Fan System Design and Performances Prediction Through Optimization Process

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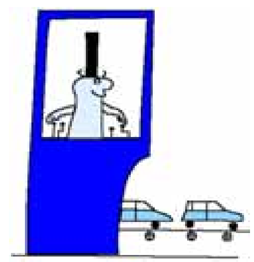
1 – Industrial background

Industrial background

Components

Module

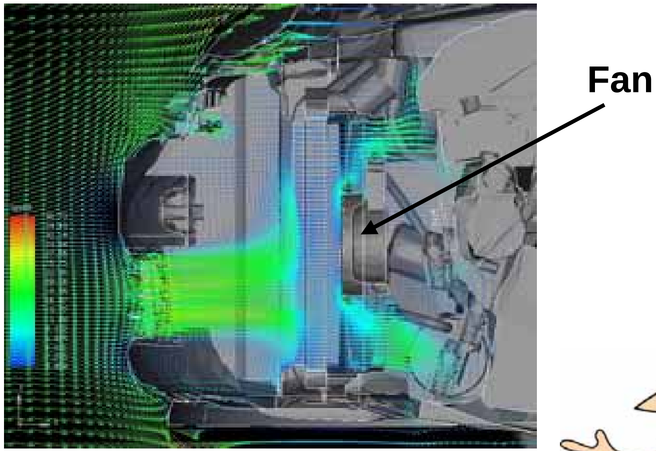
Front-end

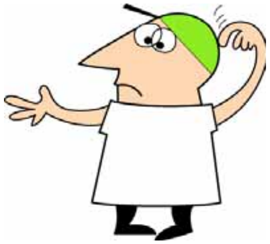


- **Fan system product lines and thermal components**
  - ➔ Components intended for mass production
  - ➔ High pressure for reducing the cost of these products

Technical constraints for fan system

- **More and more constraint of packaging in the underhood**
  - ➔ The downstream flow of the fan is affected by the aerodynamic blockage created by mechanical components (motor, gear-box, …)
  - ➔ The fan is no longer working as a standard axial turbomachinery





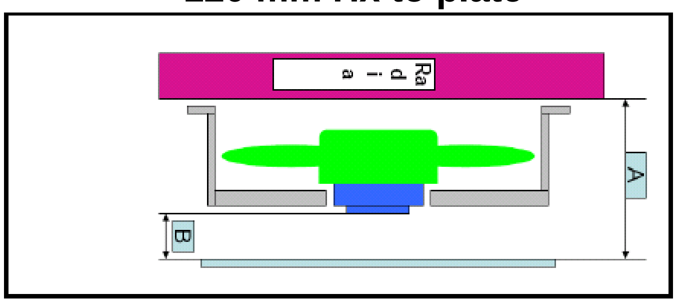
- **Need to improve development methods**
  - ➔ Standard theory for axial machine not fully valid for such flow
  - ➔ For energy efficiency, the fan must provide optimum performances

2 – Objectives

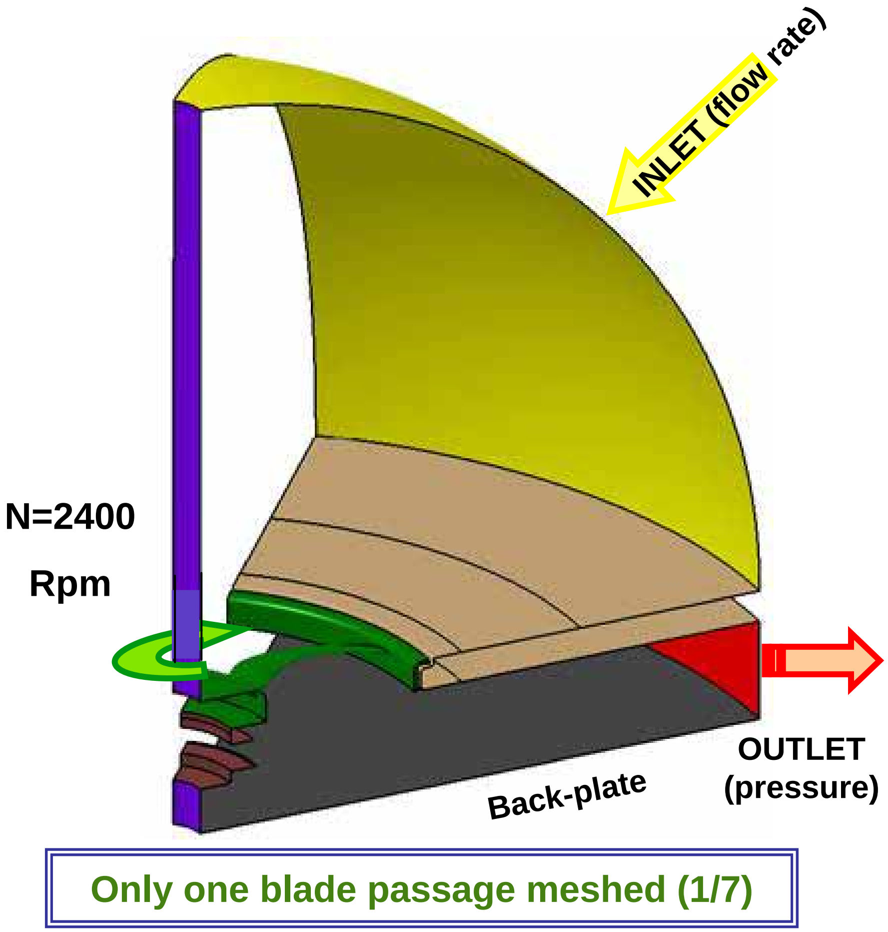
New type of specifications for fan system

- **Fluid simulation intended to improve fan systems**
  - ➔ Simulation can take into account complex environments
  - ➔ Realistic configuration compared to real usage of the fan in the under hood

Black-plate configuration:
120 mm Hx to plate



Specifications

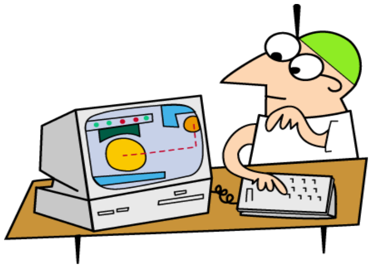


Domaine of simulation

Build a methodology to conduct complex development

- **Combine optimization method with aerodynamic fan simulation**
  - ➔ Build the methodology on the base of the know-how of experts
  - ➔ Link the CFD tool CFD++ (Metacomptech) with Hyperworks platform (Altair)
  - ➔ Provide solutions for best performances with a high level of confidence

- **Experiment and test the method to be implemented with high power computing**
  - ➔ Demonstrate the benefit of big computing capacities (Expamtion Project)
  - ➔ Save time and resources to go further in our research (acoustic for instance with CAA++…)



3 – Methods

The different steps

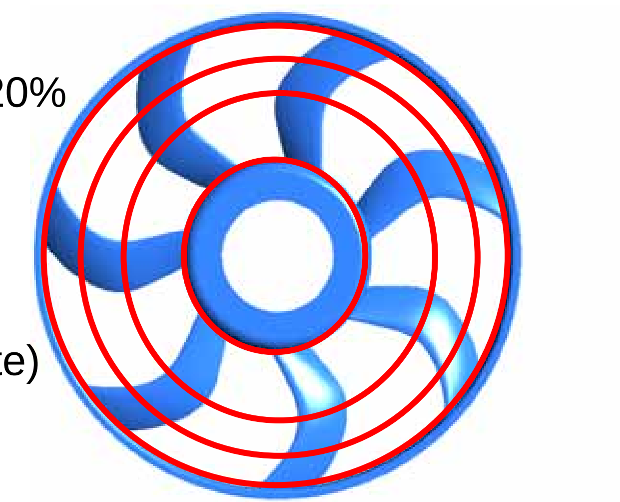
- **Sensitivity analysis**
  - ➔ Several parameters are chosen on the base of the know-how of experts
  - ➔ A first DOE is conducted with coarse meshes
  - ➔ Results analysis help ranking parameters and determine cross-correlation between them

- **Optimization conducted with a reduce set of parameters**
  - ➔ Most influent parameters are selected to drive the optimization with fine meshes
  - ➔ The objective is to minimise the torque
  - ➔ Two constraints are established:
    - Pressure rise > 210 Pa at nominal point (QN)
    - Pressure rise > 0 at high flow rate (QH)

- **Optimization conducted with a full set of parameters (to be continued)**
  - ➔ Demonstrate the ability of using highly parallelised computing to reduce development time
  - ➔ Evaluate the cost and benefit of running the full set of parameter compared to the reduce one

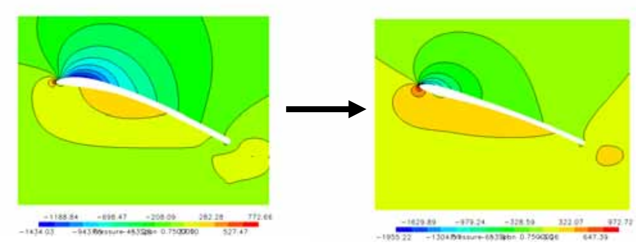
Parameters

- **Chosen Parameters to describe a complex blade surface**
  - → 4 selected radius to obtain the effect of the twist: bottom, mid span, 80% of the span, top
  - → For each radius, chord can be move from 80% to 120%
  - → For each radius, camber can be modified from 100% to 20%
  - → For each radius, stagger can be changed by +/- 4°



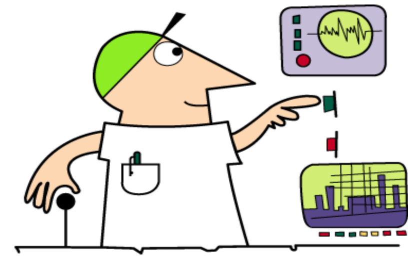
  - → A total of 12 independent parameters
  - → 2 different flow rates (the nominal one and a high flow rate)
  - → Initial geometry based on a existing one

  - → Blade thickness distribution kept constant
  - → Sweep variation not studied

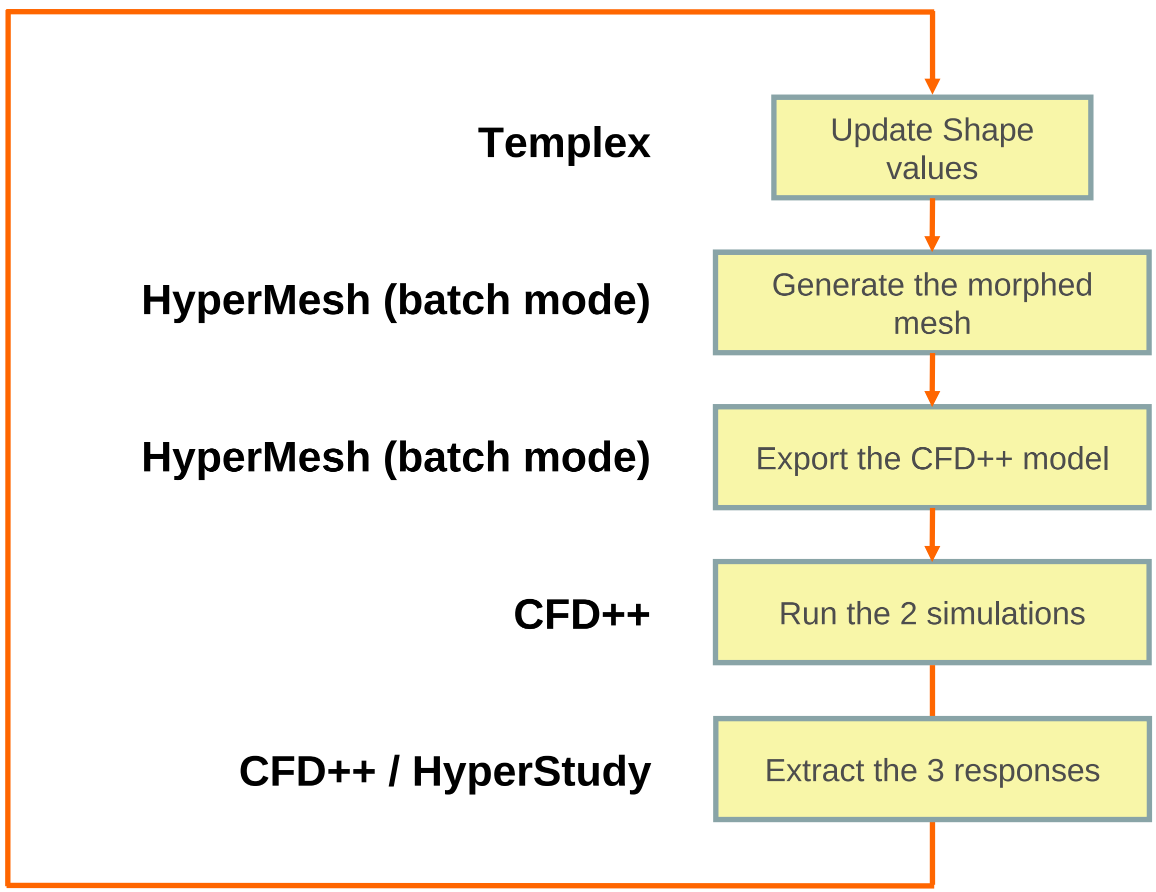


Variations can be considered as small
→ Local optimization in the field of solutions

Process



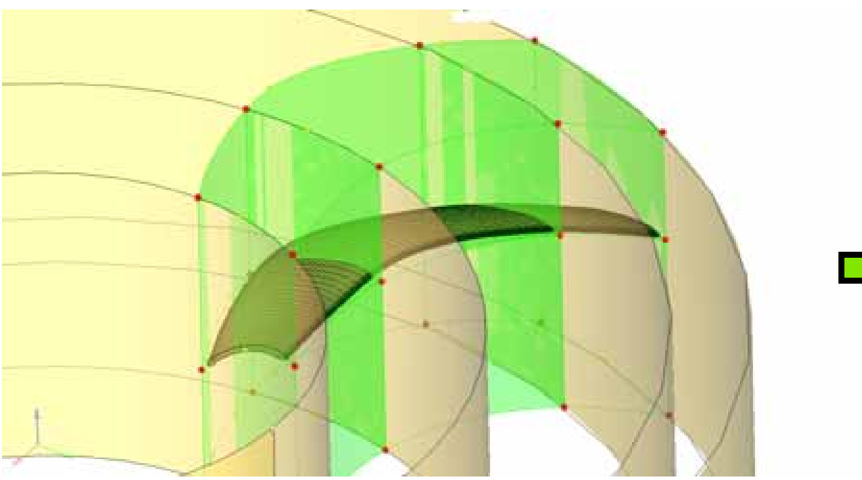
HyperStudy
Optimization Algorithm

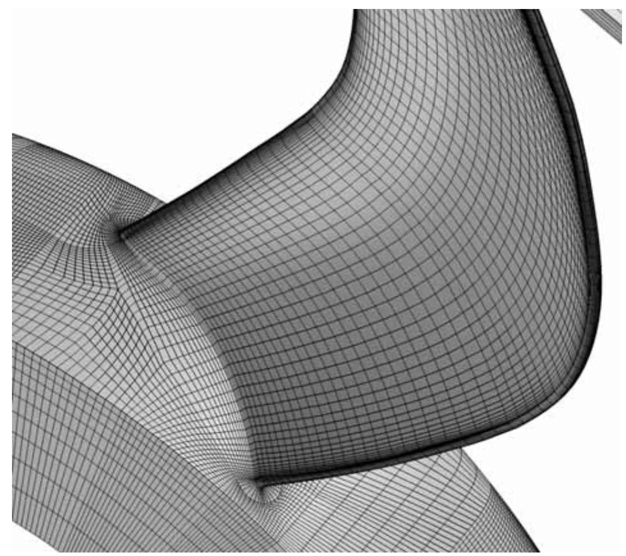


Mesh morphing

Process to deform the mesh (full hexa meshing)

- ➔ The blade surface mesh is deformed by the help of handles
- ➔ The mesh around the blade aimed to catch the boundary flow is morphed according to the new shape (O-grid topology)
- ➔ The external domain is reconstructed to kept constant dimensions although the package of the fan has changed
- ➔ Automated re-meshing between the O-grid and the external limits of the domain

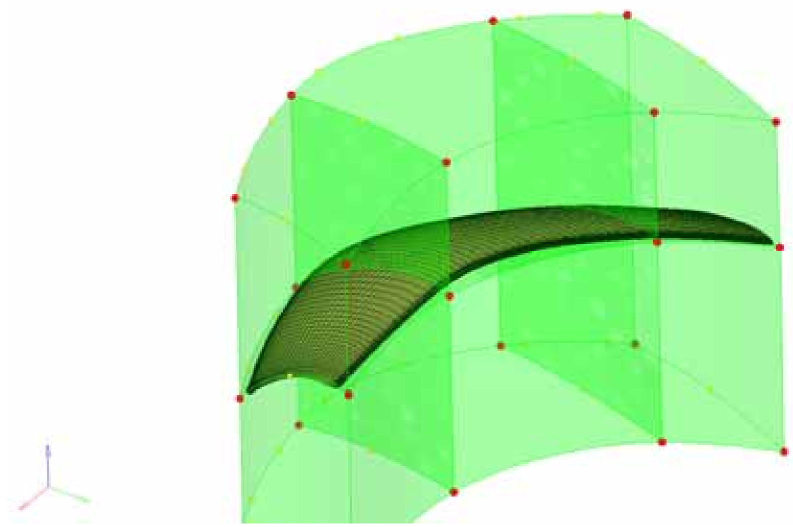




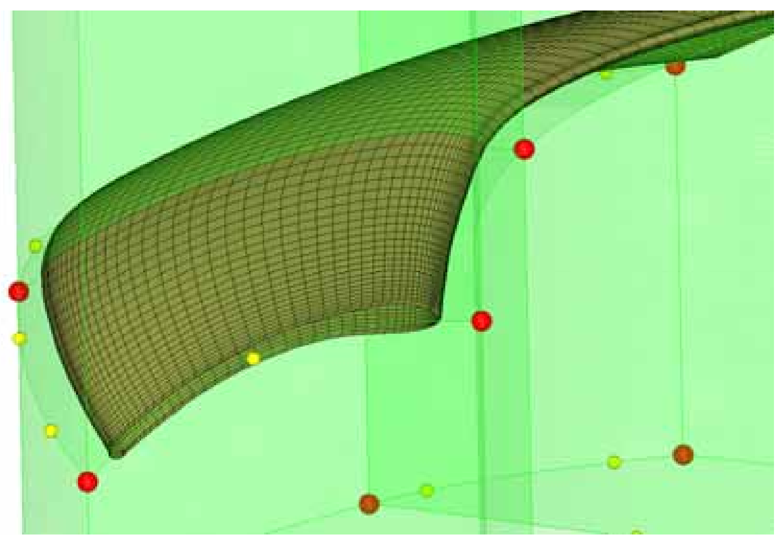
Mesh morphing

Handles control the morphing

- ➔ Handles placed according to the description of a aerodynamic profile: leading edge, trailing edge, mid chord
- ➔ Handles are located at for different radius (bottom, mid-span, ¾ span and top)



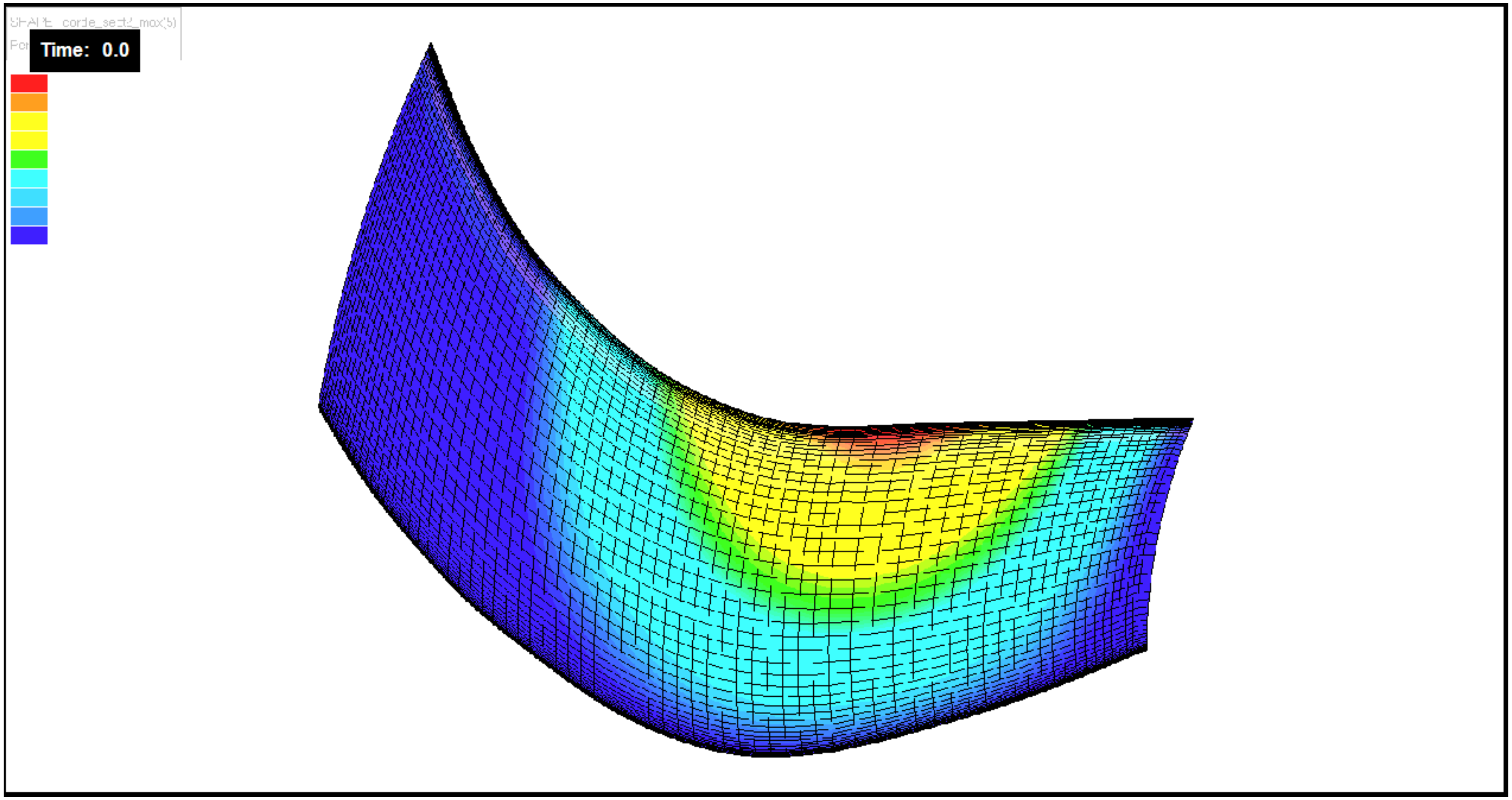
General view of the blade with 4 chosen radius



Locations of handles:
Red = master (can be move independently)
Yellow = slave

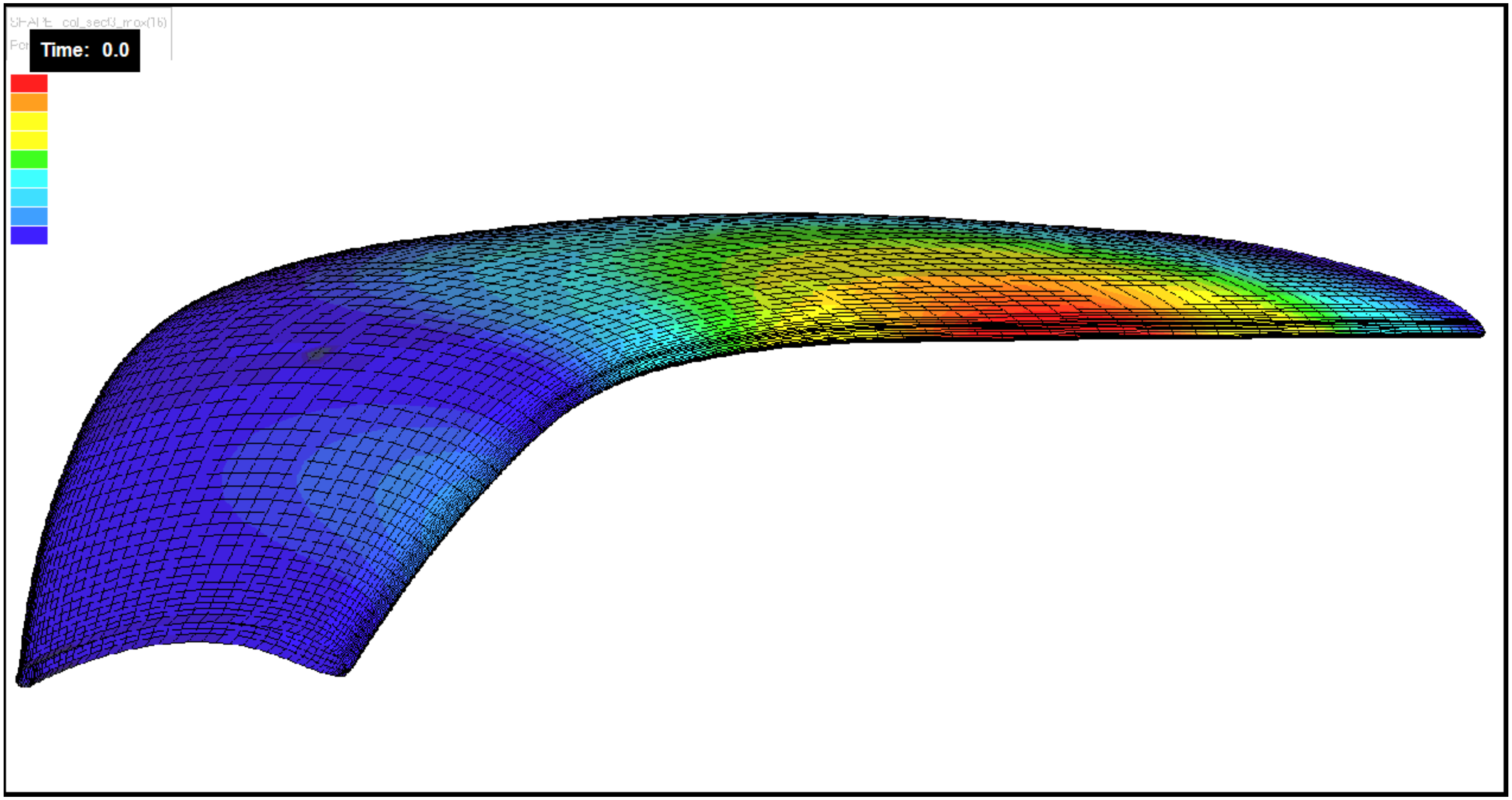
Mesh morphing

- **Chord variation**



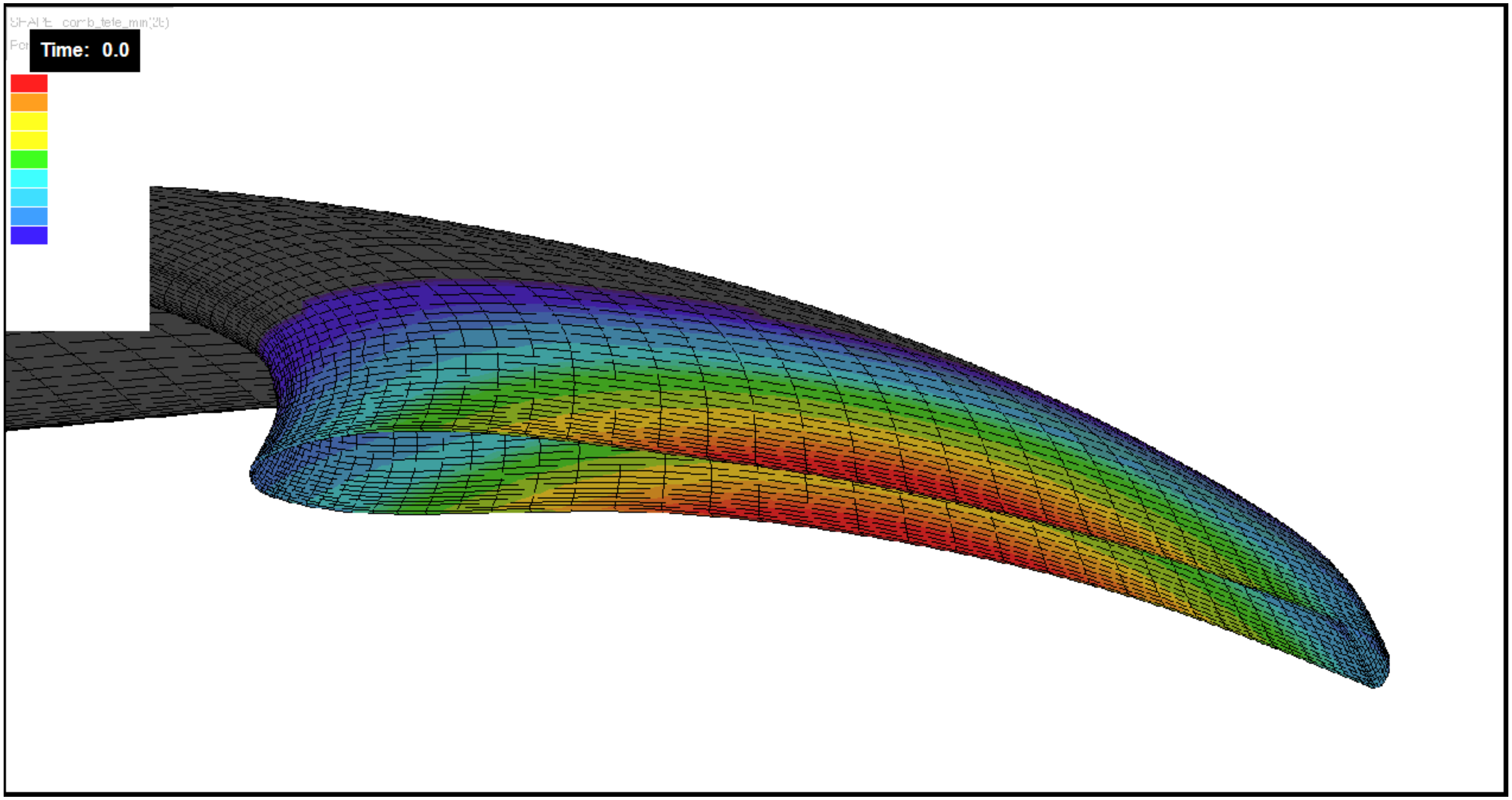
Mesh morphing

- **Stagger angle variation**



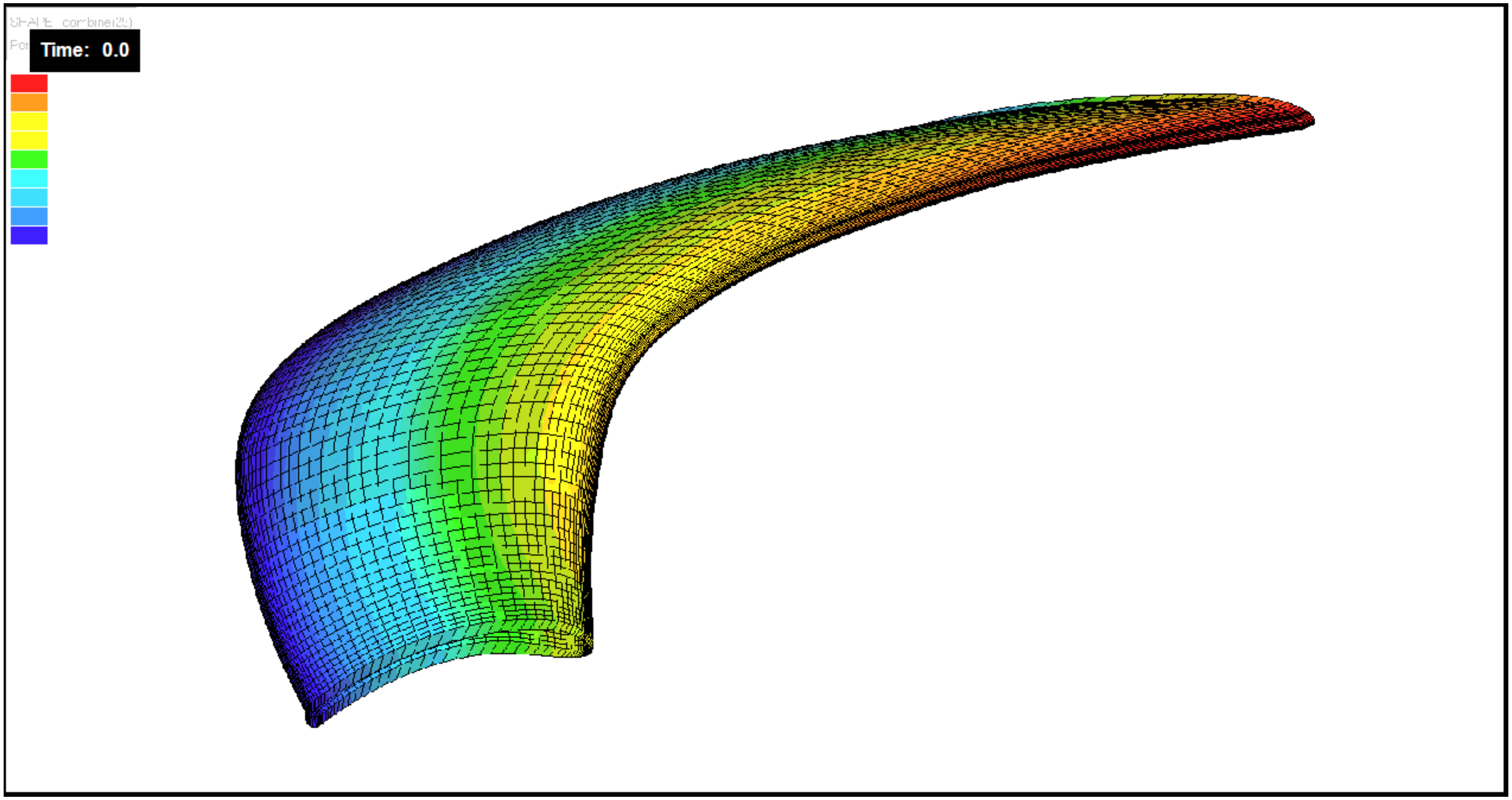
Mesh morphing

- **Camber variation**



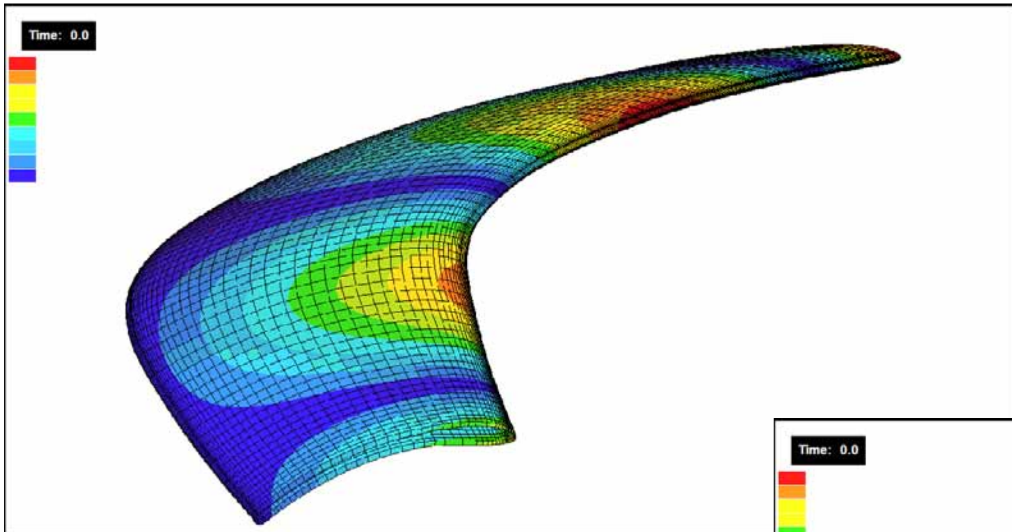
Mesh morphing

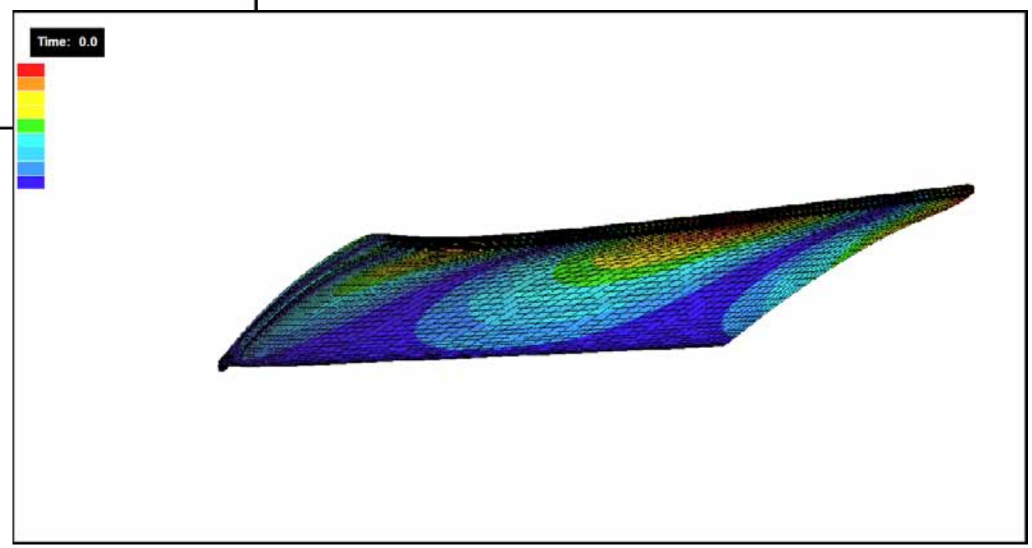
- **Maximum envelope**



Mesh morphing

Some variations



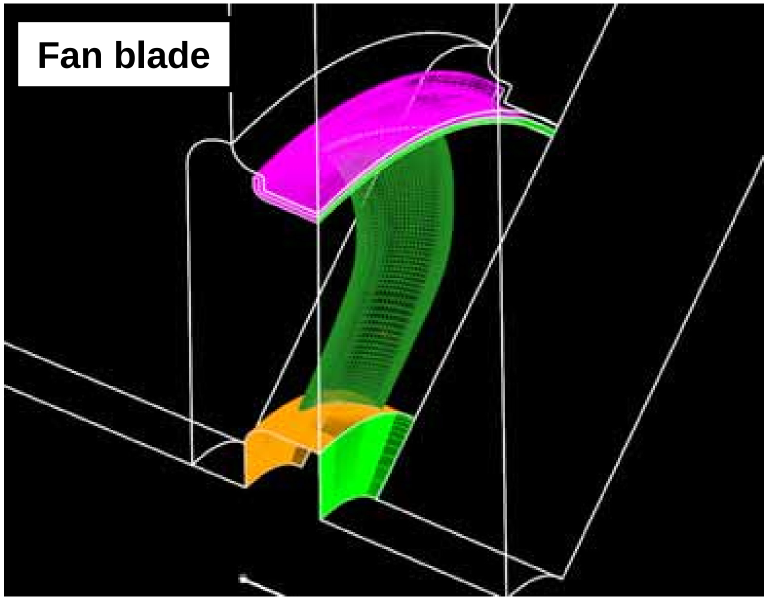


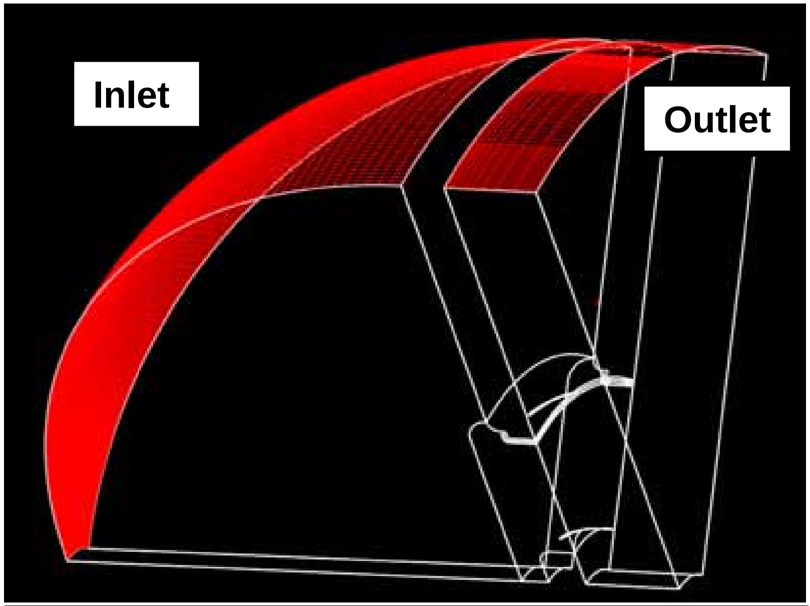
Objective: give a maximum of freedom to the shape

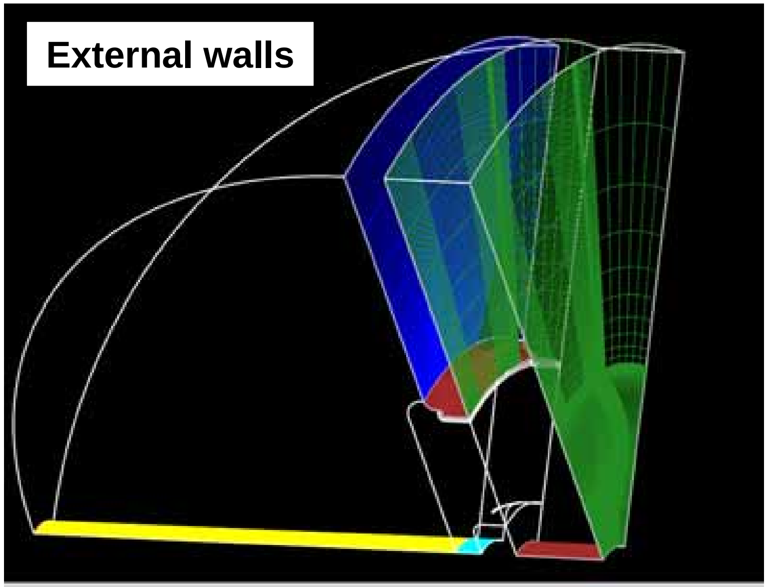
Fan simulation (CFD++)

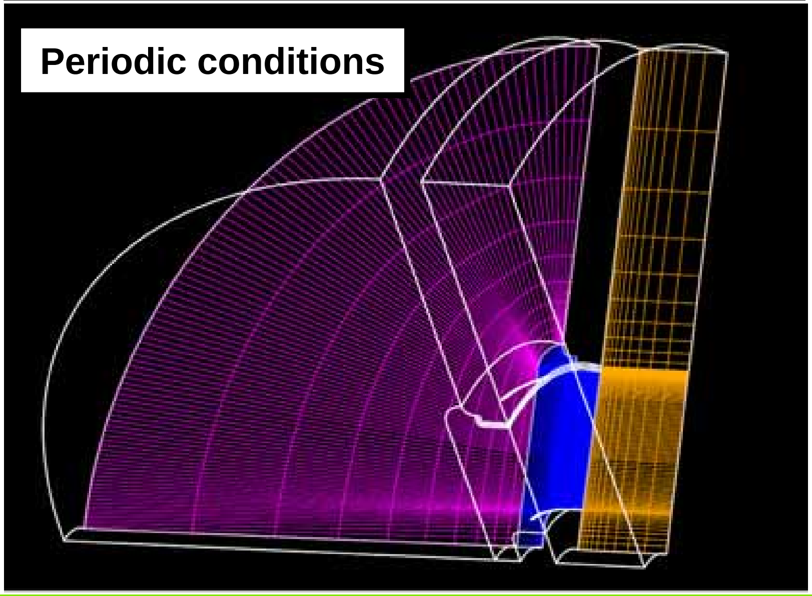
Mesh size: 616 500 nodes / 585 000 cells

(Inlet: 92 500 cells / Fan: 398 000 cells / Outlet: 94 000 cells)









4 – DOE and sensitivities

First set of simulations

- NOLH designs (*Nearly Orthogonal Latin Hypercube***)**
- 65 designs
- Each parameter has only one time the same value
- Theoretically, the distances between each design are maximized

Rayon	85,3	131,88	186,21	209,5	85,3	131,88	186,21	209,5	85,3	131,88	186,21	209,5
copie	**0,9**	**0,9**	**0,9**	**0,9**	**-4**	**-4**	**-4**	**-4**	**0**	**0**	**0**	**0**
	1,1	**1,1**	**1,1**	**1,1**	**4**	**4**	**4**	**4**	**0,8**	**0,8**	**0,8**	**0,8**
	2	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
	corde 1	**corde 7**	**corde 14**	**corde 17**	**calage 1**	**calage 7**	**calage 14**	**calage 17**	**camber 1**	**camber 7**	**camber 14**	**camber 17**
1	1,04	0,91	0,97	0,97	-3	2,13	2,38	-0,13	0,78	0,58	0,44	0,75
2	1,09	1,04	0,92	0,98	-1,25	-2	0,38	2	0,58	0,74	0,61	0,39
3	1,08	0,97	1,09	0,94	-1,63	2,88	-2,75	-0,38	0,33	0,46	0,64	0,7
4	1,03	1,08	1,04	0,99	-3,5	-0,63	-1,88	-1,88	0,1	0,79	0,73	0,5
5	1,08	0,99	0,94	0,9	-3,25	-2,75	-2	0,88	0,49	0,39	0,05	0,68
6	1,01	1,08	0,95	1	-2,75	1,25	-2,88	2,88	0,71	0,09	0,33	0,63
7	1,05	0,94	1,01	0,91	-2	-1,38	3,13	-0,63	0,13	0,35	0,28	0,73
8	1,06	1,05	1,08	0,96	-1	3,38	1,63	-3,88	0,2	0,25	0,01	0,51
9	1,04	0,91	0,9	1,06	-0,75	0,88	-0,88	-3,25	0,64	0,24	0,68	0,31
10	1,09	1,04	1	1,05	-4	-1,75	3,38	-1	0,54	0	0,54	0,03
11	1	0,9	1,09	1,01	-2,38	-0,5	-1,5	1,5	0,01	0,19	0,58	0,15
12	1,1	1	1,04	1,08	-2,63	-3,5	-1	2,5	0,25	0,3	0,43	0,2
13	1,01	0,94	0,97	1,03	-0,88	-0,13	-2,5	-1,75	0,76	0,76	0,11	0,04
14	1,06	1,01	0,98	1,08	-1,88	3,75	-3,63	-4	0,41	0,43	0,2	0,24
15	1,02	0,97	1,06	1,09	-0,5	-2,25	-0,25	3,5	0,11	0,66	0	0,35
16	1,03	1,02	1,01	1,04	-2,88	3,63	4	0,5	0,36	0,65	0,29	0,09
17	1,07	0,99	0,98	0,93	1,38	4	2,25	3,75	0,46	0,48	0,25	0,23
18	1,01	1,07	0,95	0,97	0,63	-0,38	2,63	2,38	0,29	0,59	0,09	0

Second set of simulations

- Extreme values + Hammersley run
- 116 designs
- Fitted for design of experiment

Complement extrême -->	66	0,9000	0,9000	0,9000	0,9000	4,0000	-4,0000	-4,0000	4,0000	0,0000
Complement extrême -->	67	1,1000	0,9000	0,9000	0,9000	-4,0000	-4,0000	4,0000	4,0000	0,8000
Complement extrême -->	68	0,9000	1,1000	0,9000	0,9000	-4,0000	4,0000	-4,0000	4,0000	0,8000
Complement extrême -->	69	1,1000	1,1000	0,9000	0,9000	4,0000	4,0000	4,0000	4,0000	0,0000
Complement extrême -->	70	0,9000	0,9000	1,1000	0,9000	-4,0000	4,0000	4,0000	-4,0000	0,0000
Complement extrême -->	71	1,1000	0,9000	1,1000	0,9000	4,0000	4,0000	-4,0000	-4,0000	0,8000
Complement extrême -->	72	0,9000	1,1000	1,1000	0,9000	4,0000	-4,0000	4,0000	-4,0000	0,8000
Complement extrême -->	73	1,1000	1,1000	1,1000	0,9000	-4,0000	-4,0000	-4,0000	-4,0000	0,0000
Complement extrême -->	74	0,9000	0,9000	0,9000	1,1000	-4,0000	4,0000	4,0000	-4,0000	0,8000
Complement extrême -->	75	1,1000	0,9000	0,9000	1,1000	4,0000	4,0000	-4,0000	-4,0000	0,0000
Complement extrême -->	76	0,9000	1,1000	0,9000	1,1000	4,0000	-4,0000	4,0000	-4,0000	0,0000
Complement extrême -->	77	1,1000	1,1000	0,9000	1,1000	-4,0000	-4,0000	-4,0000	-4,0000	0,8000
Complement extrême -->	78	0,9000	0,9000	1,1000	1,1000	4,0000	-4,0000	-4,0000	4,0000	0,8000
Complement extrême -->	79	1,1000	0,9000	1,1000	1,1000	-4,0000	-4,0000	4,0000	4,0000	0,0000
Complement extrême -->	80	0,9000	1,1000	1,1000	1,1000	-4,0000	4,0000	-4,0000	4,0000	0,0000
Complement extrême -->	81	1,1000	1,1000	1,1000	1,1000	4,0000	4,0000	4,0000	4,0000	0,8000
un tirage dit de Hammersley	1	0,9011	1,0728	0,9508	1,0295	2,4134	0,5059	1,1689	1,1459	0,1643
un tirage dit de Hammersley	2	0,9022	1,0148	0,9176	0,9013	-1,1999	0,6841	0,5373	-0,1887	0,1163
un tirage dit de Hammersley	3	0,9033	0,9255	1,0619	1,0481	1,4244	3,9262	0,4149	-1,5214	0,2217
un tirage dit de Hammersley	4	0,9044	1,0071	0,9328	0,9776	-1,4591	-1,2378	0,4956	-1,0296	0,6303
un tirage dit de Hammersley	5	0,9055	1,0957	0,9670	0,9909	-2,8725	-2,9943	2,0093	-1,9189	0,1705
un tirage dit de Hammersley	6	0,9066	0,9933	0,9808	1,0250	-3,8134	1,3546	3,9562	-2,8254	0,0362
un tirage dit de Hammersley	7	0,9077	1,0338	0,9027	0,9417	-0,6654	-2,3189	-1,0741	3,2272	0,2176

Result Analysis

Correlation

- 65 designs (NOLH) + 116 designs (Hammersley)
- Low correlations between parameters: all are useful (green area)
- High correlation between objectives: non independent (blue area)

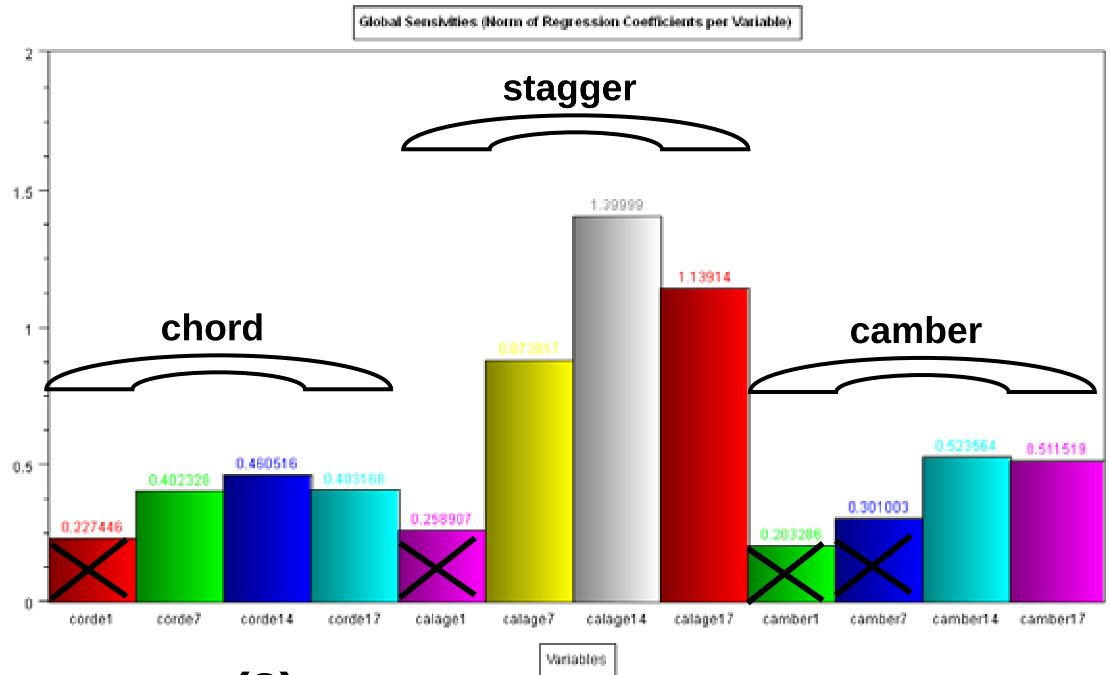
- [-1, -0.67]
-]-0.67, -0.33]
-]-0.33, -5.6e-17]
-]0, 0.33]
-]0.33, 0.67]
-]0.67, 1]

	Dp2300	T2300	Eff2300	Dp4000	T4000	Eff4000	corde1	corde7	corde14	corde17	calage1	calage7	calage14	calage17	camber1	camber7	camber14	camber17
Dp2300	1	0.96	0.86	0.82	0.88	0.8	0.15	0.15	0.12	0.22	0.091	0.39	0.6	0.52	0.18	0.079	0.019	-0.33
T2300	0.96	1	0.68	0.87	0.95	0.86	0.094	0.079	0.082	0.19	0.077	0.39	0.72	0.48	0.09	0.055	-0.088	-0.27
Eff2300	0.86	0.68	1	0.55	0.57	0.53	0.2	0.21	0.16	0.22	0.092	0.31	0.28	0.47	0.29	0.093	0.2	-0.36
Dp4000	0.82	0.87	0.55	1	0.9	0.98	0.025	0.18	0.094	0.15	0.005	0.45	0.6	0.52	0.1	-0.14	-0.24	0.06
T4000	0.88	0.95	0.57	0.9	1	0.9	0.1	0.092	0.066	0.12	0.094	0.34	0.72	0.45	0.079	-0.045	-0.3	-0.27
Eff4000	0.8	0.86	0.53	0.98	0.9	1	-0.0086	0.12	0.11	0.11	0.027	0.42	0.61	0.5	0.069	-0.14	-0.26	0.02
corde1	0.15	0.094	0.2	0.025	0.1	-0.0086	1	-0.018	-0.0075	0.0061	-0.056	0.014	0.056	0.019	0.11	0.017	0.022	0.017
corde7	0.15	0.079	0.21	0.18	0.092	0.12	-0.018	1	-0.12	0.026	-0.028	0.029	-0.041	0.023	-0.014	0.039	-0.062	-0.018
corde14	0.12	0.082	0.16	0.094	0.066	0.11	-0.0075	-0.12	1	0.029	-0.012	-0.13	0.0078	-0.044	0.075	-0.053	0.025	0.055
corde17	0.22	0.19	0.22	0.15	0.12	0.11	0.0061	0.026	0.029	1	-0.046	-0.038	0.1	-0.072	-0.011	-0.12	-0.0024	0.023
calage1	0.091	0.077	0.092	0.005	0.094	0.027	-0.056	-0.028	-0.012	-0.046	1	-0.0028	-0.027	-0.052	0.12	-0.1	-0.11	-0.03
calage7	0.39	0.39	0.31	0.45	0.34	0.42	0.014	0.029	-0.13	-0.038	-0.0028	1	0.0072	0.091	0.077	-0.057	0.041	-0.058
calage14	0.6	0.72	0.28	0.6	0.72	0.61	0.056	-0.041	0.0078	0.1	-0.027	0.0072	1	0.036	0.022	0.12	-0.036	-0.093
calage17	0.52	0.48	0.47	0.52	0.45	0.5	0.019	0.023	-0.044	-0.072	-0.052	0.091	0.036	1	0.034	0.034	0.063	-0.016
camber1	0.18	0.09	0.29	0.1	0.079	0.069	0.11	-0.014	0.075	-0.011	0.12	0.077	0.022	0.034	1	0.024	-0.042	-0.07
camber7	0.079	0.055	0.093	-0.14	-0.045	-0.14	0.017	0.039	-0.053	-0.12	-0.1	-0.057	0.12	0.034	0.024	1	0.0058	-0.1
camber14	0.019	-0.088	0.2	-0.24	-0.3	-0.26	0.022	-0.062	0.025	-0.0024	-0.11	0.041	-0.036	0.063	-0.042	0.0058	1	-0.069
camber17	-0.33	-0.27	-0.36	0.06	-0.27	0.02	0.017	-0.018	0.055	0.023	-0.03	-0.058	-0.093	-0.016	-0.07	-0.1	-0.069	1

Result Analysis

Global sensitivities

- ➔ All parameters count, with different loads
- ➔ Stagger is the main parameter
- ➔ Chord 14 (80% span) is the most important location



Reduce set of parameters (8)

- ➔ Parameters at bottom can be rejected at first (chord, stagger, camber)
- ➔ Camber at mid span is also rejected

4 – Optimization

Optimisation with Adaptative Surface Response Method (ARSM)

➔Parameters at bottom and camber at mid span are disabled

Design variables

	On	Label	Variable Name	Model Parameter	Variable Type
▶	☐	dv1	m_1_corde_pied	m_1.corde_pied	Design
	☐	dv2	m_1_cal_pied	m_1.cal_pied	Design
	☐	dv3	m_1_camb_pied	m_1.camb_pied	Design
	☑	dv4	m_1_corde_sect2	m_1.corde_sect2	Design
	☑	dv5	m_1_cal_sect2	m_1.cal_sect2	Design
	☐	dv6	m_1_camb_sect2	m_1.camb_sect2	Design
	☑	dv7	m_1_corde_sect3	m_1.corde_sect3	Design
	☑	dv8	m_1_cal_sect3	m_1.cal_sect3	Design
	☑	dv9	m_1_camb_sect3	m_1.camb_sect3	Design
	☑	dv10	m_1_corde_tete	m_1.corde_tete	Design
	☑	dv11	m_1_cal_tete	m_1.cal_tete	Design
	☑	dv12	m_1_camb_tete	m_1.camb_tete	Design

➔Minimize the torque (in absolute value)

Define objective

Goal: Maximize

	On	Label	Varname	Apply On	Evaluate from
▶	⊙	Objective_1	obj_1	torque_rpm230	SOLVER

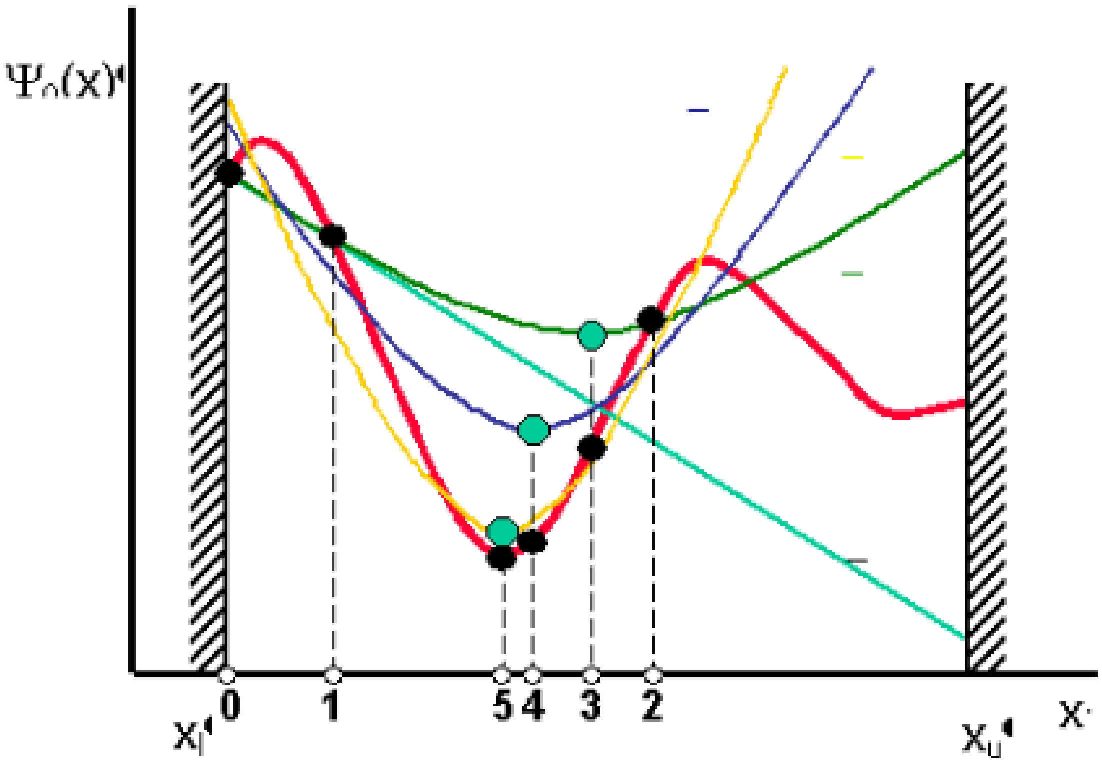
➔ 2 constraints on the pressure rise

Define constraints

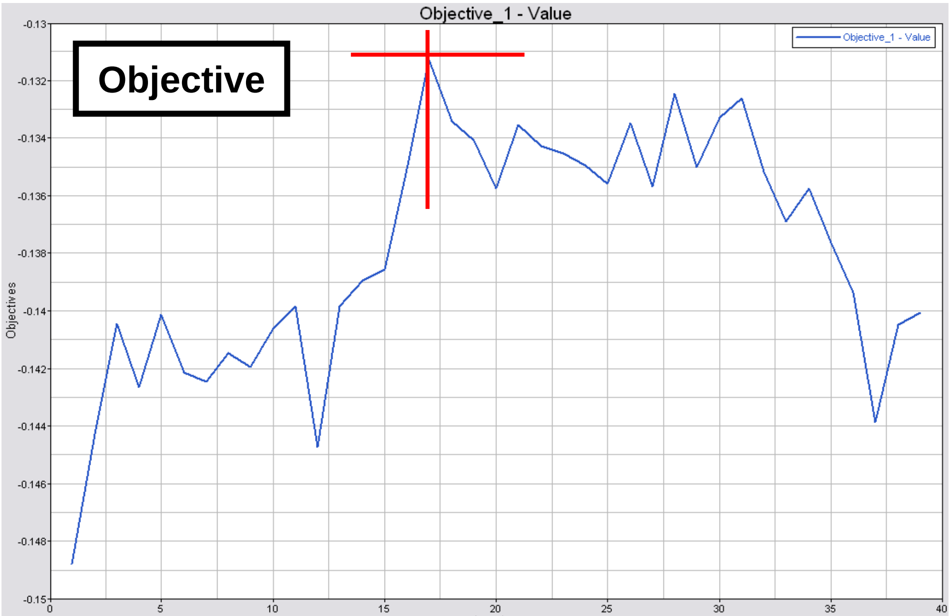
	On	Label	Varname	Type	Apply Constraint On	Bound Type	Bound Value	CDF Limit	Evaluate From
▶	☑	Constraint_1	c_1	Deterministic	delta_p_rpm2300	>=	210.00000		SOLVER
	☑	Constraint_2	c_2	Deterministic	delta_p_rpm3500	>=	0.0000000		SOLVER

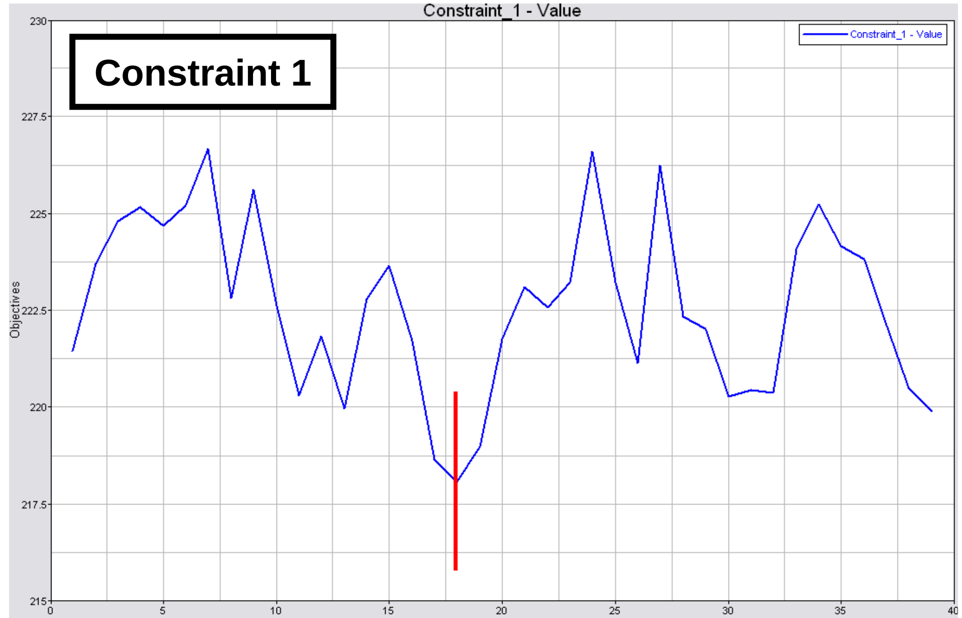
Optimisation with Adaptative Surface Response Method (ARSM)

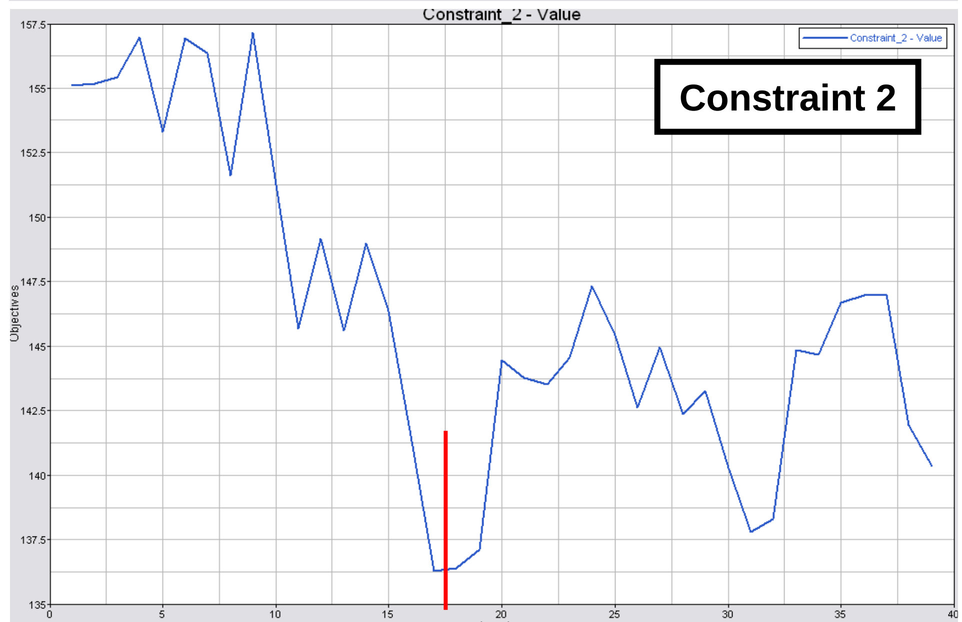
- ➔Objectives and constraints are approximated with a second order polynomial
- ➔The polynomial coefficient are determined using a square fit on previous design points
- ➔ Stop when converged bellow a certain level of error from one iteration to the other



Convergence of the process



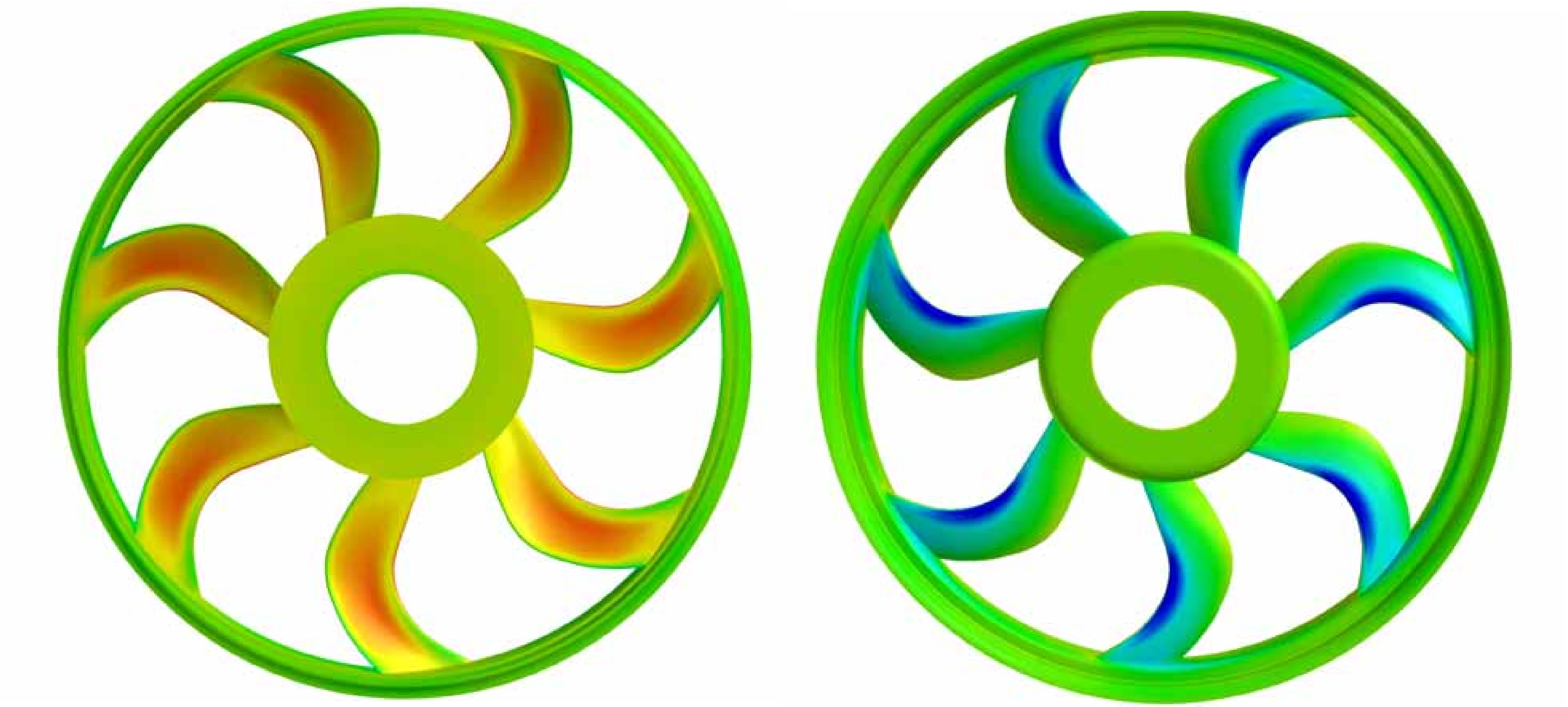




	Pressure rise	Torque	Efficiency (%)
Initial Run	221,45 Pa	1,0416 N.m	54,0
Optimized shape	218,65 Pa	0,9184 N.m	60,5

- ➔Great improvement on the objective (+6.5%)
- ➔ Constraint are still met
- ➔ not so much iterations

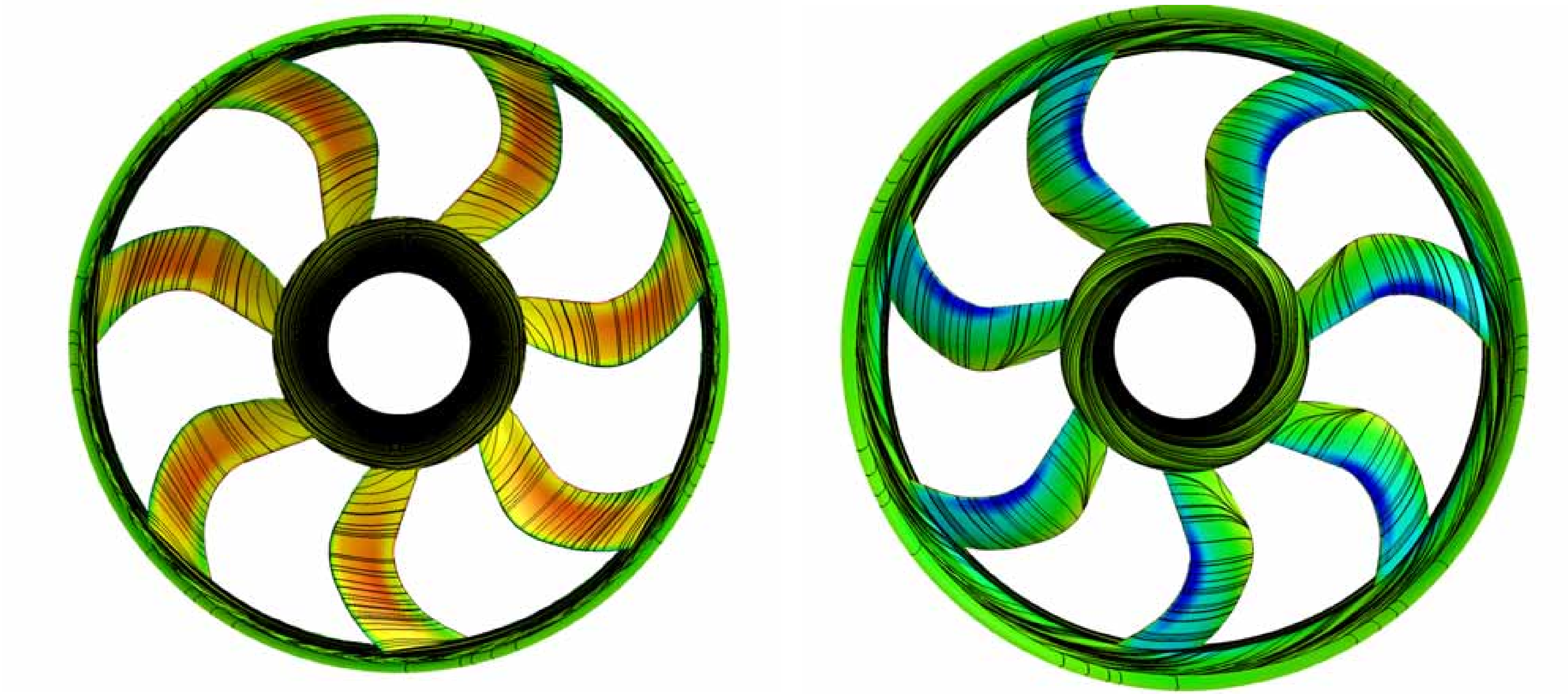
Result: pressure distribution on the optimized blade



➔ The fan blade is not highly loaded at the top, probably a consequence of the objective of reducing the torque (pressure momentum increases with radius)

➔ Low load at tip may improve the acoustic

Result: radial distribution on the optimized blade

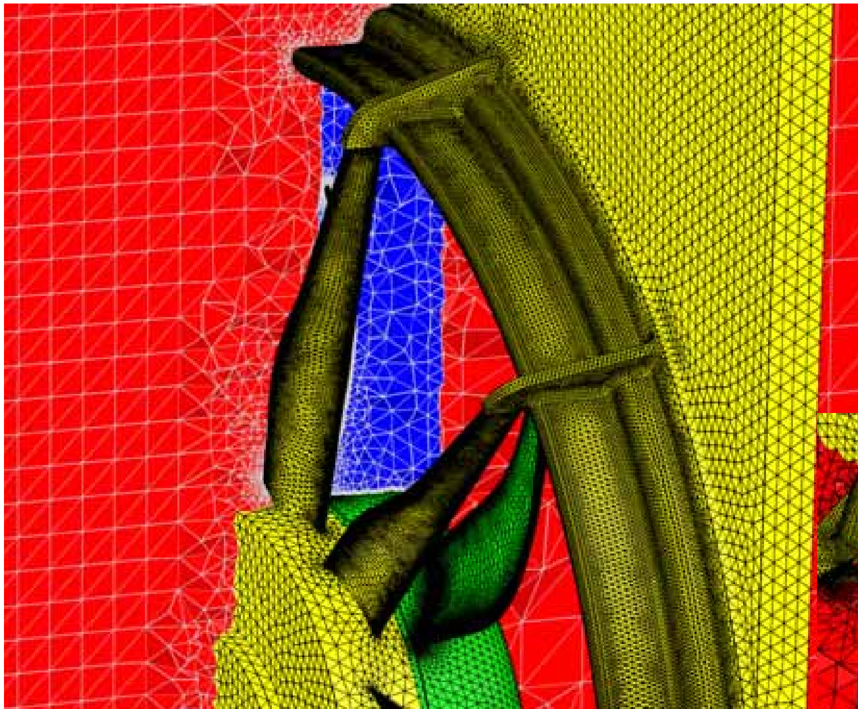


➔The optimization went naturally to a radially equilibrated fan (concentrically flow pattern on the blade), which is in theory the optimum

➔Less good at bottom, where parameters were disabled for the reduced set

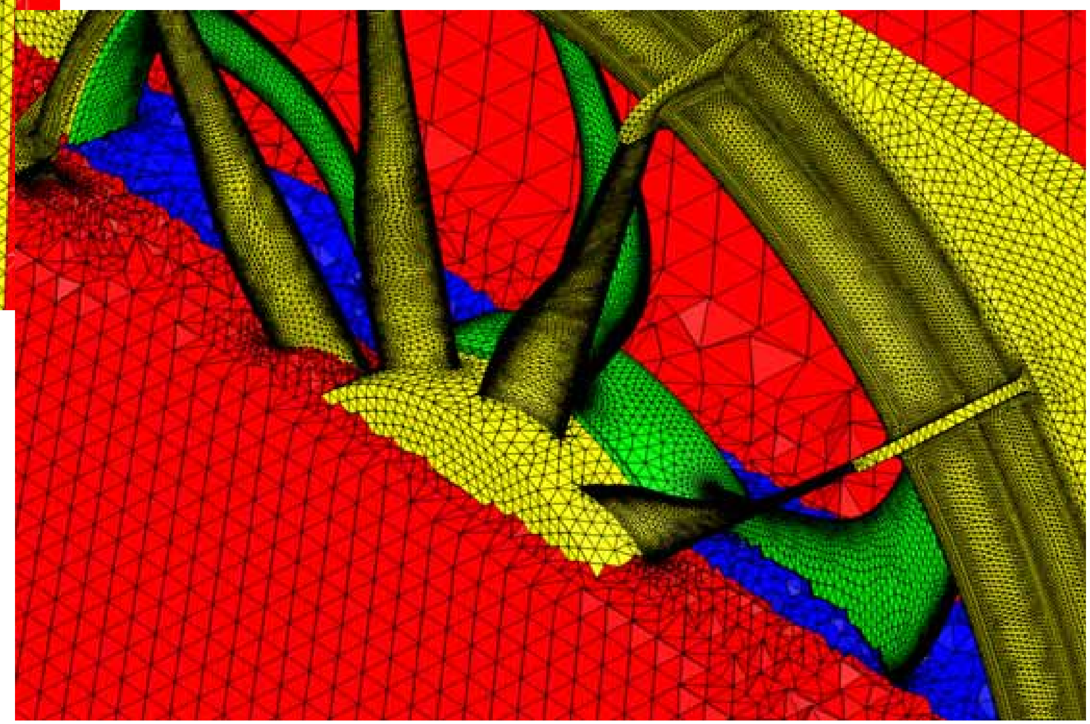
5 – Aeroacoustic

Aeroacoustic: module simulation (CFD++ / CAA++)



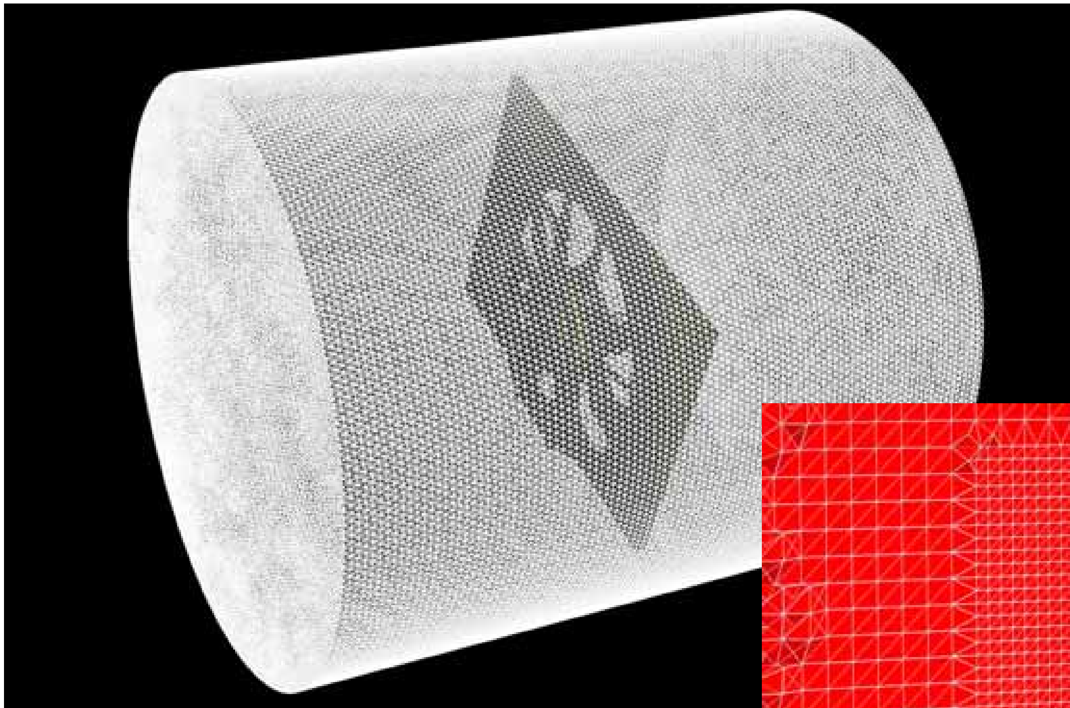
Aeroacoustic capabilities provided by the simulation:

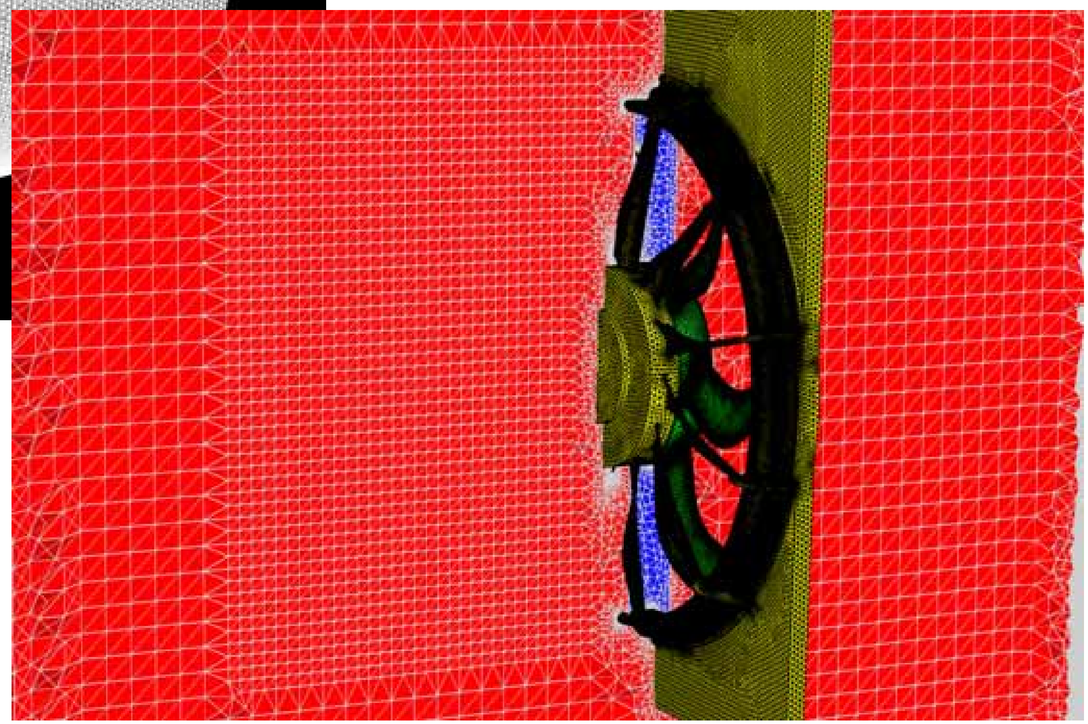
➔ A complete mesh of the module (rotor-stator interaction) is build to predict pressure fluctuation on surfaces



➔ Regular mesh required for propagation

Aeroacoustic: sound propagation and directivities





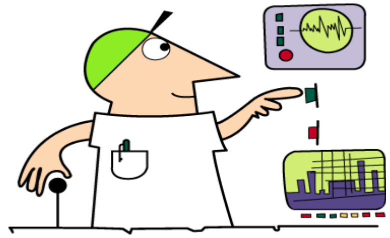
➔ Tonal noise is predicted from pressure post-processing

➔ Domain of propagation allows studies on directivities

➔ Provide data to understand noise mechanism and related geometrical effects

6 – Conclusions

Conclusions: results



- **Fan systems optimisation**
  - ➔ Main parameters were chosen by expert in charge of fan system development
  - ➔ Analysis of sensitivity was conducted to check the relevancy of these parameters
  - ➔ A reduce set of parameters was used to perform a optimisation

- **Optimization results**
  - ➔ A complete loop of optimization has been established on Hyperworks platform linked to CFD++ to evaluate the fan performance
  - ➔ Despite the initial run started from a blade considered as good, a great improvement (+6,5%) on efficiency was obtained in few iterations

- **Gain on the methodology**
  - ➔ The development time can be reduced from one month with the “standard human process” to less than one week with a reduced set of parameters
  - ➔ High power computing can even improve the process to 2 days of simulation with the complete set of 12 parameters (estimated time, work on progress)

Conclusions : the role of an optimization process

- **Standard design process is more complicated regarding new specifications**
  - ➔ Some risks exist wit classical methods: no solution found in the timeframe or bellow the optimum

- **Optimization process should secure the situation**
  - ➔ Establish the methodology helps capture the current know-how and the expertise
  - ➔ Several preferred solutions can be evaluated by accurate numerical simulations

- **Need to concentrate our human resources on system analysis**
  - ➔ Less human time on fan development
  - ➔ Going further in our research (acoustic, module, under hood…)

Product design must be automated by the help of optimization process
R&D efforts must be focused on innovation

Valeo

Enabling a better automotive world