Meta-model Based Optimization of a Large Diameter Semi-radial Conical Hub Engine Cooling Fan

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Abstract :

The conception of a new turbomachinery design requires numerous operating envelopes of different geometries. The design process is, consequently, time-consuming due to high experimental cost. We proposed to use a new methodology with a parametrized geometry operating envelope using CFD computations. Our methodology involved an elusive art of meta-model based optimization. It is applied to the design of a new concept of engine cooling fan, the aim of which is to find a design of weaker torque and higher static efficiency. Firstly, a new concept engine cooling fan has been proposed to better integrate the underhood environment of the automotive vehicle. From this design, an optimization is done with the method. By a mesh morphing technique based on the Radial Basis Function, the computational geometry is parametrized, so that, a geometry database is constructed. The aerodynamic database is built whereafter by a CFD solver. The database is firtly extrapolated with a second order sensitivity method. Then a genetic-algorithm optimizer is employed to explore on the meta-model. One of the optima is found to improve the efficiency by 3.05%.

Mots clefs : **meta-model ; optimization ; parametrization**

1 Study context

Fan systems are used in automotive engine cooling module to increase air flow rate through heat exchangers. These latter are used for the thermal management of the vehicle, both for the engine with the radiator or the charge air cooler, or for the cabin climate control.

The willing to decrease power consumption of all electrical accessories in the vehicle pushes to improve the efficiency of the fan system. For the classical shrouded fan which has a tip ring, the tip gap flow is one of the main causes of loss, so called tip losses. L.Soulat [7] has proposed a new casing treatment for a classical Valeo fan, the analogue has demonstrated the potential to improve the fan performance by limiting the tip inverse flow. Because the tip flow is consequently impacted by this modification, in reality, the direct casing treatment does not necessarily improve the performance. The further study by M.Buisson [1] has successfully enhanced the fan performance by re-adapting the fan design according to the modified tip flow.

With the absence of the tip ring, a new concept of semi-radial fan providing high performances has been proposed. The current study presents the methodology used to conduct the optimization of this axial wheel.

2 Initial improved design

For a conventional cylindrical hub fan, it has been observed that the lower radius part of the fan blade contributes very little to guide the air flow through the fan passage, in fact, often a local separation region is seen near the hub, which deflects the main air flow and brings significant losses. This is mainly due to the fact that the downstream flow creates a stagnation region, and consequently an adverse pressure gradient due to the presence of back-plate. The conical hub can effectively relax this situation by deflecting the fluid radially. This is the origin of the idea of a conical hub.

Following this idea, a first conception study has been performed and eventually a new concept fan is proposed with three innovative points comparing with the conventional engine cooling fan:

- Conical hub, as explained previously, the flow is driven radially, more work is imposed to the fluid by shifting the rotating flow to higher radius.
- Absence of tip-ring. The wetted area is effectively reduced due to the absence of tip ring, it allows to reduce the torque due to viscous effect, and eventually gain efficiency, lower the cost of electrical motor.
- Reduced number of blade. In the same sense, the torque can be largely reduced with less blades.

The fan geometry in the current study is an optimized geometry coming from this new conception. The radius of hub at the inlet and outlet are 110 mm and 132 mm respectively. The chord length at hub and tip measure 104 mm and 81 mm respectively. The blade tip radius is 212 mm with tip gap of 2.4 mm. Provided a flow rate 2300 m^3/h and rotation speed 2800 rpm, this configuration gives an augmentation of pressure 235.1 Pa, torque 0.8808 Nm, which result in an efficiency 58.16%.

3 Proposed methodology

Regarding the classical fan blade design procedure, there are mainly 4 principal elements :

- A procedure to describe and modify the mesh through its geometrical control parameters ;
- A numerical simulation with classical solver ;
- A database building with meta-model ;
- An optimization method .

The 4 steps are fulfilled by 4 tools in the current study :

- Turb'Mesh : continuous unstructured mesh deformation that depends on geometrical parameters;
- SC/Tetra : incompressible pressure based RANS finite volume solver with Menter turbulence model ;
- Meta-model : database building with polynomial extrapolation ;
- NSGA-2 : a genetic algorithm to explore database and to find the multi-objective solutions .

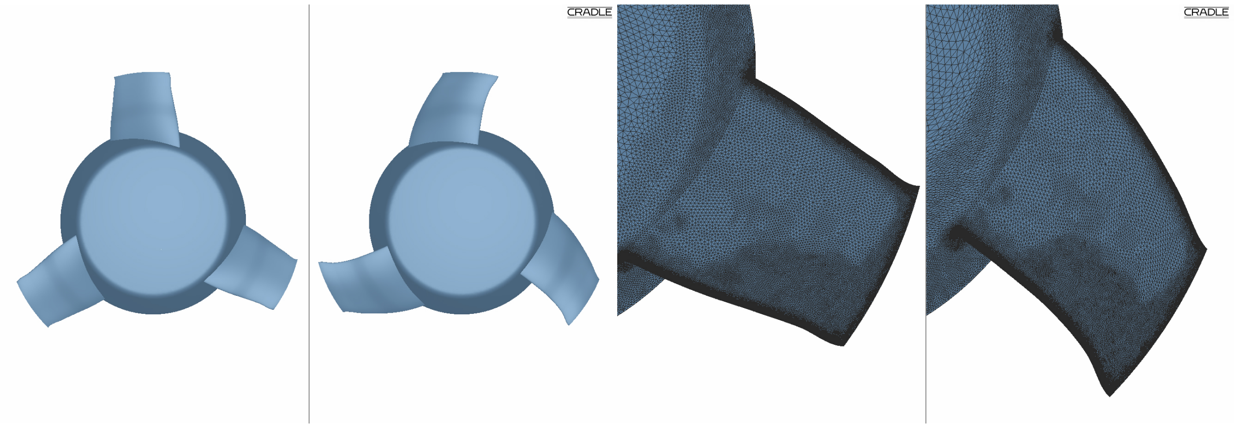
A meta-model is constructed based on the new geometry with selected variables and objectives, and optimizations are realised to find several optima corresponding to different criteria. This is the methodology proposed in this paper.

Three objectives are chosen for the current study, they are the static pressure rise ΔP, the torque T and the efficiency η.

3.1 Selection of control variables and mesh deformation

Based on this existing geometry, four parameters are considered to modify the fan geometry tridimensionally. Stagger angles at hub(γ_{hub}), mid-span(γ_{mid}) and tip(γ_{tip}) are classical variables used for fan geometry design, in addition, an user defined parameter is taken into account: sweep(S).

The sweep parameter is defined to modify all the 3 sweep angles on the hub, mid-span and tip sections. The deformation is done in this fashion that the sweep angle at hub section and the sweep angle at tip section have inverse variation (Figure 1), the sweep angle at mid-span does not vary. A positive sweep angle leads the hub section forwards and the tip section backwards in the sens of the rotating direction.



(a) Geometry view

(b) Surface mesh

Figure 1: Example of deformation: Sweep - 8°

The current study is based on one single unstructured mesh, which is generated with the help of octant blocks technique.

The mesh deformation tool Turb'Mesh relies on a morphing technique based on Radial Basis Function (RBF). Constraints are imposed to the hub and shroud to keep their radius at different axial position.

3.2 Database building and optimization approach

The meta-models are initially developed as surrogates of the expensive simulation process in order to improve the overall computation efficiency. The objectives can be directly extracted from the meta-model for specific parameter inputs.

The parametrization technique provides significant advantages for understanding the flow behavior. The next step is to take advantage of this technique and construct a surrogate model which could actually be used for the optimization purpose. The parametrization study returns the derivatives of the objectives with respect to each parameter, which allows us to figure out the second order Taylor polynomials for 3 objective functions.

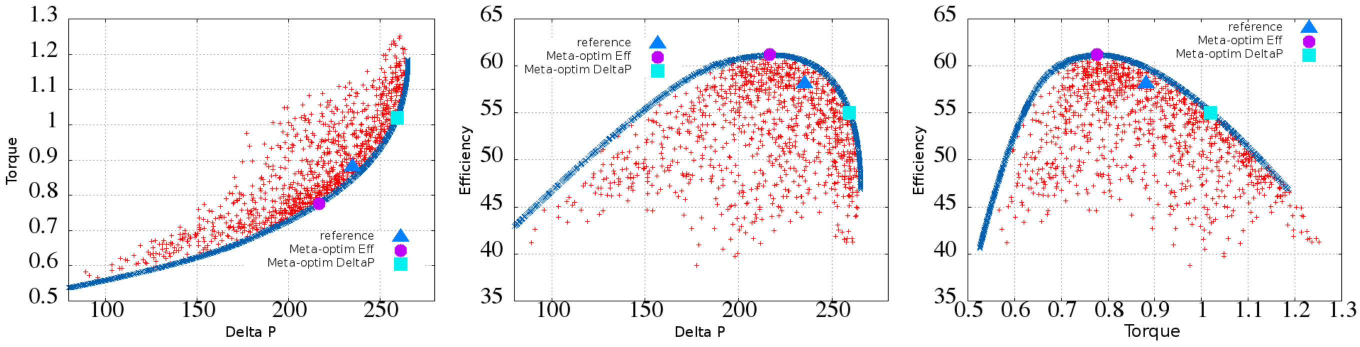
The original configuration has an efficiency of 58.16%, as summerized in Table 1. The range of extrapolation differs among parameters because the validated deformation ranges are different for different parameters. Taking the stagger angle at hub for example, the range is [-2°2°] comparing with [-4°4°] for the stagger angle at mid-span, because the validated range is limited by one of "fixing radius" constraints on the conical hub. The sweep angle can be validated up to ±8°, as it is shown in the Figure 1.

Once the meta-model is built, the optimization can be performed. Traditionally, the objectives are paired to form respective Pareto fronts.

The second version of Non-dominated Sorting Genetic Algorithm (NSGA–2) proposed by Srinivas and Deb has been applied in for our multi-objective optimization problem. Due to high dimension of design space, the optimization loop was carried out by taking as much as 1000 individuals over 200 generations.

4 Result analyses

Our methodology provides an improved design which ultimately shows advantages with respect to the initial design(Figure 2).



(a) ΔP-T (b) ΔP-η (c) T-η

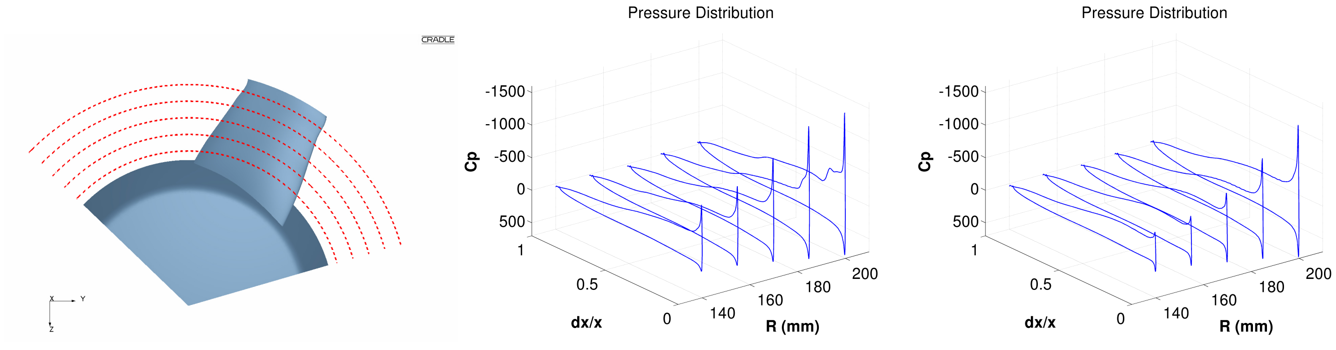
Figure 2: Pareto fronts for 3 objectives

In this Pareto front graph, the red dots are those individuals of the first generation. And the blue line is the Pareto optimal solution, formed by the NSGA–2 optimization tool. The triangle point points to the reference objective values, ΔP 235.1Pa, torque 0.8808Nm and efficiency 58.16%.

Depending on the criteria, different optimal points can be positioned. The filled circle is the maximal efficiency point, which we name "Meta-optim η", even thought the ΔP at this point is a little lower comparing with that of the reference, the efficiency can possibly be increased by 3.05%, and a significant improvement on the torque is also shown according to the optimization.

Provided a requirement on efficiency, say the efficiency not less than 55% for example, another point "Meta-optim ΔP" can be positioned on the graph with a maximum ΔP, which is illustrated as a filled square in Figure 2.

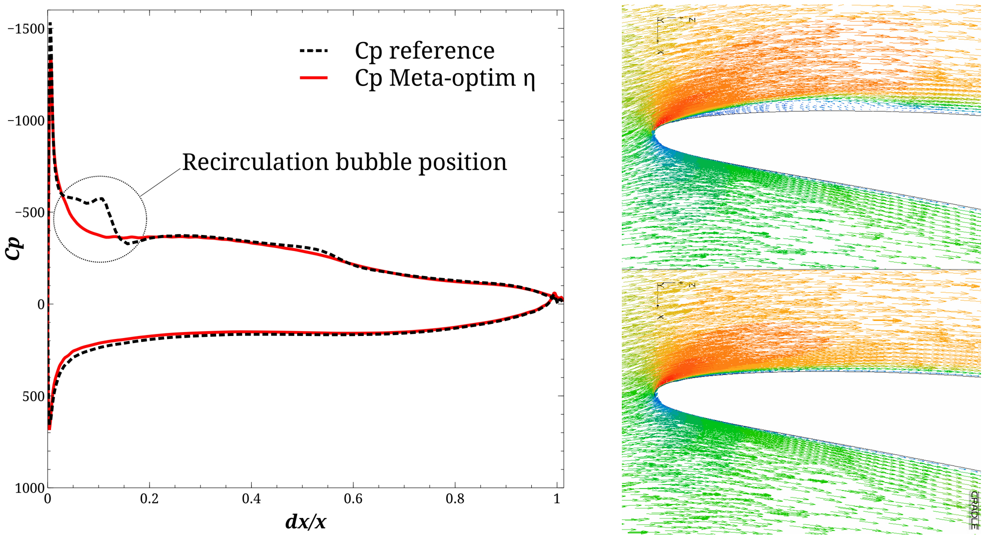
Those two optimal points are further studied by lauching the corresponding CFD runs. The pressure distribution are shown, by comparing the reference and the optimization results: 5 constant radius sections are extracted, from 140mm to 200mm, and their pressure coefficients are calculated by taking the static pressure P_∞ and the dynamic pressure $\frac{1}{2}\rho V_\infty^2$ at the inlet.



(a) Positions (b) Reference (c) Optimum η

Figure 3: Pressure distribution spanwise view (reference and optimum case)

Immediately it is observed from the pressure distribution, the pressure profile at 200mm behaves different with the rest 4 profiles. At greater radius, i.e. at the vicinity of the tip gap, the high adverse pressure gradient at the leading edge has caused separation of the flow, leading to loss and consequently lower efficiency. Depending on the position of maximum camber, the separation may increase the pressure drag of the blade.



(a) Pressure distribution (b) Relative velocity

Figure 4: Comparison at R = 200mm between reference and Meta-optim η configurations

Table 1: Validation of optimizations by CFD run

	Design parameters				Objectives		
	$\gamma_{hub}(°)$	$\gamma_{mid}(°)$	$\gamma_{tip}(°)$	Sweep(°)	ΔP(Pa)	T(Nm)	η
Reference	0	0	0	0	235.1	0.8808	58.16%
Range explored	[-2 2]	[-4 4]	[-5 5]	[-5 5]	-	-	-
Meta-optim η	2.0	2.4	-2.0	0	216.7	0.7762	61.21%
CFD validation η	2.0	2.4	-2.0	0	216.3	0.7668	61.47%
Meta-optim ΔP	1.18	-1.43	-2.98	0.43	259.3	1.0194	55.03%
CFD validation ΔP	1.18	-1.43	-2.98	0.43	254.3	0.9955	55.67%

After the optimization, the separation region has been effectively removed from the leading edge. This is a complex tridimensional effect, since the optimum is found to be [2°, 2.4°, -2°, 0°], i.e. the stagger angle at the tip is reduced by 2°, intuitively, it should charge the blade due to higher incidence. But actually the 2 dimensional profile is discharged. The relative velocity vector is shown in Figure 4b to demonstrate the separation and the reattachment.

The optimum given by the optimization tool shows an improvement on efficiency by 3.05%, with significant less torque acting on the fan. This result has been validated with a corresponding CFD run shown in Table 1. The computation has confirmed this optimum with a slightly higher efficiency (0.26%) and lower torque (0.0094 Nm).

The higher efficiency is found with positive hub stagger angle, positive mid-span stagger angle and negative tip stagger angle, which is the case for the optimization. The sweep angle is found to be already at its optimum value in terms of maximizing efficiency.

Although the configuration optimized has better global aerodynamic performance, the numerical incertitude always present in the current study. For example, the mesh refinement level, the turbulence model used, and so on, can possibly change the meta-model and hence the result of optimization. Experiment validation needs to be performed.

5 Conclusions

Following an initial design, a new concept engine cooling fan was further studied with a meta-model based multi-objective optimization tool assisted by a mesh morphing technique. Derivatives up to second order were calculated with finite difference method. The polynomial meta-model was explored using NSGA-2, and the results were analysed according to different criteria. 3 global performance objectives and 4 geometrical parameters were taken into consideration, in which 2 parameters were found to be the most important for the selected objectives. An optimum was found to be able to raise the efficiency by 3.05%, and reduce significantly the torque which is the main factor determining the cost of the electric motor.

6 Acknowledgement

The current study is part of an on-going project of VALEO powertrain thermal systems group, it is strongly supported by the research team of FLUOREM S.A.S. And the author gratefully acknowledges Cradle Co., LTD for putting into place the software SC/Tetra.

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