MULTI-OBJECTIVE OPTIMIZATION OF THREE DIMENSIONAL TURBOMACHINERY BLADES

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Abstract

The recent progress in simulation technologies in several fields such as CFD, structures, thermal analysis and unsteady flow combined with the emergence of improved optimization algorithms makes it now possible to develop and use automatic optimization software and methodologies to perform complex multi-disciplinary shape optimization process.

In the present applications, the MAX optimization software developed at CENAERO is used to perform the optimization. This software allows performing parallel derivative free optimization with very few calls to the computer intensive simulation software. The method employed in this paper combines the use of a genetic algorithm using real coded variables very significantly accelerated using an approximate model.

In this paper, this optimization methodology is used for the optimization of three-dimensional turbomachinery blades for multiple operating points and multi-disciplinary objectives and constraints. The aim is to find the optimal geometry for 3 different operating conditions at the same rotational speed. Finite-element structural mechanics software is used to compute the blade mechanical responses such as the maximum von Mises stress or the dynamic vibration frequencies. A Navier-Stokes solver is used to calculate the aerodynamic performance.

High Performance Computer (HPC) is used in this application. Cenaero's HPC infrastructure contains a Linux cluster with 170 3.06 GHz Xeon processors.

Introduction

Traditionally, the three dimensional blade shape is very often designed by experienced designer able to iteratively and manually modify the blade shape taking into account several results coming form aerodynamic computations (CFD), FEM structural mechanics computations (static and dynamic) among others disciplines. In recent years large progress has been made in the development of automatic optimization packages able to optimize complex shape using advanced CFD solver and optimization algorithms. Although these optimization methodologies are starting to be used in industry, they are not yet used very intensively in the real shape optimization. A more intensive use still requires progress in the field of automatic shape optimization.

In the present application, the optimization software developed at CENAERO (MAX) is used to perform the optimization. This software allows performing derivative free optimization with a reduced number of calls to the computational intensive simulation software. The methods employed and compared in this paper are:

- A genetic algorithm using real coded variables,
- An optimization method based on the construction of an approximate model (also called meta-model or response surface) and the use of a genetic algorithm to find the optimum predicted by the approximate model [1] and [2].

This paper presents several applications of this optimization method. First the performance of the method is demonstrated on algebraic test functions. Then, this methodology is applied to the redesign of the full three-dimensional geometry of the NASA rotor 67 that is optimized for several operating points simultaneously and for a large number of design variables. The performance of the method based on the genetic algorithm accelerated by the metal model is compared to the performance of the pure genetic algorithm. Finally, the aerodynamic mechanical optimization is performed and the results are compared to the pure aerodynamic optimization.

The Optimization Method

The basic principle of the optimization algorithm developed in this research project is based on the use of genetic algorithms (GA) because they provide a very robust method having various advantages. However, one drawback of GA is that they suffer a slow convergence because they use probabilistic recombination operators to control the step size and searching direction. As a consequence, for real industrial problems involving expensive function evaluations, the CPU time required by GA is usually not practical even with today's computing power. Therefore, a lot of effort has been put in this research project to accelerate the optimization process by using approximate model and using robust and efficient genetic operators.

The blade design algorithm is therefore organized with the following 5 steps:

- The first step consists in building a database using a design of experiments procedure (DOE). Numerous techniques exist: Full factorial, fractional, central composite, D-optimal, Latin-hypercube and random selection among others.
- Then an approximate model is build using the DOE points in order to construct an analytical relation between the design variables and the simulation responses,
- Third, an optimization algorithm is used to find the optimum using the approximate model to evaluate the objective functions and constraints,
- Then the accurate simulation is used to evaluate and verify the real objective function and constraint values. This new simulation result is added to the database. The database is therefore always improved with new design points therefore leading to improved approximate model.
- Go to step 2 until the maximum number of optimization specified by the user is not reached.

In this work the design of experiments is very often performed using random selection of design points improved with techniques to ensure a maximum filling of the design space. This is a generic method because it allows generating a number of points independently on the number of design variables. DOE can very often be generated very rapidly by making use of massively parallel computers to evaluate the expensive objective functions. The software developed in this research is parallelized using MPI. In general the number of design points generated in the DOE is equal to 2 to 5 times the number of design variables.

Several multi-dimensional and non-linear interpolation techniques can be used to construct the approximate model. They are kriging, artificial neural network, radial basis functions or lazy learning. Compare to simple polynomial interpolation these techniques offer the advantage of decoupling the number of free parameters in the model with respect to the number of design parameters. In this research, the radial basis function interpolation technique is very often used mainly because of its robustness in providing an accurate approximate model. Moreover it allows constructing a global approximate model which is valid for the entire design space. This is an important aspect for the application of the method to multiple objective optimization techniques based on the Pareto front concept.

Validation Tests

The scope of the numerical experiments in this section is to validate the capability of the design method to find the objective function optimum and to assess the convergence speed of the optimization algorithm.

The test case aims at demonstrating the capability of the optimization algorithm to converge to the global optimum of a multi-modal function. This function with 2 design variables is represented in figure 1 and the exact mathematical definition can be found in [1].

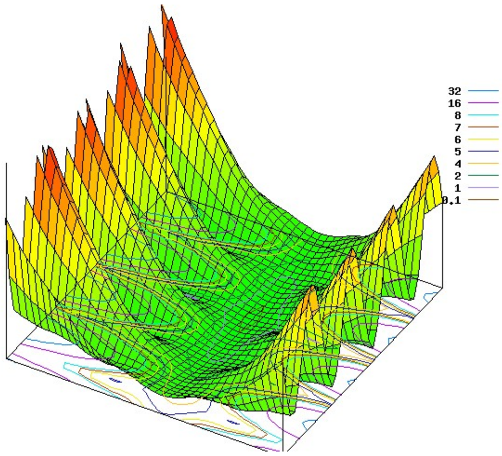

Fig. 1: Multi-modal function

This optimization test case is run using the same type of test function but with 4 design variables. With 4 design variables, the square domain [-10, 10] x [-10, 10] contains 625 local minima.

This optimization task is first solved using the genetic algorithm alone with a population of 50 individuals. The convergence history shows that the global minimum is found and also that more then 1000 function evaluations are required.

More interesting is the result obtained by the coupled method. An initial database with 12 points is used and then only 100 optimization iterations are needed to find the global minimum with an accuracy of 10^{-6} (figure 2).

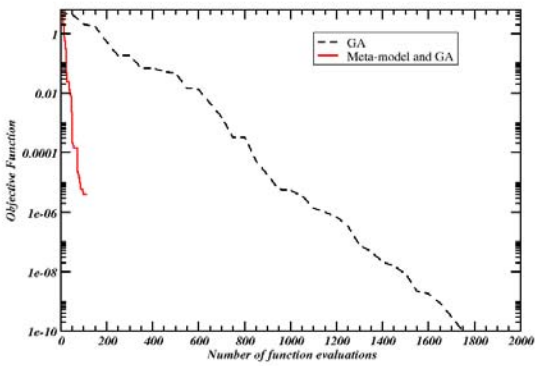

Fig. 2: Optimizer convergence history on multi-modal function.

Rotor 67 Redesign

The purpose of this test case is to demonstrate the capability of this design method when large simulation cost is involved, large number of design parameters and multi-objectives, multi-disciplinary optimization problems are tackled. In the present study the geometry of the NASA rotor 67 has been used to demonstrate the capabilities of the method to optimize the geometry for several operating points simultaneously.

This compressor is representative of fan blades. The rotational speed is 16043 rpm, there are 22 blades and the design mass flow is 33.25 kg/s. The aim is to find the optimal geometry for 3 different operating conditions: one at chocked mass flow, one at near efficiency peak mass flow and one near the stall flow. The three points are analyzed at the same blade rotational speed which is the design speed.

In the context of this work, a computational code solving the Reynolds-Averaged Navier-Stokes equations (RANS) is used to predict the aerodynamic performance of turbomachinery blades. The TRAF code which is developed by the University of Florence is used in this research [3].

A C-type mesh is used in this study. The mesh used for the computations contains 700 000 mesh points having 233 points along the C mesh lines, 53 from the blade walls to the mid-pitch and 57 in the spanwise direction. The code is capable of obtaining a converged solution in an hour on a Xeon processor (3.06 GHz). The Baldwin-Lomax turbulence model is used.

The first optimization is performed with pure aerodynamic objectives. The objective is the summation of the efficiency at the 3 operating points together with penalties on the mass flow at choked mass flow and penalties to ensure that the total pressure is at least larger than the one on the initial blade.

The three-dimensional geometry is parametrized using 5 two-dimensional sections equally distributed from hub to tip. The two-dimensional sections are parametrized using B-Spline curves. 35 design parameters are used in total defining modifications of the blade geometry with respect to the original blade geometry.

The aerodynamic optimization process is composed of:

- The shape parameterization module which transform the design variables into the detailed shape definition of the three-dimensional blade section,
- The CFD software including the mesh generation, the flow solver and the post-processor which extract aerodynamic responses such as the aerodynamic efficiency, the pressure ratio and the mass flow. Three CFD computations are performed for three different static pressure imposed at the domain outlet boundary.
- The parallel application manager which is a MAX component and is capable of managing very efficiently the simulation submission based on many criteria such as the number of available processors or the number of available licenses for the software used in the simulation chain,
- The optimizer based on the meta-model,
- The database containing the initial DOE results together with an incremental storage of the simulation responses computed by the simulation chain.

Rotor 67 Aerodynamic Optimization

The genetic algorithm is run using a population of 60 individuals which are evaluated in parallel on 60 processors.

Figure 3 shows the progress in the optimization process. With the GA a large gain is obtained during the first 2 reproduction cycles. Then smaller amplitude gains are still obtained during the next reproduction cycles.

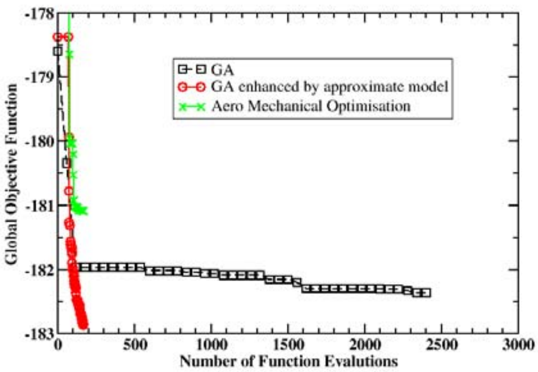

Fig. 3: Rotor 67 - Optimization convergence history

The same optimization problem has been solved using the methodology based on the combined used of genetic algorithm and meta-model. This optimization process is first initialized by constructing a design of experiments based on 70 geometries. This DOE is run in parallel on Linux cluster using 20 processors. Then the optimization is run for 100 function evaluations to reach the optimal shape. The convergence with the genetic algorithm and the meta-model is also shown on figure 3. Moreover the optimum found by the second optimization algorithm is better and probably correspond to the fully converged solution that could be found by the genetic algorithm alone. As a consequence, the use of the meta-model together with the genetic algorithm is at least 20 times faster than a simple genetic algorithm.

Figure 4 shows the compressor performance map at the design rotational speed for both the initial blade geometry and the optimized blade geometry. The adiabatic efficiency of this already highly optimized blade has been improved by more than 2% along the whole operating curve.

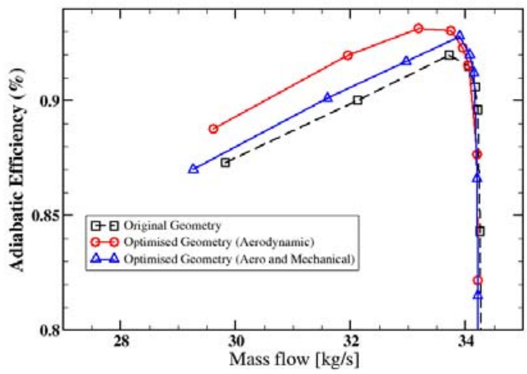

Fig. 4: Rotor 67 - Efficiency curve

Figure 5 highlights the geometry variations for three sections: at hub, at mid-span and close to the tip section. The tip section clearly shows S-shape suction side. However, the tip section clearly has a negative thickness portion, while the mid-span section has very thin leading edge and the hub section has a too thin trailing edge. These unrealistic thicknesses of the optimized blade clearly demonstrate that mechanical objectives and constraints must be added to the optimization procedure in order to reject such blade geometries.

Rotor 67 Aero-Mechanical Optimization

Then the same shape optimization problem is treated but a FEM structural mechanic code (SAMCEF) is used in order to compute the static stresses and dynamic vibration modes. These new quantities are then included in the optimization process as constraints.

The Samcef finite element model used for the blade simulation consists of 20 x 20 nodes forming a volumic shell with varying thickness along the blade geometry. The 20 first vibration frequencies are computed

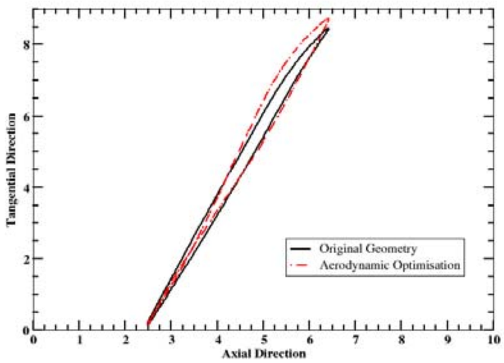

Fig. 5: Rotor 67 – Tip section geometry obtained with aerodynamic optimization

An imaginary material is used for this computation. The Young's modules, Poisson's ratio and density are chosen to be 1.422e+11 Pa, 0.3 and 4539.5 kg/m^3 respectively which looks reasonable when comparing vibration frequencies of the original blade compared to the nominal rotational speed. The first five vibration frequencies at cruise speed on the original geometry are: 557 Hz, 1307 Hz, 1923 Hz, 2760 Hz and 3111 Hz.

The objective function contains the objectives and constraints already defined for the pure aerodynamic optimization. However, several constraints are added. The first one aims at limiting the maximum static stresses inside the blade metal. This is performed by imposing a maximum limit on the von mises stress to 4.8 MPa compared to a value of 4.75 MPa on the initial geometry.

The vibration frequencies are controlled at design speed by imposing several constraints on the first and second vibration modes. The rotational speed is 16043 rpm or 267.4 Hz. This value is defined as N = 267.4 Hz. In practice the blade vibration modes should not be equal to 1N, 2N, 4N, 6N, 8N, etc. Moreover a margin of +/- 2.5 % is imposed with respect to these forbidden frequencies leading to these forbidden ranges for the first and second blade vibration modes: 260 - 274 Hz, 521 - 548 Hz, 1042 - 1096 Hz, 1564 - 1644 Hz, 2085 - 2192 Hz.

The maximum von Mises stress of the optimized blade is 3.9 MPa while the first two vibration modes are 599.6 Hz and 1360 Hz. These values are outside the forbidden ranges specified during the optimization.

Figure 6 shows that the blade thickness is now much better than for the pure aerodynamic optimization. The blade thickness along the first part of the blade close to the leading edge is still small on the mid-span and tip section. This last point probably comes from the fact that only centrifugal forces are imposed for the FEM mechanical computation and not the effect of the aerodynamic pressure field onto the three-dimensional blade shape. The next step of the current research will then be to impose the pressure field along the blade walls in order to further increase the simulation and optimization accuracy.

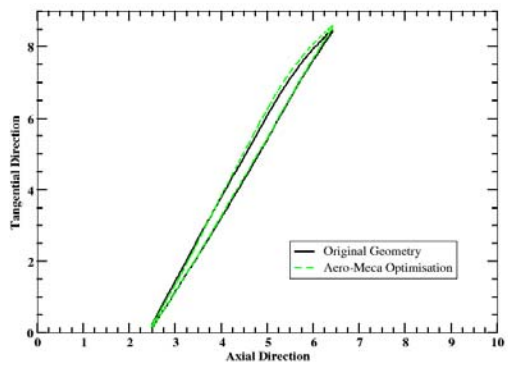

Fig. 6: Tip section geometry obtained with aero-mechanical optimization

Conclusions

This paper demonstrates that the design method based on genetic algorithm accelerated by approximate models has many advantages compared to other optimization techniques: provides efficient blades in a very short time, can be run automatically, mimics the so-called intelligent behavior of the designer (an approximate model is constructed iteratively during the design process) and can easily be applied to any type of equations (Euler, Navier-Stokes, mechanics or acoustic among others).

The optimization method has been largely validated on various test functions of which one test case is presented in this study. The genetic algorithm and DOE have been parallelized using the MPI library allowing for a rapid turn around time for the design of turbomachinery blades.

This paper presents the first results in an effort to reduce the computational effort for real industrial optimization tasks involving multiple objectives and multiple disciplines (CFD, mechanics, thermal analysis and acoustic). The elapsed time required to perform the design of a fully three-dimensional blade is reduced to less than a week. This has to be compared to a time of more than 2 to 3 weeks required by an experienced designer to 'manually' design a three-dimensional blade including the aerodynamic and the mechanical objectives.

A first step towards an automatic aero-mechanical optimization chain has been performed with several improvements among with:

- Optimize the blade shape along the whole performance curve,
- Use a larger number of parameters than used in more conventional optimization problems,
- Use of aero and mechanical simulation in the same integrated optimization process,
- Deal with uncomputable functions that usually arises in such processes,

However, further developments are needed in order to further model the real process by including the pressure mapping of the fluid onto the three-dimensional blade. After this next development, it will become possible to further increase the number of design variables in order to have more freedom in the shape modification process and to modify the number of blades during the optimization process.

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