
- A certain level of swirl at draft tube inlet avoids the flow detachment at cone wall, and improves the conversion of the excess of kinetic energy into static pressure.
- VB is associated with a central quasi-stagnant region; the "vortex rope" is a rolled-up vortex sheet which originates between the central stalled region and the swirling main flow.

Helical vortex breakdown in decelerated swirling flows



- The decelerated swirling flow in Francis turbine discharge cone evolves in helical vortex breakdown (precessing vortex rope) when the swirl number at runner outlet increases above a critical value.

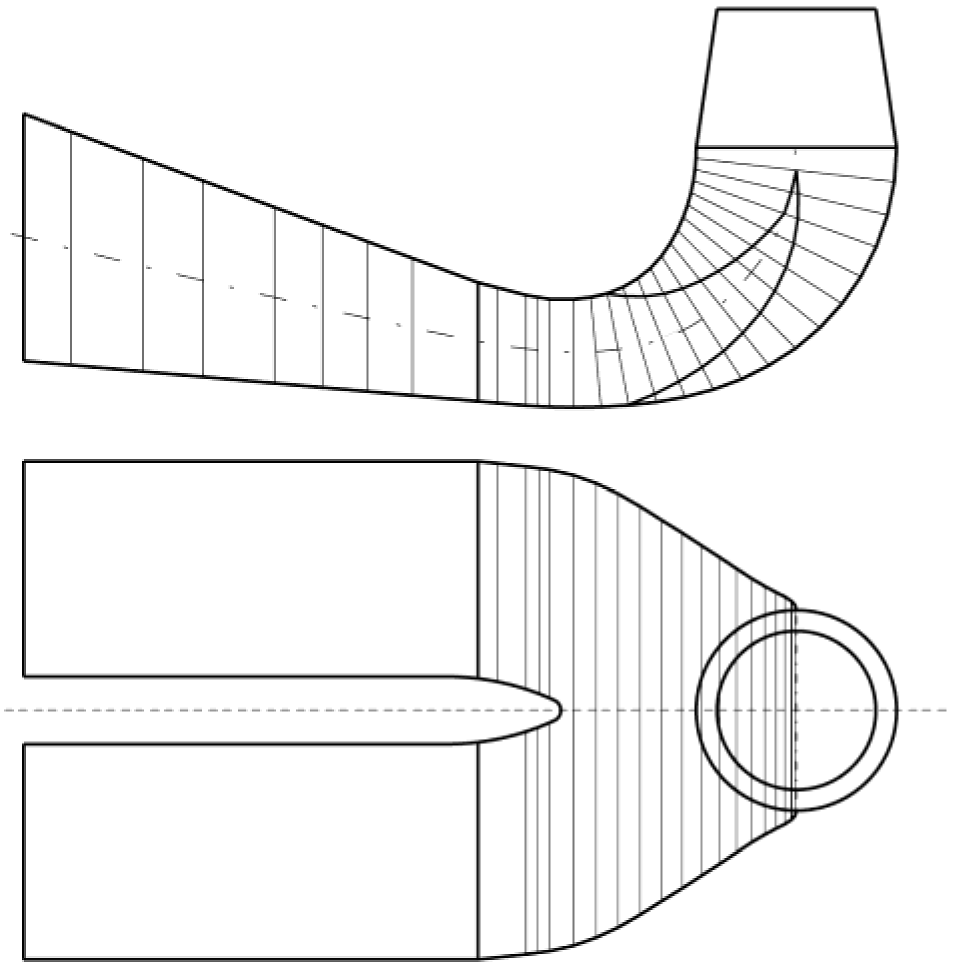
- Nishi et al. (1988) suggest that the circumferentially averaged velocity field in the cone could be represented as a "dead" (quasi-stagnant) water region surrounded by the swirling main flow.

- The spiral vortex is a rolled-up vortex sheet originating between the central stalled region and outer swirling flow.

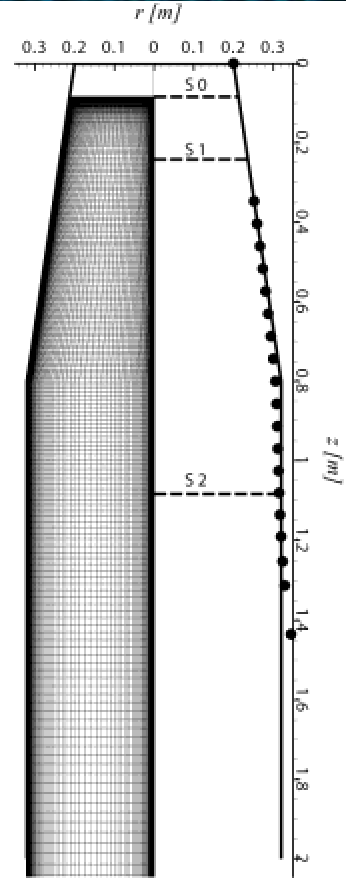
Content

- 3D computational domain and BCs (computational domain corresponds to the swirling flow apparatus from test rig)
- Numerical set-up with FLUENT and OpenFOAM
- 3D unsteady turbulent flow simulation of decelerated swirl in a straight draft tube
- Vortex rope visualization
- Pressure field analysis comparison against experimetal data

Francis turbine draft tube and simplified straight conical diffuser



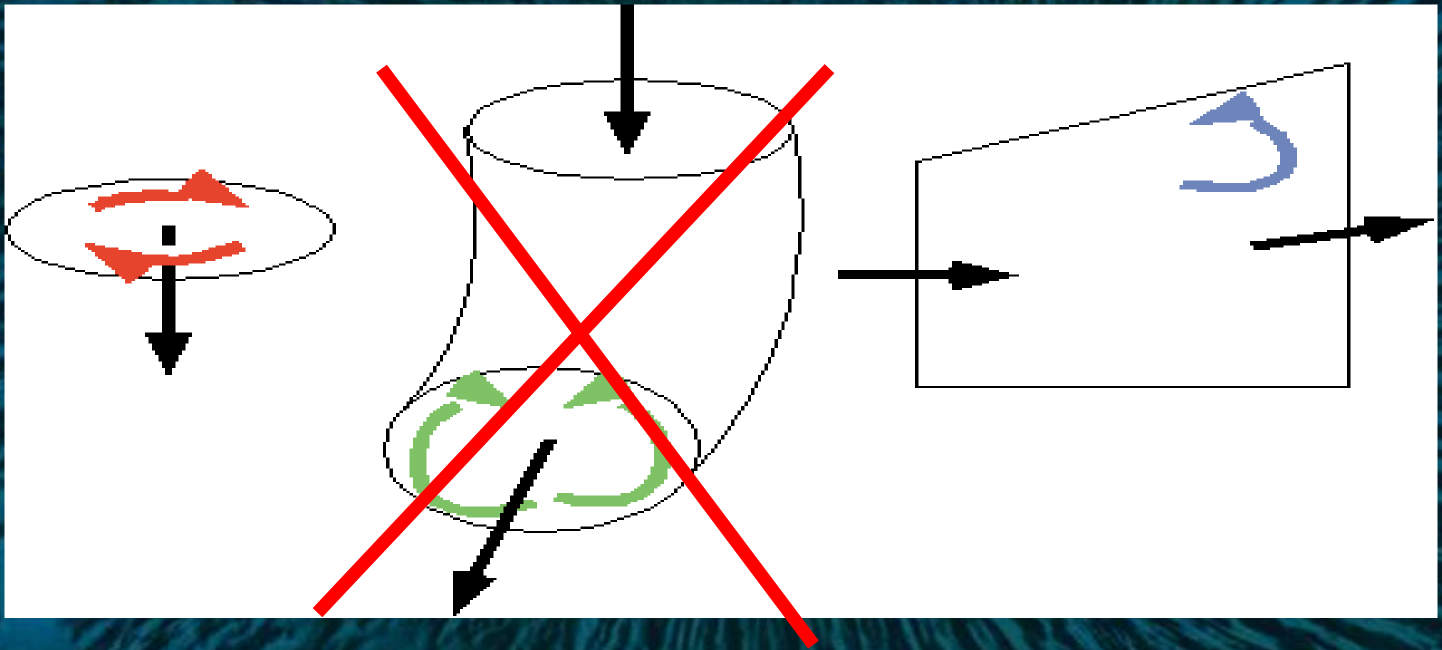
a) Side and top view, respectively, of the FLINDT draft tube



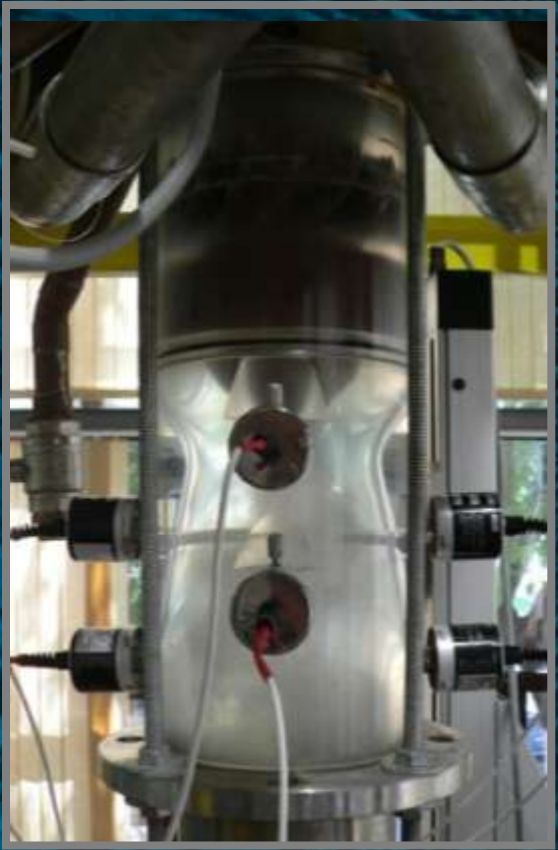
b) Simplified straight conical diffuser

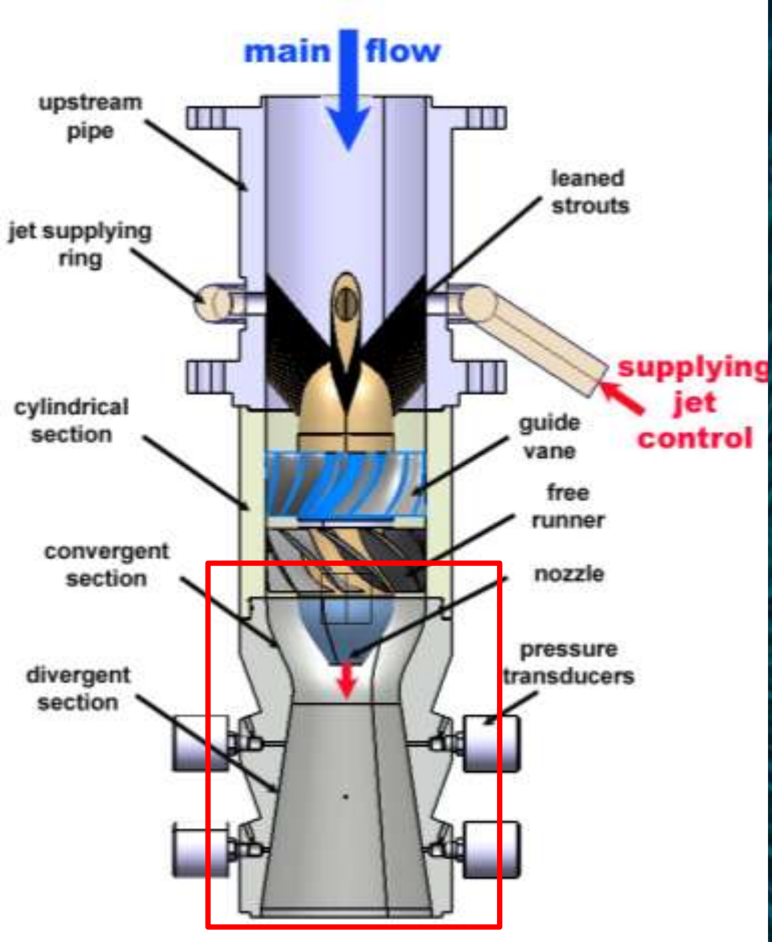
Phenomena in the draft tube flow

- Swirling flow
- Flow into a bend – secondary flows
- Positive pressure gradient in the diffuser - separation

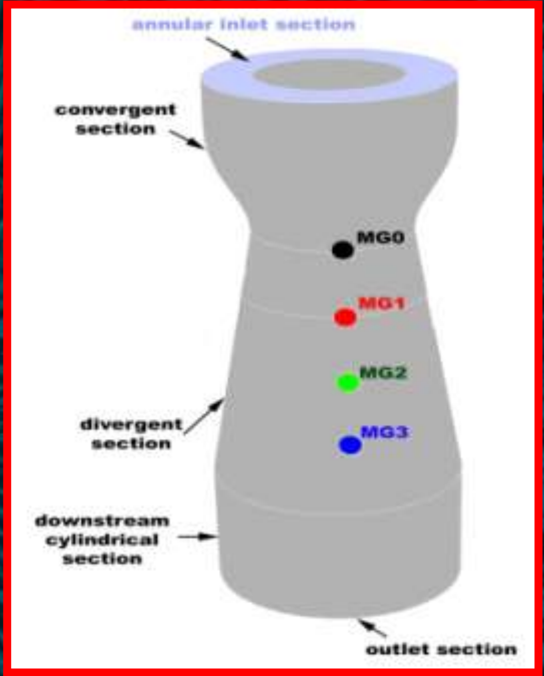


3D Computational domain & BCs





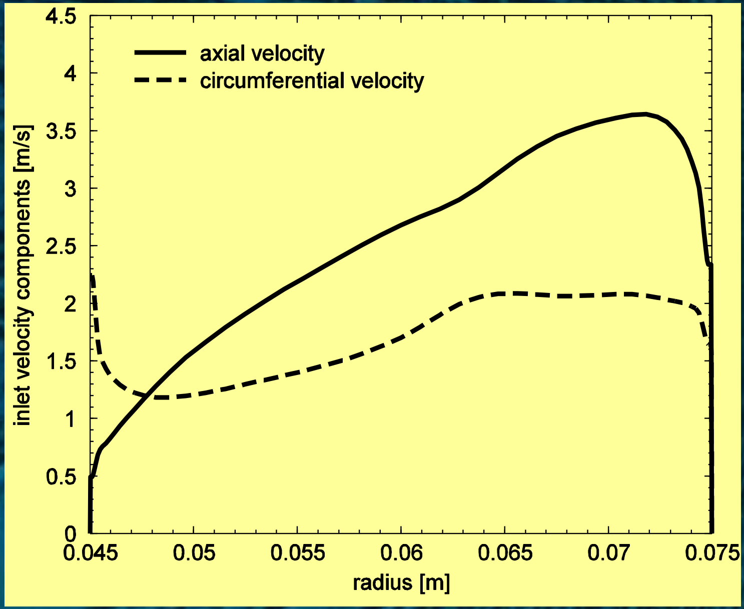
Meridian cross section of the swirling flow apparatus.



3D computational domain and BCs

Boundary conditions

Inlet velocity profiles as computed downstream the swirl generator (fixed and rotating blades)



Axial and circumferential velocity profiles imposed on the inlet section of the 3D computational domain.

Fluent outlet radial equilibrium condition for pressure (relationship between pressure variation in radial direction and circumferential velocity, obtained from the radial momentum equation)

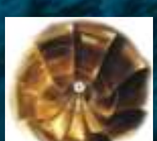
$$\frac{\partial p}{\partial r} = \frac{\rho V_\theta^2}{r}$$

OpenFOAM outlet uses zeroGradient for all variables and sets the outlet average pressure to zero.

Wall-functions at walls

Numerical setup

	FLUENT	OpenFOAM
Structured mesh	2 millions cells	
Velocity-pressure coupling	SIMPLE	SIMPLE
Turbulent model	k-ε RNG	Standard k-ε
Pressure discretization	PRESTO	Rhie&Chow
Momentum discretization	2^{nd} order	2^{nd} order
Time discretization	1^{st} order	2^{nd} order
Time step	1e-4	5e-5



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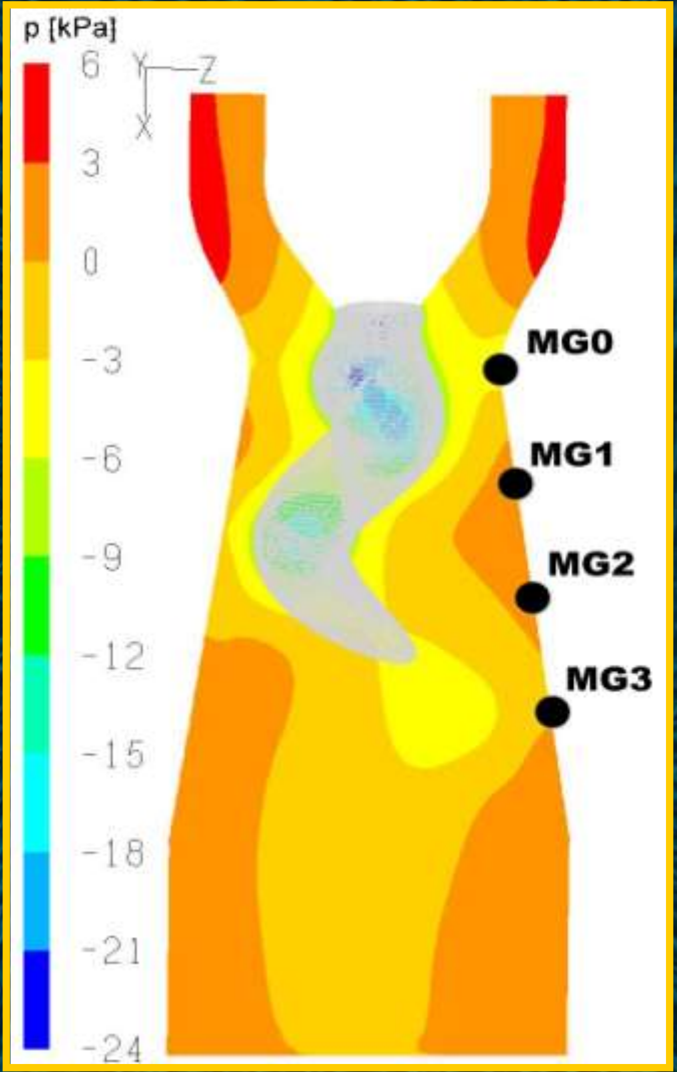
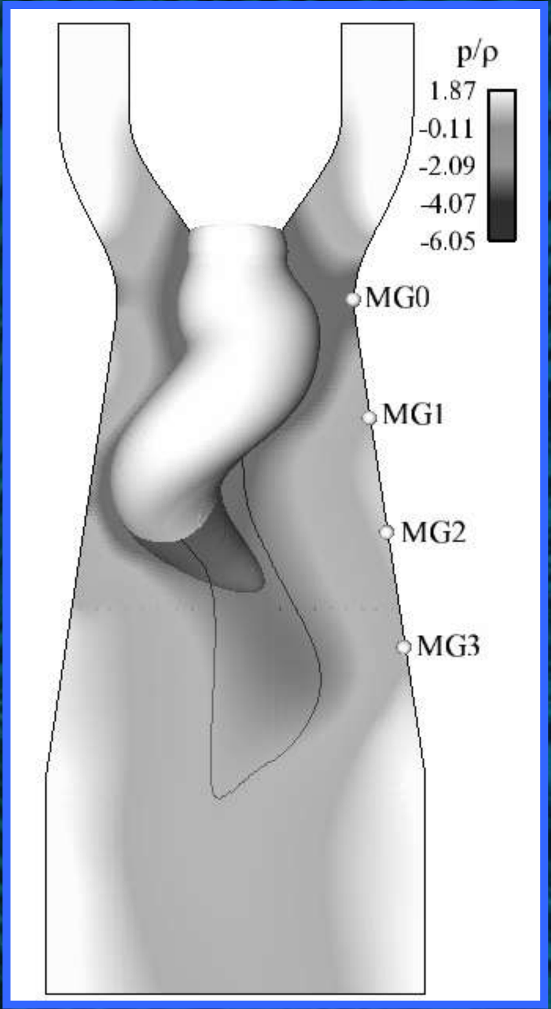
Vortex rope visualization





St= 0.387 FLUENT 0.406 (+6%) OpenFOAM 0.427 (10%)

Fourier reconstruction on signal function

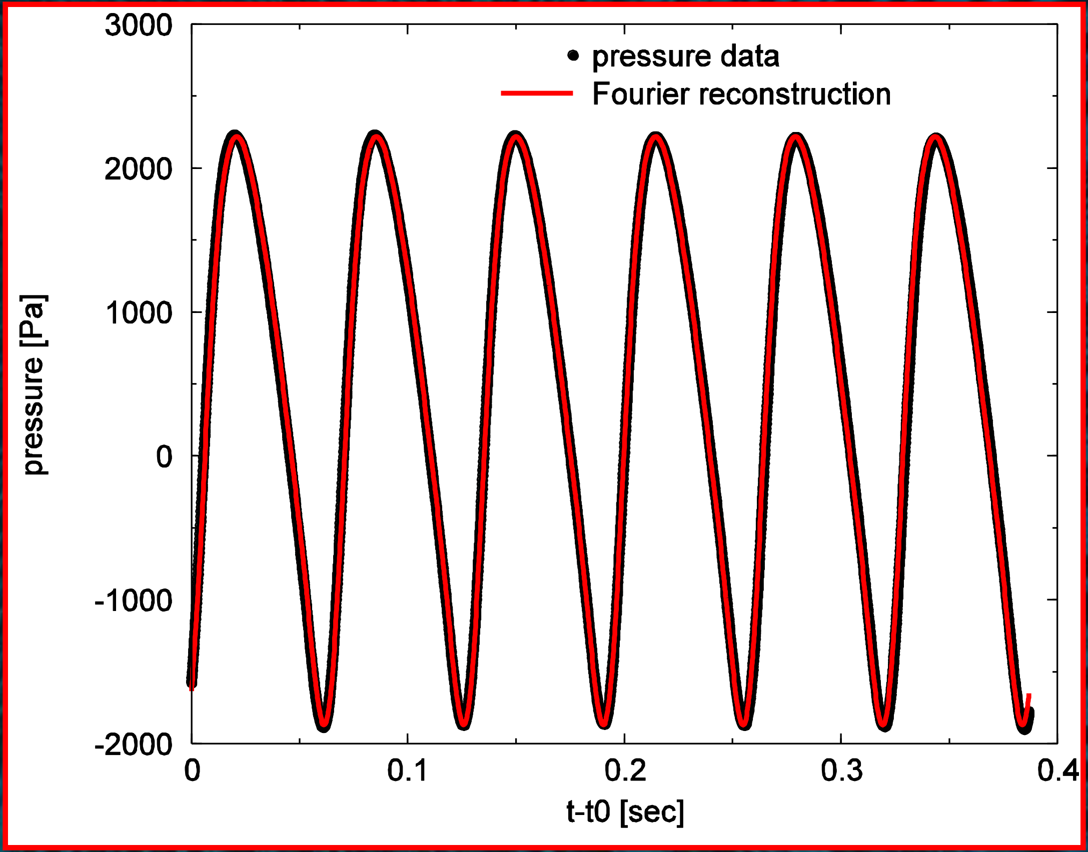
$$g(t) = A_0 + \sum_{n=1}^{(N-1)/2} A_n \cos[\omega_n (t - t_0)] - \sum_{n=1}^{(N-1)/2} B_n \sin[\omega_n (t - t_0)]$$

$$A_0 = \frac{c_0}{N} = \frac{1}{N} \sum_{n=0}^{N-1} s_n$$

$$A_n = \frac{2c_{2n}}{N}$$

$$B_n = \frac{2c_{2n+1}}{N}$$

$$\omega_n = \frac{2\pi(n+1)}{N\Delta} = \frac{2\pi(n+1)}{T}$$



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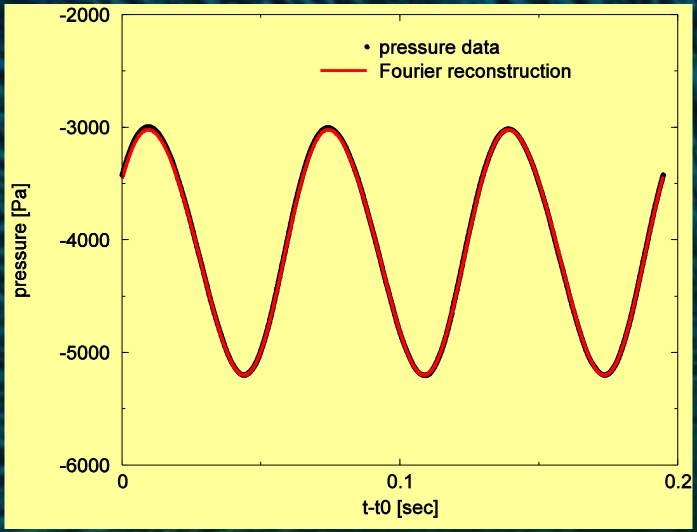
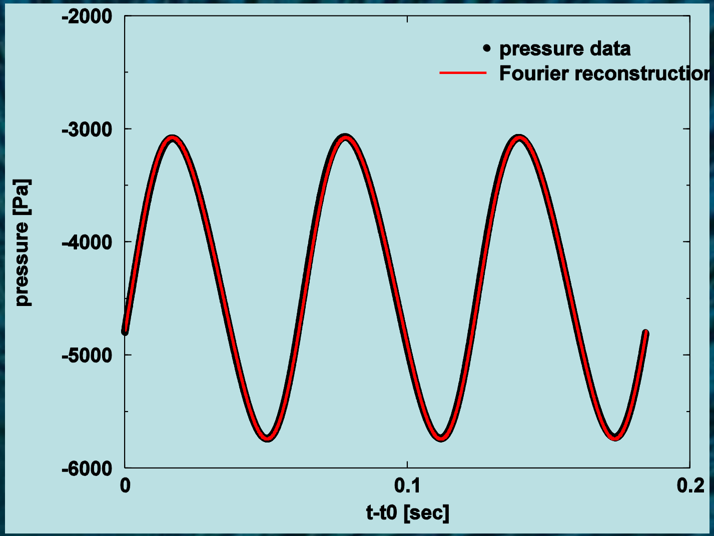
FLUENT and OpenFOAM numerical results

MG0

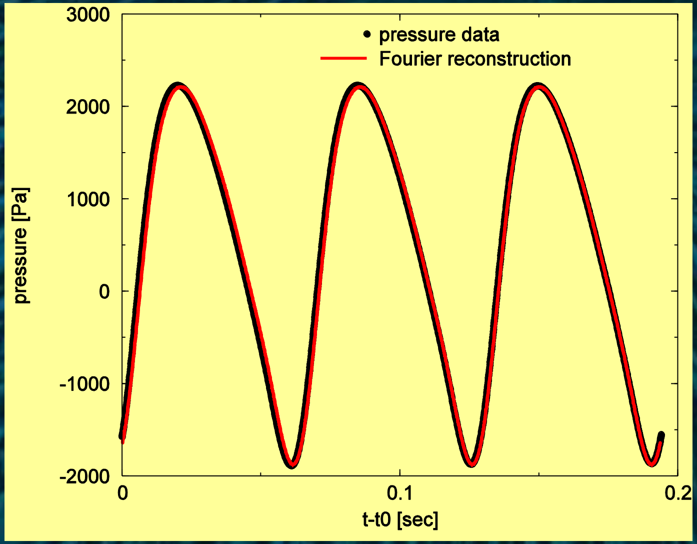
(base harmonics and 2^{nd} harmonics)

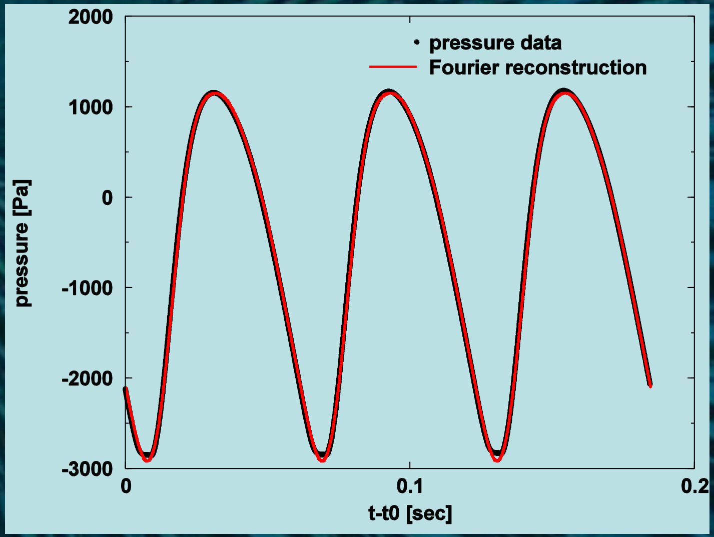




MG1

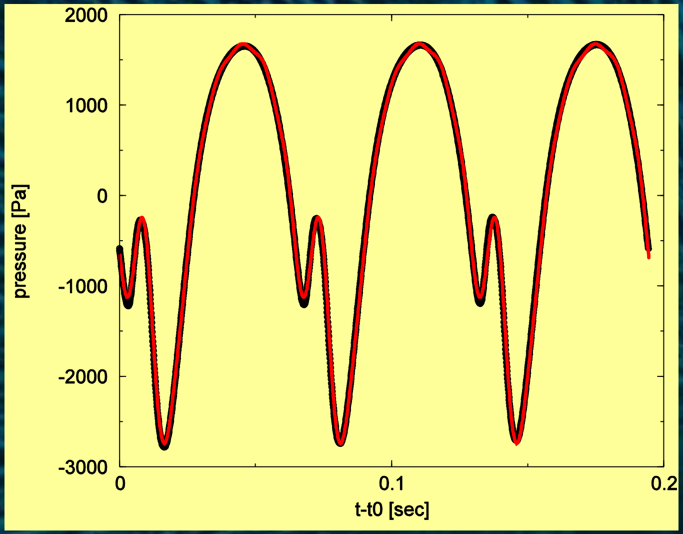
(base harmonics and higher harmonics up to 4^{th})

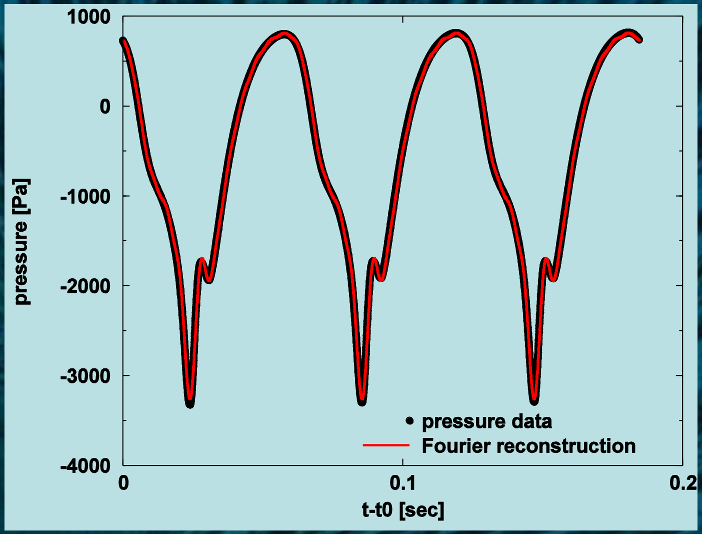




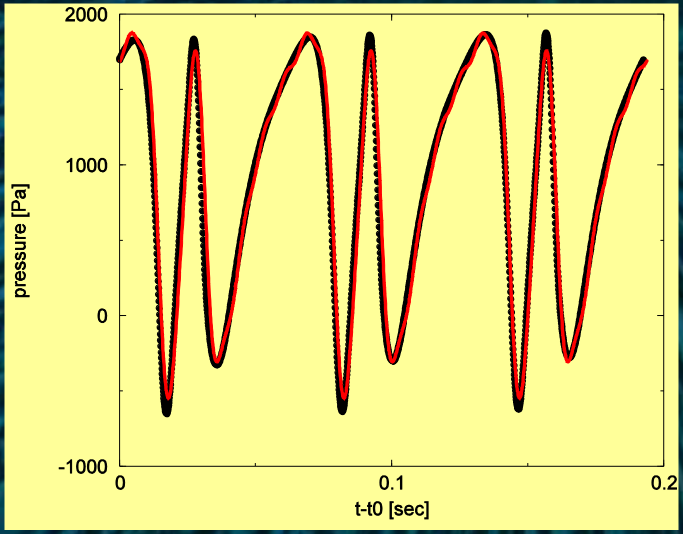
FLUENT and OpenFOAM numerical results

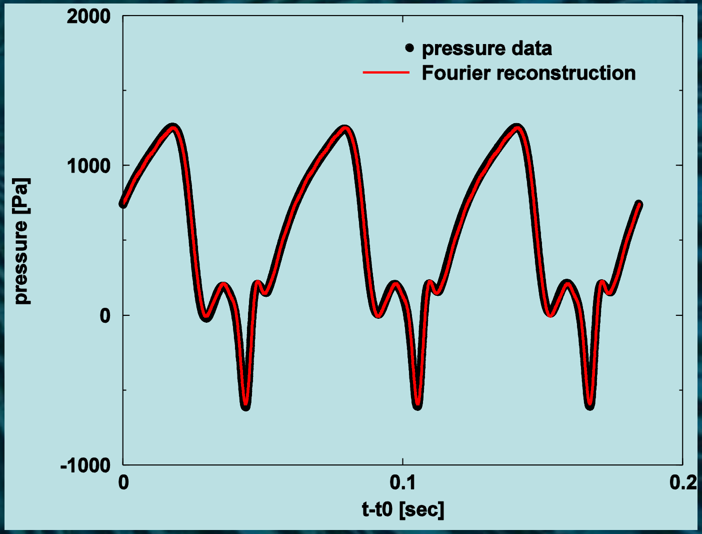
MG2
(base harmonics and higher harmonics up to 7^{th})





MG3
(base harmonics and higher harmonics up to 8^{th})





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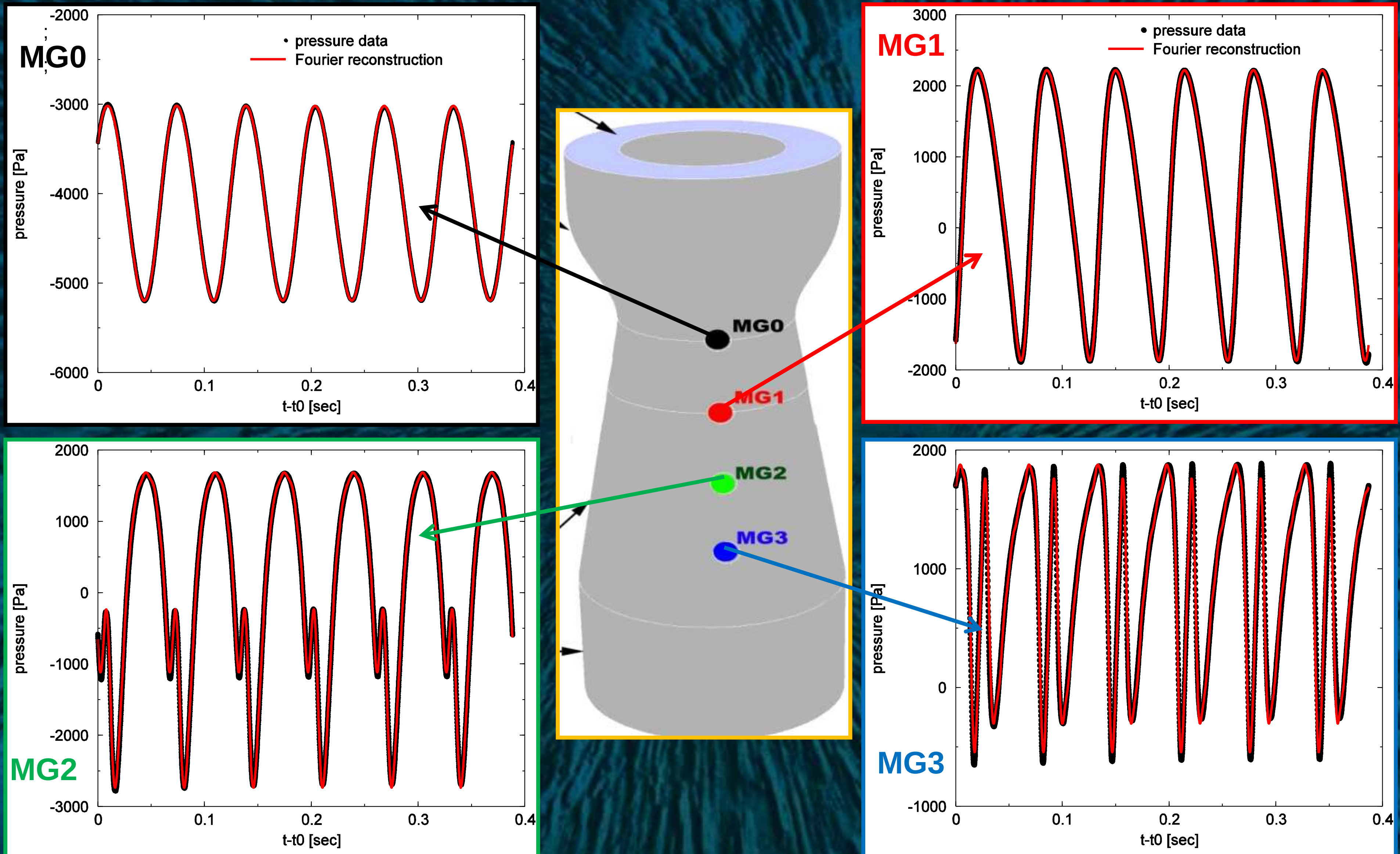
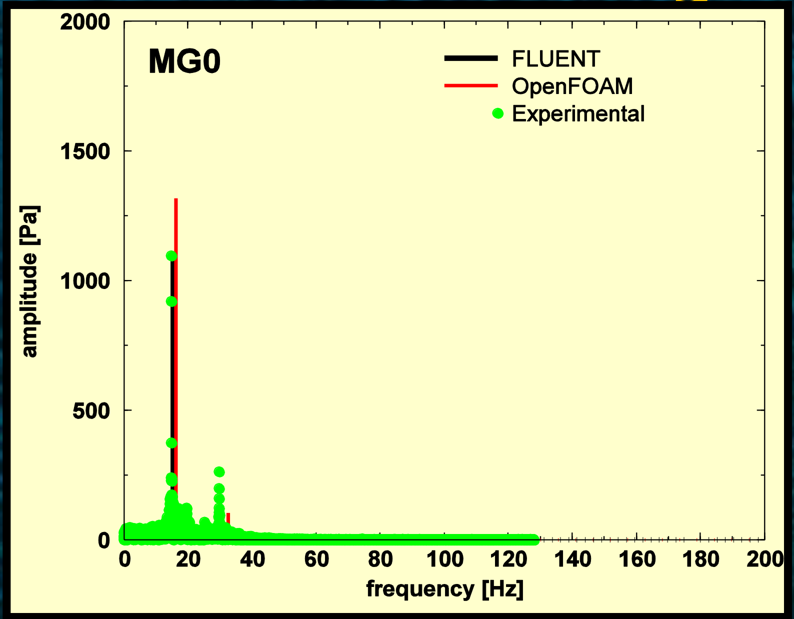
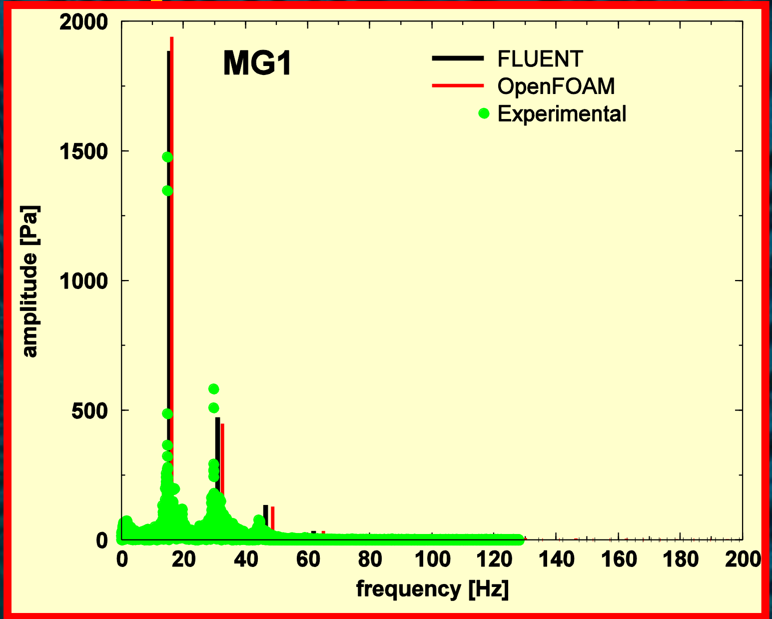
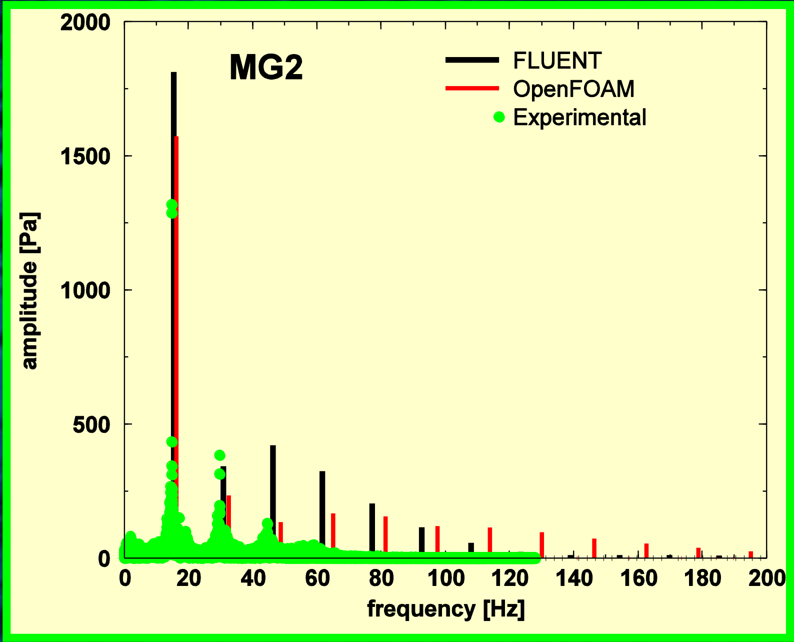
Pressure field analysis

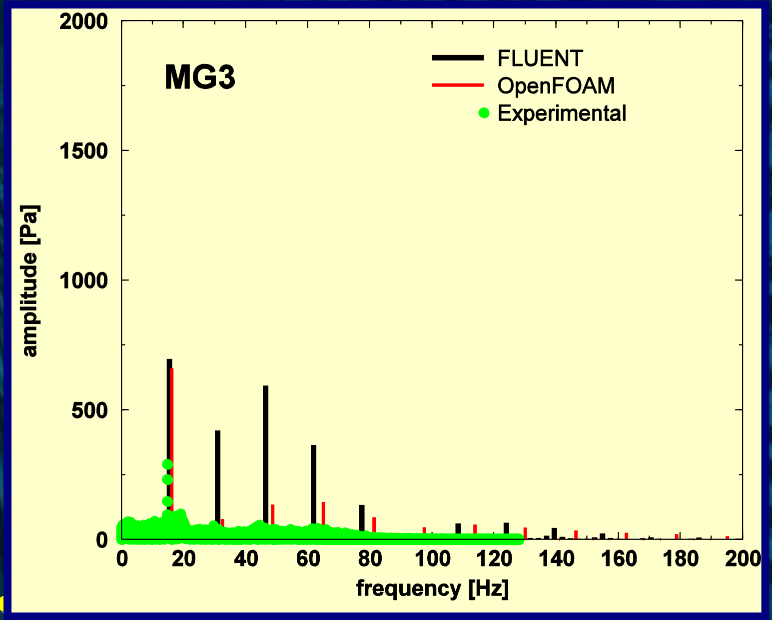


Numerical results against Experimental data









CONCLUSIONS

- 3D unsteady turbulent (k-ε) simulations were performed using FLUENT and OpenFOAM in order to <u>understand the physics</u> of the decelerated swirling flow with vortex rope in conical diffuser
- The frequency is reasonably evaluated
- Pressure fluctuations associated with the vortex rope are computed in four sections of the conical diffuser ➔ these are compared with experimental data
- The unsteady pressure field is quite well computed in the throat where the vortex rope is compact
- A significant discrepancy between numerical results and experimental data is obtained in the downstream part of the conical diffuser due to the vortex rope is too compact than the real one ➔ improved turbulent model (DES)

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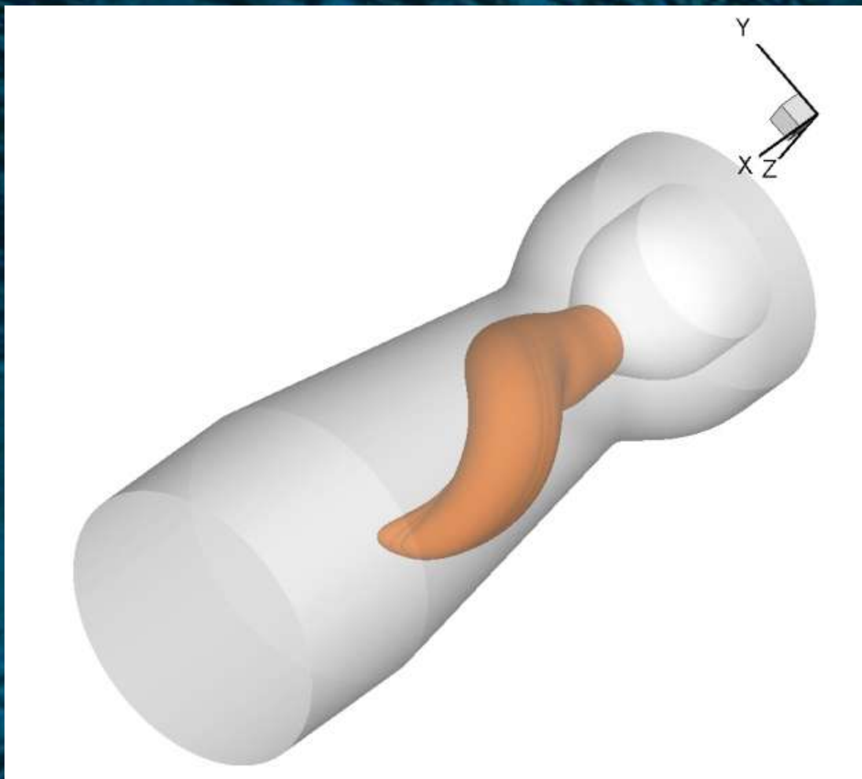
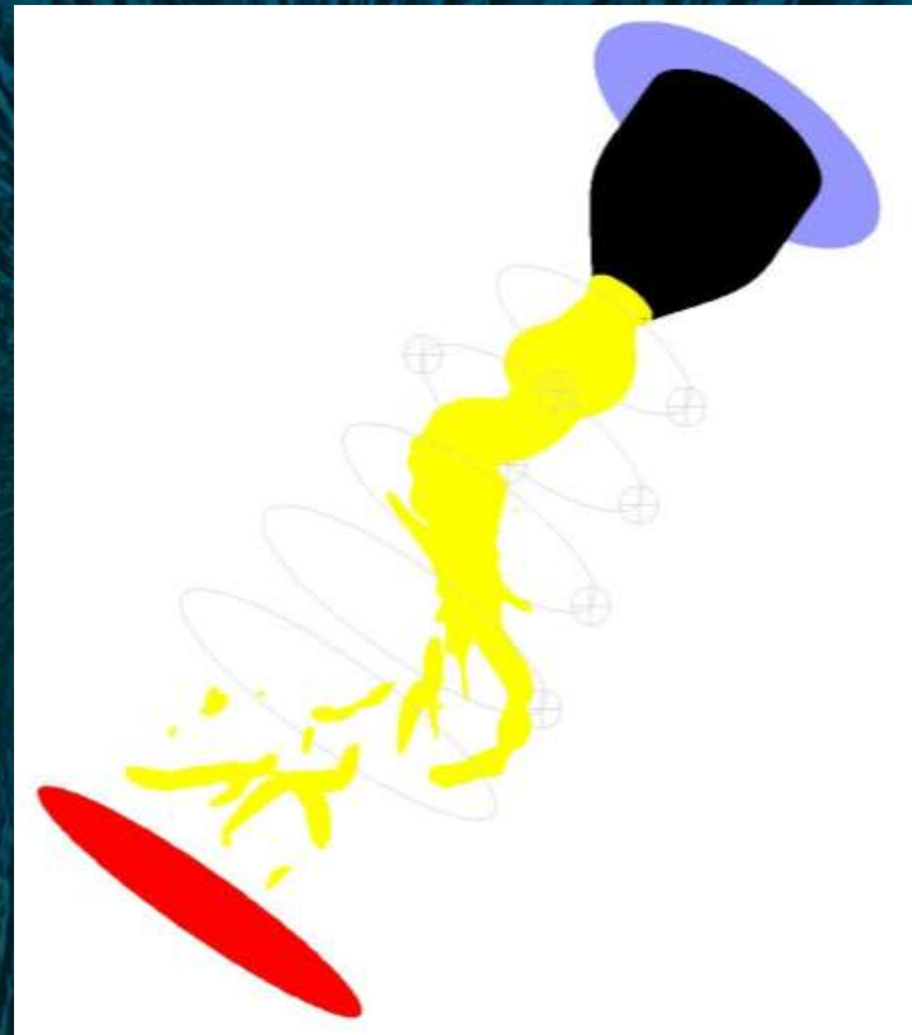
PERSPECTIVES



vortex rope computed
with k-ε model



vortex rope computed with DES model