Optimization techniques applied to centrifugal compressor design

Using RSM to save design time and speed time-to-market

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During the development of a centrifugal compressor stage, different challenges arise if the focus is not only on the best efficiency, so critical nowadays. Time-to-market is also critical and once a new product is created, sales support and the improvements feasible during the product's life are also subject to time constraints. Computational time has been reduced significantly compared to the past due to latest algorithms and information technology. Carefully analyzing the available tools it is possible to combine them to optimize the process flow and use them in an "unconventional" way. Optimization tools, and specifically response surface methods (RSM), can be adapted very well in the design process to provide information around the design of a compressor stage. This article will cover two of the possible optimization uses: the search of optimum performance and data generation.

The design of a centrifugal compressor, as any other industrial equipment, is a specific process that involves a variety of disciplines. The most relevant aspect is the level of interconnection between the various technical features, to the point that iterative design processes are on the agenda of every engineer and designer. These processes can be implemented within the single component of the design's characteristic or within the same project.
The incredible scenario of available software helps creating easy connections and data exchange and is also automating most of the iterative processes.

Optimization is a now growing process supporting design activities. An interesting perspective offered by optimization is the possibility, within the same analysis, to connect various design aspects into a single "box" to achieve a unique objective. This objective is actually shared by all the technical features involved and that are represented by the different engineering disciplines.
Several different centrifugal compressor challenges can be faced during design. Nevertheless, the dimension of the problem can be easily reduced through proper evaluation of subsystems and interfaces among them. Once a design objective is identified, it is possible to use optimization techniques to speed up the gathering of information.

For example it is possible to minimize/maximize each stage independently and then moving on to the optimization of the assembly. RSM (response surface methods) can be used to get the design space behavior (i.e. stress distribution under different loads) or compressor maps. Another interesting approach is the statistical one, which allows an appreciation of the impact that one design parameter change can have on the others.
At the beginning of the design activity, identifying the objectives and the interaction between the stages/components of interests becomes relevant in order to establish the correct routine and prioritization of analyses needed.
As when building a house, the foundations can be defined as the design process (see Fig. 1): it is possible to add a brick (functional block) at each step. The various optimizations phase can be connected one another in order to pass information and to refine the entire design. In the compressor stage design, the process identified is useful to decide the parameters that contribute to the important design features: efficiency, reliability, manufacturability, range of functioning and cost.
The workflow also presents connections with other design aspects: the Multidisciplinary block, not expanded in this case, can be integrated with any of the green ones, to any level of detail.
Breaking down the process to the ground level allows the optimization of each component individually, so that when the full machine is put together the optimization can be done on the process and interfaces, eventually taking care of refining the components' design.
In Fig. 2 a workflow is represented dedicated to identifying the best possible diffuser within a stage design (that includes an inlet, an impeller

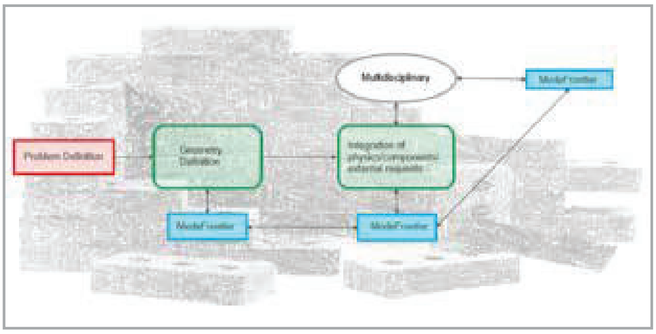

Fig. 1 - Process flow of centrifugal design stage

Fig. 2 - Stage workflow

and a diffuser). The design has been segmented to study and define some of the diffuser's parameters. modeFRONTIER is the software used to perform the optimization task. In the software workflow two main nodes are present (where a node identify a software and/or process phase and/or activity). The first node (Concepts NREC) manages design variables and second one (Ansys) is used to run computational fluid dynamics (CFX in the specific). In the first optimization the variable to optimize is just one. It is the first block needed to build the full process.

PiIOPT has been chosen as the algorithm to find the optimum even if it is a single variable problem because it is a simple design space with few input variables. This algorithm allows the quick search of the best solution. With these results it is possible to launch a statistical analysis to fully understand the impact of each input variable on the output one. It is then the designer's choice whether to refine the optimization by choosing a Simplex algorithm taking into account statistical results, or to move on to the next design step, maybe integrating the stress evaluation and the definition of the best fillet radii around the vane.

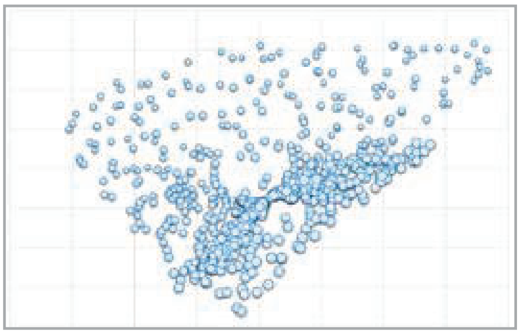

Fig. 3 - results distribution on a pressure-power range

This process can be followed for each and every variable and/or component used to design a multistage compressor. At this point, the structure of the workflow can be the same as Fig. 2, where the geometrical and the Ansys node include multiple stages. The optimization process can follow the same criteria in order to maximize and/or minimize the relevant variables.

In case of a complex workflow or a long computational time, the RSM (Response Surface Method) can improve to speed up the process. Before accessing to this tool, it is fundamental to have a reasonable number of DOE (Design of Experiments) or test cases to use as database. RSM is very powerful but potentially dangerous. It calculates the results based only on the amount of historical data it has, so it is important that this history includes all the areas of the design space (so algorithms which scan the entire design space are preferable for generating the test cases).

For example, a 2 stage-compressor with 1 output and 9 input variables using an algorithm that generates 1665 cases needs 8325 hours of computational time running on 48 CPUs. With RSM and a reasonable number of DOE solutions, the entire space can be scanned and calculated in 2 minutes and 5.5 seconds.

At this point, a judgment has to be made in the results evaluation. Good engineering practice and final design objective guide the selection of results of interest and, if needed, the decision to run the full case. From an entire workflow perspective, RSM helps managing large or complex system, allowing the designer to gather the necessary information in a reduced amount of time, which is valuable from both project and time-to-market perspective.

RSM can have another interesting use, due to its own features. It allows the calculation of a large design space anchored to a good database and can be used to generate maps. It is sufficient to define the problem (correct inputs, output and supporting variables), run DOE or collect test data, then train and run RSM. The result table includes all the necessary information to create maps as happens during a standard CFX simulation. Starting from a complex model the possibility to run in few minutes (i.e. example above) has allowed the generation of a pressure-power map (see Fig. 3), that is used to verify the entire range of operation of the new design.

This methodology can be successfully used to analyze the design space in any context, but it is interesting when physical quantities are among the input variables because it is possible to observe trends for certain phenomena. It is possible to characterize the compressor characteristic curve at different pressure, or inlet conditions, early in design phase in order to change and manage properly the geometrical design variables. For example, the search of stall or surge limits before running a transient analysis of the entire stage can be conducted observing the results of the RSM. The amount of data available allows the selection of critical areas, and supports the possibility to vary some parameters in order to evaluate the impact of changes before final simulation and design assessment are conducted.

Using all the optimization techniques illustrated the designer has the freedom to investigate alternative solutions minimizing the computational cost, including inputs coming from different disciplines (like cost) that typically are known at the end of the design process, and to evaluate a design space broader than what was used to. The tools used in the design process can support the various design goals provide that geometrical and physical quantities are in a parametric format, a process is defined and input/output variables are defined.

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