Challenges and progress in turbomachinery design systems

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Abstract. This paper first describes the requirements that a modern design system should meet, followed by a comparison between design systems based on inverse design or optimization techniques. The second part of the paper presents the way these challenges are realized in an optimization method combining an Evolutionary theory and a Metamodel. Extensions to multi-disciplinary, multi-point and multi-objective optimization are illustrated by examples.

1. Design System Requirements
Navier Stokes solvers and Finite Element Stress Analysis are now routinely used to predict the performance and verify the mechanical integrity of new geometries. However they do not specify what modifications are needed to improve the performance or to minimize weight while keeping stress and vibrations below some limit values. Although they provide very detailed information, the designer will often base his decisions on overall parameters such as efficiency, pressure ratio and mass flow, leaving huge amounts of information unexploited. Present paper discusses some design systems for turbomachinery applications that have been developed over the years in order to assist the designer in finding the optimal geometry by making better use of the available information.

Further progress in performance requires incorporating all 3D designs features, such as lean and sweep, that may help to improve the performance or to reach other design targets. Limitations or simplifications of the geometry are acceptable only if they are needed to satisfy other design requirements such as manufacturing or in service cost. Design systems for advanced turbomachinery should define the final geometry. Any post design geometry modification may result in a suboptimal geometry.

The quality of a design depends on the accuracy of the analysis methods that have been used. Approximate solvers or surrogate models can only used for a first approximation in order to speed up the design procedures. The use of accurate solvers is mandatory to verify the final geometry because any inaccuracy of the flow solver could drive the design system towards a suboptimal geometry.

The outcome of a design should not only be optimum in terms of aerodynamic/hydraulic performance but should also respect all other objectives such as cost and manufacturing limitations while assuring a safe operation over the preset lifetime. This requires a multi-disciplinary approach (fluids, stress vibration, economics etc) and a delicate balance between the different sometimes contradicting targets.

Guaranteeing a stable operation over a sufficiently large operating range requires a multi-point approach. Designing for maximum efficiency or large operating range may result in different
geometries or impact on the manufacturing cost. **Multi-objective design** systems should be able to find a compromise between these sometimes conflicting objectives.

Computerized designs have the tendency to have peak performance but to be very sensitive to geometrical imperfections. All design parameters are stressed to their limit and even small variations may result in a rapid deterioration of performance. **Robust** design systems provide geometries that are less sensitive to geometrical imperfections and to inherent inaccuracies of the evaluation programs.

An **affordable computer** effort is a prerequisite for a design system to be economically acceptable. Combining all previous requirements in a design system is the major challenge for the developer. Following discusses how advanced design systems respond to these challenges

2. **Inverse design versus Optimization**

Inverse design systems define the geometry that corresponds to a pre-defined Mach number or pressure distribution. This requires a very good insight in fluid dynamics of the designer to find out how an optimum distribution should look like. This is more or less understood for 2D flows and has resulted in controlled diffusion blades. The main problem is to find out how such an optimum distribution is influenced by secondary and tip leakage flows and how to guarantee the geometrical constraints such as minimum or maximum blade thickness (existency problem). The geometry is the outcome of the inverse design so that the mechanical constraints can be verified at the end of the procedure. The latter is often avoided by specifying a thickness- and loading distribution whereby the velocity is then a consequence of the meridional contour [1]. Hence there is no direct control of the local velocity deceleration which according to Lieblein is a major factor influencing the losses.

Inverse methods are often based on simplified (inviscid) flow equations eventually corrected for boundary layer blockage and neglecting secondary flows. The outcome will be different from what would be obtained by solving the real flow equations and the performance cannot be guaranteed. In what follows one will limit our self to optimization systems that are based on the accurate analysis methods commonly used now in industry.

Optimization systems find the geometry that best satisfies the design objectives (OF) expressed in terms of performance, cost etc. while respecting the constraints (max. stress, lifetime). This is illustrated on figure 1 showing the iso-loss contours in function of the two design parameters X₁ and X₂.

![Figure 1. Optimization with two parameters](image)

Objective is to find the combination of the design parameters X₁ and X₂ that result in a minimum loss coefficient \( \omega \) while respecting the constraints. Most systems make use of an iterative procedure and start from an existing geometry (X₀). Simple mechanical and geometrical constraints (\( X₁ < X₁_{\text{max}} \) and \( X₂ < X₂_{\text{max}} \)) can already be verified before any time consuming flow analysis is started. First order methods find the optimum geometry by following the direction of steepest descend. This requires the calculation of the derivatives \( \frac{\partial \omega}{\partial X₁} \) and \( \frac{\partial \omega}{\partial X₂} \), and the calculation of the optimum step length to reach the point X₁. New steps are calculated until the optimum geometry is found (zero gradient) or the path is blocked by a constraint.

Most optimization systems make use of existing and well proven solvers to predict the OF of different geometries so that the outcome is very trustworthy. The large number of analyses that are needed to calculate the gradients and the large number of steps that may be required to reach the
optimum, results in a computational effort that may be prohibitive for most real cases. A first challenge is to reduce this effort by reducing the number of required iterations and/or reducing the computational effort for each iteration.

Adjoint methods allow calculating the steepest gradient with a computational burden that is comparable to the one of an analysis. This requires a modification of the flow solver, excluding the use of “off the shelf” solvers. It also complicates the extension to multidisciplinary designs.

An alternative are the zero-order or stochastic search mechanisms requiring only OF evaluations. The systematic exploration of the design space, indicated by “X” on figure 1, requires only nine OF evaluations to obtain a rather good idea of the optimum geometry. However the number of evaluations increases exponentially with the number of design parameters, leading to prohibitive computer efforts for more complex geometries. Zero order methods have fewer chances to get stuck in a local minimum.

Evolutionary strategies such as Genetic Algorithms (GA), Simulated Annealing (SA), Kriging and many others can accelerate the procedure by replacing the systematic sweep by a more intelligent selection of new geometries using in a stochastic way the information obtained during previous calculations.

A way to reduce the computational burden is by working on different levels of sophistication, combining approximate but fast prediction methods with accurate but time consuming ones [2,3].

Such a system is illustrated on figure 2. The fast but less accurate optimization loop is to the right; the expensive but accurate one is to the left. The OF driving the GA is predicted by means of a Metafunction or surrogate model i.e. an interpolator using the information contained in the Database to correlate the OF to the geometry similar to what is done by the accurate analyzers. Surrogate models have the same input and output as the analysis methods they replace. Once they have been trained on the data contained in the Database, they are very fast predictors and allow the evaluation of the OF of the many geometries, generated by the GA, with much less effort than the accurate solvers. The optimized geometry is then verified by the accurate one. The procedure is stopped when the accurate solver confirms that the surrogate model makes accurate predictions i.e. confirms that the optimizer was driven by accurate predictions. Otherwise a new GA optimization is started after a new learning of the metafunction considering also the new optimized geometries.

The main advantages of such an approach are:

- The existence of only one “master” geometry i.e. the one defined by the geometrical parameters used in the GA optimizer. This eliminates possible approximations and errors when transferring the geometry from one discipline to another.
- The possibility to shorten the design time by making all expensive analyses in parallel
- The existence of a global OF accounting for all disciplines. This allows a concurrent optimization driving the geometry to a compromise between all requirements without iterations between the aerodynamically optimum geometry and the mechanically acceptable one.

3. Multidisciplinary Optimization of a Radial Impeller

Previous approach can easily be extended to multidisciplinary optimization by calculating the different contributions to the OF (performance, heat transfer, stress, etc.) in parallel. The method is illustrated by the design of a radial compressor impeller for a micro-gasturbine application with a diameter of 20 mm rotating at 500,000 rpm [3] The objective is a maximum efficiency while respecting the stress limits.
The first step in an optimization is the parameterization of the geometry. This is a very important issue as it should be sufficiently general, not to exclude the optimal geometry, without increasing the number of design parameters beyond a limit where it starts to slow down or prevent convergence. The 3D radial impeller is defined by the meridional contour (figure 3), in combination with the blade camber line at hub and shroud (figure 4).

The meridional contours are defined by fourth order Bezier curves. Design variables are the six coordinates of the control points that can be varied and indicated by arrows on figure 3. The camberlines are defined by third order polynomials specifying the distribution of the angle $\beta(m)$ between the meridional plane and the camberline (figure 4).

$$\beta(u) = \beta_0 (1-u)^3 + 3\beta_1 u(1-u)^2 + 3\beta_2 u^2 (1-u)^2 + \beta_3 u^3$$

$u$ is the non-dimensional meridional length. $\beta_0$ and $\beta_3$ are the blade angles at leading- and trailing edge. The splitter blades are a short version of the full blades, with the leading edge cut back. The design is completed by a prescribed thickness distribution normal to the camber line and the number of blades. The latter could also be a design parameter to be optimized, but has been fixed to 7 for manufacturing reasons. A parameterization with more degrees of freedom is described in [4].

The $OF$ to be minimized is a weighted sum (weight factor $w$) of three penalties:

$$OF(\bar{G}) = w_{stress} \cdot P_{stress}(\bar{G}) + w_{q} \cdot P_{q}(\bar{G}) + w_{massflow} \cdot P_{massflow}(\bar{G}) + w_{Mach} \cdot P_{Mach}(\bar{G})$$

The first one concerns the mechanical stresses and starts increasing when the maximum von Mises stress in the impeller $\sigma_{max}$ exceeds a prefixed value $\sigma_{allowable}$.

$$P_{stress} = \max \left[ \frac{\sigma_{max} - \sigma_{allowable}}{\sigma_{allowable}}, 0.0 \right]$$

Expressing this constraint as a penalty does not guarantee that it is respected but has the advantage that all geometries that have been analyzed provide information that leads the GA towards the optimum geometry.

The mass flow penalty increases when the error exceeds .3% of the required mass flow ($\dot{m}_{req}$) and with the difference in mass flow between the blade channels on both sides of the splitter blade. The latter favours an equal blade loading between splitter and full blade and improves the periodicity of the impeller exit flow.
The penalty on the Mach number penalizes non-optimal loading distributions. The first part increases with negative loading. The second part increases with the loading unbalance between main blade and splitter blade. It compares the area between the suction- and pressure side Mach number distribution of main blade $A_{bl}$ and splitter blade $A_{sp}$, corrected for the difference in blade length.

$$P_{\text{Mach}} = \int_0^1 \max \left[ M_{ps}(s) - M_{ss}(s), 0.0 \right] ds + \left( \frac{A_{bl} - A_{sp}}{A_{bl} + A_{sp}} \right)^2$$

![Figure 5. Negative loading and loading unbalance in a compressor with splitter vanes.](image)

![Figure 6. Aero - versus stress penalty for baseline, database- and optimization geometries.](image)

![Figure 7. von Mises stresses due to centrifugal loading in the baseline (left) and optimized (right) impeller.](image)
The optimization starts from the outcome of a simple aerodynamic optimization without stress computation, called “Baseline” impeller. Although this geometry has a good efficiency, it cannot be used because a FEA stress analysis predicts von Mises stresses in excess of 750 MPa. The initial database contains 64 geometries selected by the DOE technique. About 40 optimization cycles are needed to obtain a good agreement between ANN predictions and the NS and FEA analyses. It means that the optimization is achieved with only 100 NS and FEA analyses.

The aero penalty is plotted versus the stress penalty in figure 6. The geometries created during the optimization cycles are all in the region of low penalties. Most of them outperform the geometries of the Database. From all geometries at zero stress penalty, the one with minimum aero penalty is the optimum. The reduction of the maximum stress level with 370 MPa is at the cost of a 2.3 % decrease of efficiency.

Figure 7 compares the von Mises stresses in the baseline geometry with the optimized one. The drastic reduction in stress is the consequence of:
- the reduced blade height at the leading edge, resulting in lower centrifugal forces at the leading edge hub
- the increase of blade thickness at the hub
- the modified blade curvature resulting in less bending by centrifugal forces

4. Robust Design
Robustness expresses the in-sensitivity of the design to manufacturing noise, variations in the operating conditions and inaccuracies of the OF calculations. It is normally verified a posterior by perturbing the geometrical and operating parameters. Doing this by means of the accurate metafunction, available at the end of the design, allows very large time savings.

Analysing the Database of the iterative methods, as the one presented in section 3, provides also valuable information about the robustness. This is illustrated on figure 8 showing the variation of the stress and efficiency in function of the leading edge lean. The latter is defined as the angle between the blade leading edge and the meridional plane (positive in the direction of rotation). Designers intuitively try to keep it zero in order to minimize bending stresses at the hub. Figure 8 however shows that the lowest stresses occur at -12.0º. This unexpected result is a major outcome of the optimization. The small variations of the stress and efficiency in function of lean further illustrate the robustness of this design.

5. Multi-point optimization of a transonic radial impeller
Multipoint designs aim to achieve sufficient range between choking and surge, to have maximum efficiency at design mass flow and a sufficiently negative slope of the pressure rise versus mass flow curve for stability reasons (figure 9). Defining the whole operating line requires a large number of expensive NS calculations that are of little use if the choking mass flow is different from the required value.

The optimization algorithm has therefore been adapted by adding a geometry scaling to the optimizer which allows recuperating the optimized geometries that do not satisfy the choking requirements [4]. Geometries that show a potential in terms of operating range and performance are
scaled to satisfy the choking requirements. The scaled geometry is then input to a final series of NS calculations and one FEA stress analysis. Using the results of the first series of NS analyses of the unscaled impeller one can define the boundary conditions corresponding to a uniform distribution of operating points between surge and choke. The use of databases and metafunctions dedicated to predict surge and choking further allows speeding up the convergence because fewer expensive accurate calculations will be required.

The outcome of a transonic radial impeller optimization by this method is shown on figure 10. The final geometry satisfies the range requirements and the efficiency is increased by more than 2 points. The latter is due to the increased degree of freedom allowing splitter vanes that are different from the main blades. All mechanical constraints in terms of maximum stresses are respected.

6. Multi-objective optimization

The outcome of an optimization with 2 objectives can be visualized by plotting them in the 2D fitness space. The non dominated solutions i.e. the geometries \( G \) for which one objective cannot be decreased without increasing the other one, define a Pareto front. The choice is then left to the designer to select at the end of the optimization the geometry on the Pareto front that has the right balance between both objectives. A Pareto front is quite useful for problems with 2 OF as long as it remains convex. Visualization becomes more complicated when more than 2 OF are specified and special techniques are required to come to a motivated decision [5].

Defining the Pareto front is a time consuming activity requiring a large number of geometry analyses of which many will be of no interest. An alternative is a combination of the penalties corresponding to the different objectives into one pseudo-OF. Much less geometry analyses may be needed to reach the optimum.

\[
OF(G) = w_1 P_1(G) + w_2 P_2(G)
\]

This approach was already used in previous sections and is illustrated here by the optimization of the cooling system of a HP turbine blade [6]. The optimization aims to lower \( P_1 \) (increasing with the amount of cooling mass flow) and \( P_2 \) (increasing when the required life time is not reached). The lifetime depends on the equivalent stress, function of the material parameters, stress and temperature in each point of the blade. [7]. During the optimization process driven by a pseudo \( OF \) the optimization follows a path in the design space towards the point where the lines of constant pseudo OF become tangent to the Pareto front.
The main advantage of this approach is that only 30 geometry analyses are needed to find this optimum. The disadvantage is that the pseudo OF approach requires a rather good idea of the relative weights to be given to both penalties. Increasing the weight on P1 emphasizes on minimum cooling mass flow and hence cycle efficiency. Increasing the weight on P2 emphasizes on lifetime. The choice of the relative weights is rather obvious when one objective must be satisfied without compromise. This was the case in section 4 when optimizing the radial compressor, because the stress penalty has to be satisfied at all cost. The balance between the different penalties may be less clear in other cases. However perturbing the design parameters around the optimum geometry provides information about the interesting part of the Pareto front with minimum extra effort.

7. Conclusions

Turbomachinery design systems based on optimization have seen a large development in recent years. The method presented here allows an important gain in design time and performance while respecting the requirements. Extensions to multipoint and multi-objective are straightforward and result in advanced and realistic geometries.

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