Simulation-ready CAD for Fast Turn-Around Time in CFD and Optimization

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1 Introduction

Due to the rapid development in computer technology over the last decades, both in terms of computing power and affordability, the use of simulation – specifically CFD – has increased significantly. Not only is CFD being utilized to a much larger extent, largely reducing the need for physical testing, but also earlier and earlier in the product development process, Fig. 1, see also [1]. As opposed to using CFD late in the design process, where it can merely serve for validating a completed design or give some guidance for late changes, employing it early in the process turns it into a real design tool. It can be a valuable help in quickly gaining knowledge about the product's behavior and, under strict consideration of the product's performance, guide the design in the right direction from the start, when critical decisions are taken.

Apart from the availability of computing resources, another factor that has greatly contributed to the increased use of CFD is the improvement in ease-of-use. While it previously was a tool that was mostly limited to being applied by simulation specialists, it is now available to designers and engineers at large. Especially the advances made in the automation and robustness of the meshing process have fueled this development.

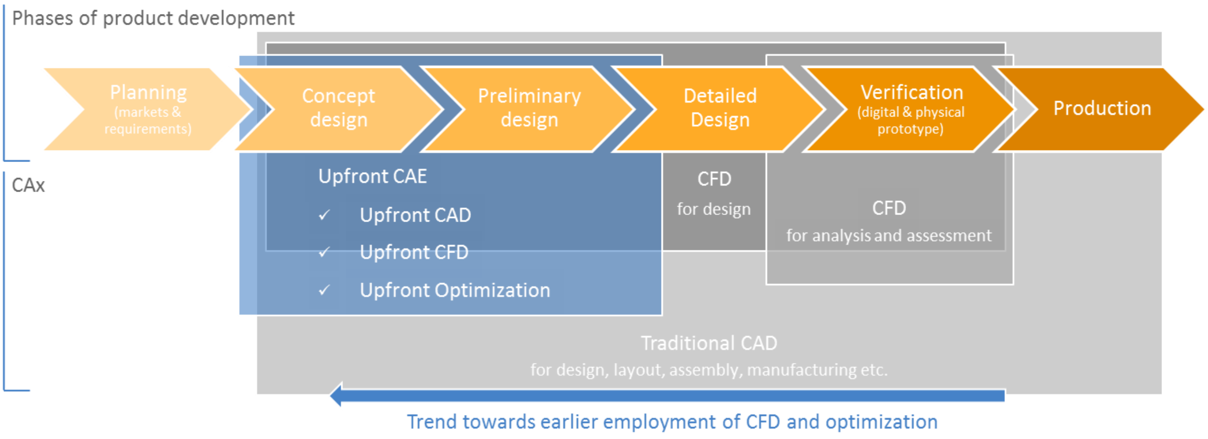

Fig. 1
Product development phases and CAx tools

2 Process Automation and Optimization

As a next logical step, applying CFD early in the process and considering its results to guide the development of the product quickly leads to the wish of employing it within an automated process for the systematic analysis of design variants – design exploration – and optimization. Shape optimization of components and systems is becoming a standard procedure in many industries that deal with flow-related geometries, such as the automotive, maritime, aerospace and power generation industries. A common denominator in all these very different products is that small concerted changes in shape often lead to substantial improvements in performance. Furthermore, even small improvements often yield important benefits for the producer, the consumer and the environment, e.g. when reducing energy consumption and emissions.

Apart from the pure CFD tools that, as previously mentioned, are becoming increasingly suited for process automation, additional complementary CAE tools are needed, which take care of other tasks required for the complete automation of the process: control of the optimization process, including variant and data management, and generation of the geometry variants that are being evaluated, providing the input for the simulations. While there are quite a few generic optimization tools on the market that can fulfill the former role, the latter – i.e., tools for shape variation – seems to be a rather sparsely populated niche. Traditional CAD systems often do not fulfill the given requirements well, at least when dealing with the complex, compound-curvature shapes that characterize many flow-related geometries, and a specialized CAD approach is called for instead. The category which this specific CAD tools fall in can either be called Upfront CAD, pre-CAD or simulation-ready CAD.

3 Upfront CAD vs. Traditional CAD

Traditional CAD packages are very powerful systems that accompany the complete design process and fulfill many different tasks, e.g. constructing production-level geometry models, creating complex assemblies, producing BOMs and manufacturing drawings, as well as managing PLM data. They are, however, often detail-centric, meaning that the geometry models include many details that are relevant for the final product, but not necessarily for the simulation, see also [2]. When pre-processing the models for the CFD grid generation, they have to be de-featured, the “wetted” surfaces have to be extracted and the geometry has to be cleaned up (e.g. making it watertight). Also, these tools are often not predisposed for quick variation of complex geometry. Changing properties of the shape can involve a lot of manual effort and is not necessarily robust, leading to many infeasible variants when attempts are made to automate the variation.

Upfront CAD tools are typically surface modelers that focus on the modeling of the CFD-relevant geometry only, providing it in a state that can directly be used for simulation. They have a strong focus on geometry variation, so that, once a model has been parameterized accordingly, they can provide geometry variants just by simply changing the model parameters, be it in a manual or an automated process. The model set-up might involve a bit more user effort, as the users builds in their ideas and creativity for the future freedom of variation, but that is easily offset by the time savings that can be obtained once variant generation takes place, where the effort is basically reduced to nil, see Fig. 2.

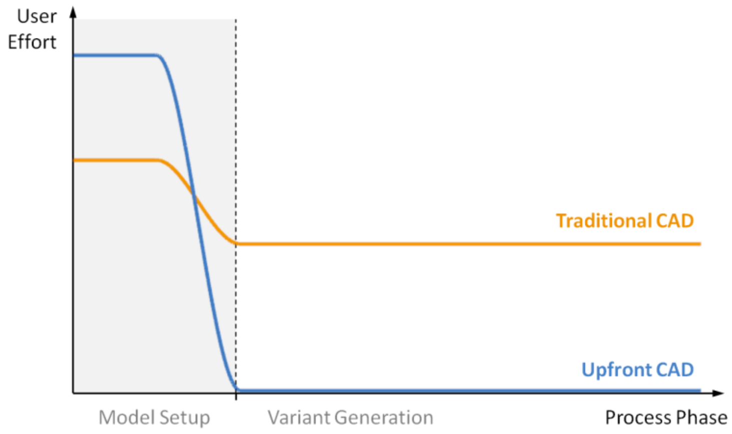

Fig. 2
User effort in different phases of the CAE process

The requirements imposed on an Upfront CAD tool can be summarized as follows:

- Geometries should be defined and controlled by as few parameters as possible, thus reducing the degrees-of-freedom. The optimization effort scales with the number of free variables (often in a quadratic fashion); therefore, a low number is highly desirable.
- It should be easy and fast to vary the geometry by controlling the values of previously defined parameters. These parameters should be independent from each other and it should not be required to change multiple parameters in a concerted way, just to obtain a specific change in shape.
- Geometry generation should be robust with a minimal amount of failed variants.
- The generated geometry should be provided in a state and format that can directly be used for the simulation tool involved in the specific process.
- The system should have the ability to manage constraints and ideally built them into the model, so that the creation of infeasible variants is prevented or at least minimized.

Another factor that distinguishes Upfront CAD from traditional CAD is the typical user group. In large corporations, a dedicated CAD department will be in charge of operating the CAD system, handing over geometries to the CFD department. When the CFD department wants to try variations of the geometry or suggests some changes, they have to request a new geometry from the CAD departments, which often leads to delays and an inefficient process. Obviously, process automation is hardly possible in this set-up. Upfront CAD, in contrast, is meant as a tool for the CFD engineers, giving them the ability to generate their own geometries and variants, even at a stage where the design is not progressed so far that the CAD department can actually hand over geometry files.

4 Upfront CAD Surface Modeling

One of the most important tasks of an Upfront CAD tool in the context of CFD-driven optimization is the efficient modeling and parameterization of complex, free-form geometries, in a way that is highly suited for automated variation. A generalized approach for the design of these geometries is to isolate a building pattern and transfer it to a surface generation process. The CAE platform and Upfront CAD tool CAESES® by FRIENDSHIP SYSTEMS offers the proprietary so-called *meta surface* technology, which makes use of this concept as follows:

In the first step, the user defines a 2D section with custom parameters, such as the maximum thickness of the blade profile section in Fig. 3. Other typical parameters are positions, tangent angles, areas and their centroids, radii and so on. The section can be swept along either a path or an arbitrary direction in the 3D space. This curve description is wrapped in a so-called *feature definition*.

In the next step, smooth function graphs can be defined for each of the custom 2D section parameters. In the example below, a function for the thickness was defined for the sweep direction of the surface. These graphs are defined in a 2D coordinate system, where the x-axis corresponds to the sweep direction, while the y-axis represents the parameter values. Finally, everything is linked together in an object that is called *curve engine*. This object holds the entire information, i.e., the 2D cross-section definition and its parameters, plus the corresponding distribution functions for these parameters.

With this information, a *meta surface* can be created within a specified range of the function graphs. The surface is then fully controlled by the function graphs, which in-turn are controlled by parameters. This means that smooth and feasible surfaces can be created with just a small number of parameters.

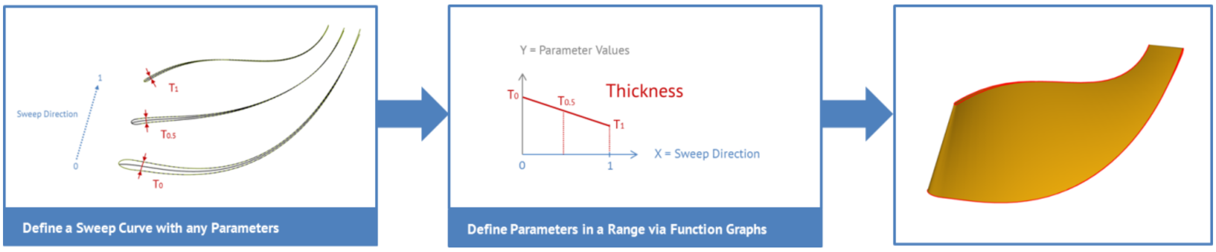

Fig 3:
CAESES® *meta surface* technology to design smooth and parameter-reduced surfaces in an Upfront CAD paradigm

The exemplary blade demonstrated so far belongs to the compressor impeller of a turbocharger, as shown in Fig 4. The sweep direction of the profiles is in radial direction from hub to shroud. Blade designers typically want to control quantities such as the leading edge shape and thickness, i.e., these parameters should change in radial direction. Each of these quantities can be directly and smoothly controlled by the *meta surface* technology, as described above.

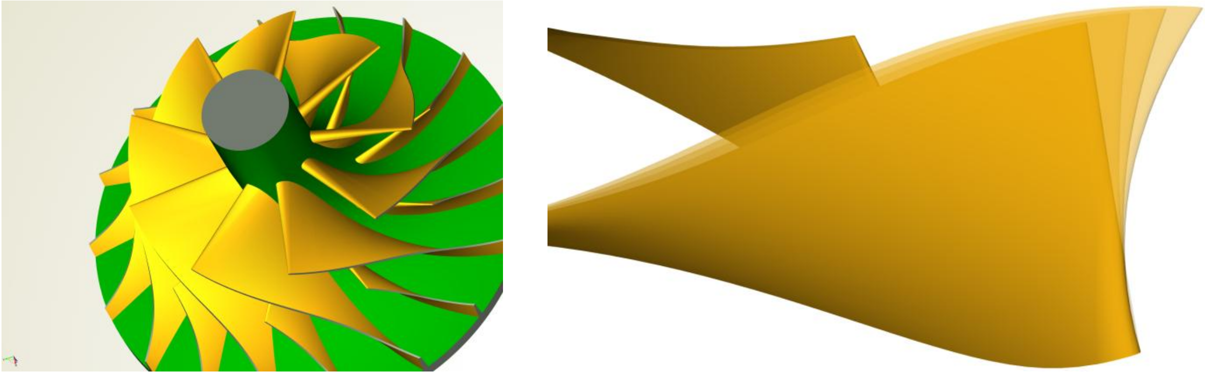

Fig 4:
Impeller model of a turbocharger compressor modeled using the *meta surface* technology and exemplary variation of the blade shape

More interesting shape parameters are given for the camber curve of such a blade. Fig. 5 shows two examples for the 3D camber curve, given at a specific radius of the impeller. The corresponding functions for the wrap angle θ control the shape of the curve from leading to trailing edge. The value “A” represents the circumferential position of the leading edge. If the value is set to ‘0’, as an example, the leading edge is located on the meridian plane, as in Fig. 5, right.

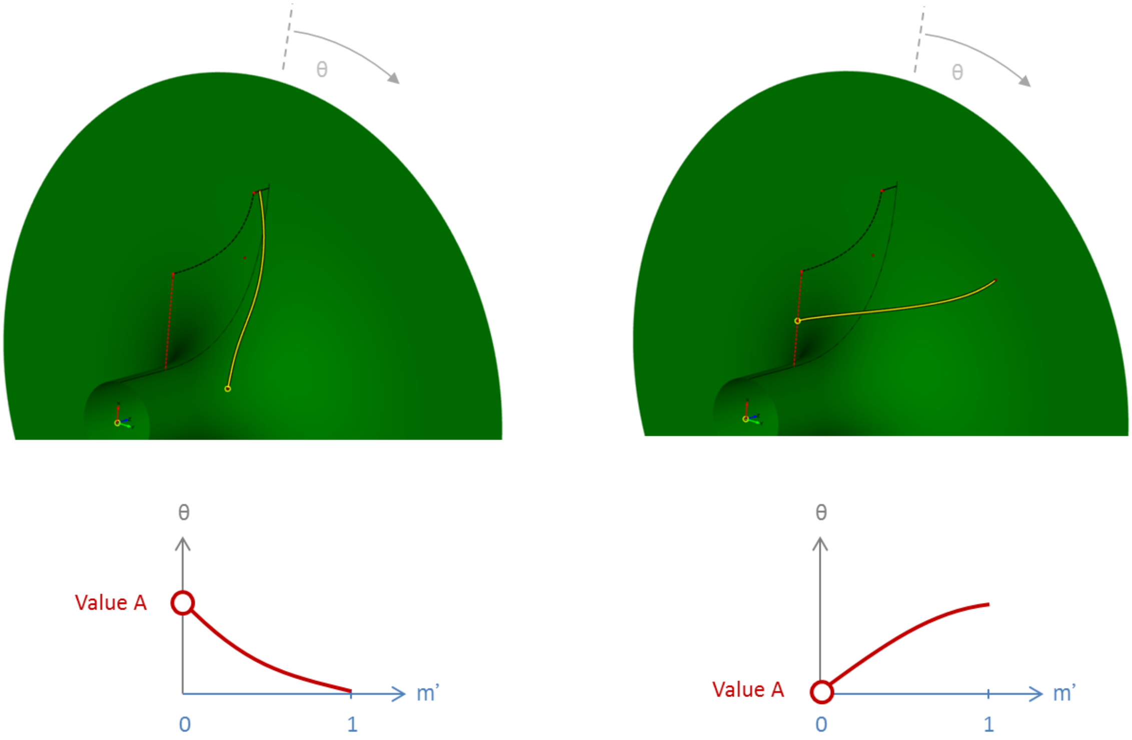

Fig. 5:
Camber curve (yellow) controlled by a function for the wrap angle θ, running from leading to trailing edge

The leading edge wrap angle “A” can now be parameterized, so that it is controlled and changed in radial direction. Such a distribution function for the inlet angle is shown in Fig. 6. These functions are typically changed in automated studies and optimizations, again with just a small set of free variables.

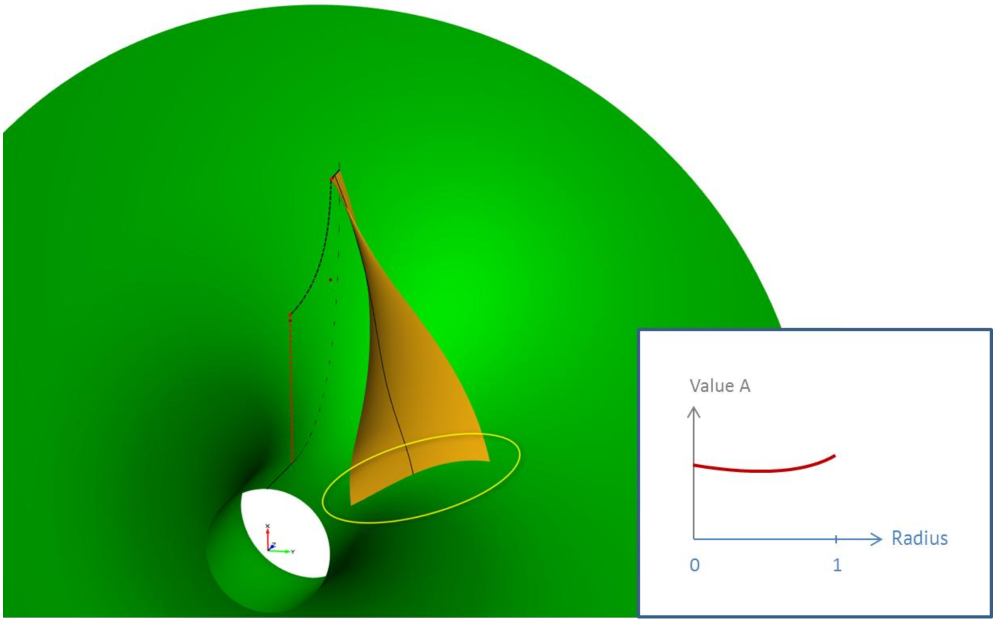

Fig. 6:
Distribution function for value “A” (wrap angle of leading edge) for parametric control in radial direction with the corresponding leading edge shape of the blade camber surface

Finally, any parameter of the wrap angle function θ that is shown in Fig. 5 can be parameterized in the same manner, not only the value "A". This depends on how the θ function is defined. Typical candidates are B-spline curves with control vertices, or mathematical expressions with coefficients. Other examples of curve parameters would be the wrap angle at the trailing edge or the tangent of the θ curve at the leading edge, which would influence the relative angle of the blade to the incoming flow, i.e., the angle of attack.

5 Optimization Example

Based on the *meta surface* approach for variable geometry, a radial compressor of a large turbocharger was optimized for isentropic efficiency [3]. CAESES® was coupled to CFD software systems by Numeca Int., specifically, Autogrid5 and Hexpress for compound grid generation and FINE/Open for flow simulation. The volute's (Fig. 7, left, in green) cross section was defined by several parameters (such as the radius as a function of peripheral angle), which themselves were subjected to change in circumferential direction. This enabled shape adaptations for given mass flow and allowed controlling the volute's diffusion characteristics. The parametric model of the vaned diffusor (Fig. 7, left, in blue) comprised the stagger angle, the vanes' twist and their pitch and trailing edge positions. These parameters were changed circumferentially, too, allowing the diffusor to be non-periodic (according to a user-specified "normal" distribution). The impeller was considered during the simulation but left unchanged in order to limit the number of free variables.

A genetic algorithm was employed in combination with an artificial neural network as surrogate model. Fig. 7 shows some results. Comparing the baseline to the best design, a small rotational shift was observed between the original diffusor vanes and the newly identified optimal vane configuration. Further to this, the stagger angle was slightly increased while the position of the trailing edge was moved a bit in radial direction (by 1.5 mm). The volute of the optimal design featured a slightly larger area distribution. Isentropic (peak) efficiency was increased by 1% (at 5.9 kg/s) with performance improvements over the entire operating range.

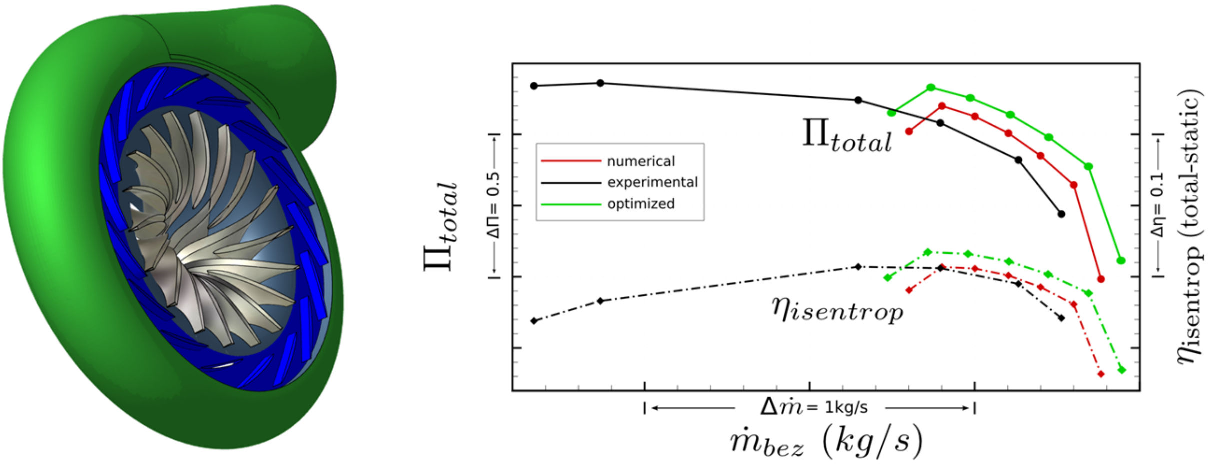

Fig. 7
Model and selected results of the automated optimization of a radial turbocharger compressor

6 References

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