Proceedings of ENCIT 2012
Copyright © 2012 by ABCM

14th Brazilian Congress of Thermal Sciences and Engineering
October 18-22, 2012, Rio de Janeiro, RJ, Brazil

OPTIMAL DESIGN OF CENTRIFUGAL COMPRESSOR USING TECHNIQUES BASED ON METAMODEL CONSTRUCTION AND COMPUTATIONAL FLUID DYNAMICS (CFD)

Sandro K. Kurauchi, kurauchi@ita.br
João Roberto Barbosa, Barbosa@ita.br
Technological of Institute Aeronautics, ITA
Gas Turbine Group
12228-900 - São José dos Campos SP, Brazil

Ramiro Gustavo Ramirez Camacho, ramirez@unifei.edu.br
Edna Raimunda da Silva, ednaunifei@yahoo.com.br
University Federal Itajubá, UNIFEI
Institute of Mechanical Engineering
37500-903 – Itajubá - MG, Brazil

Abstract. *This work presents a methodology for performance optimization of Centrifugal Compressor. The channel shape of the meridional plane is parameterized by Bezier curves, to achieve maximum efficiency. As a preliminary test, not including the effects of increased pressure caused by the diffuser. The objective is the maximization of the polytrophic efficiency or total enthalpy starting from a preliminary design. Strategy to find the maximum efficiency is based on the construction of metamodels in conjunction with optimization algorithms. The controlled random search algorithm (CRSA) is then chosen to perform the optimization task. Relatively few design points are exactly evaluated and recorded with their function values in a database for metamodel construction. Radial Basis Functions like multiquadrics are used for this construction (RBF). The optimization methodology based on the construction of metamodels is integrated with CFD techniques, using schemes automatic building of parameterized blade geometries and meshes via "script files" with editing commands written in Tcl/Tk language, which will be interpreted by the commercial software ICEM-CFD, in batch mode. For the numerical calculation of the flow in the centrifugal compressor rotor, the software CFX is used with fluid properties, turbulence model and boundary conditions set through "journal files". This methodology allows making corrections in the initial project of the channel shape meridional plane, without much computational effort.*

Keywords*: Centrifugal compressor, optimization, CFD techniques, basis radial functions, metamodels.*

1. INTRODUCTION

Centrifugal compressors are nowadays utilized for many applications. At industrial level they can be used in oil and gas and chemical industry from extraction, gas liquefaction and transportation to reforming and cracking in refinery, from gas synthesis to air fractionation, in chemical and pharmaceutical processes. However applications in the aerospace and power generation, has been the target for the development of modern design methodologies in order to achieve greater efficiencies. Power and dimensions of these machines cover a range from very small configurations for micro applications to huge multistage groups for heavy industrial plants. It is clear that, in case of large industrial applications in which the power consumption of a multistage centrifugal compressor can reach 70 MW, the search for a good efficiency of the machine has to be a must for designers.

In this sense, has dedicated many efforts to develop methods of optimal design based on genetic algorithms to find the best design point. To obtain the flow field in turbomachinery has used the techniques of CFD, which through a certain defined geometry and appropriate boundary conditions, it is possible to quantify the local and global variables of the flow field.

CFD techniques have been developed over the past decades as a powerful analysis tool for quantification of flow fields in complex geometries, especially those found in turbomachinery design. Such techniques have been used by the aeronautical industry since the 60ths, begging with the classical panel method with boundary layer interaction to account viscous effects. Nowadays, the use of computational fluid dynamics (CFD) for solving the full Navier-Stokes equations has become a common issue in several industrial design activities. Nevertheless, such computations may represent a bottleneck when a great number of concurrent geometrical and flow parameters must be analyzed during the searching of good solutions for satisfying certain design objectives. Normally, such task is better accomplished by means of a suitable optimization algorithm (OA). But taking into account real life constraints, such as the available computational environment and budget, the number of comparative evaluations required by an OA may become prohibitive in a specific design situation.

Metamodels (surrogate or response surface models) have been extensively used for representing expensive black box functions. A recent published monograph on the subject is already available (Forrester et al., 2008) focusing practical aspects. Praveen and Duvigneau (2007) classified surrogate models into four main categories: (i) data-fitting models, where an approximation of the expensive function is constructed using an available data bank; (ii) variable convergence models, where the expensive function depends of the numerical solution of a partial differential equation with a relaxed stopping criterion; (iii) variable resolution models, where a hierarchy of grids is used and the surrogate model is just the costly evaluation tool but run on a coarse grid; (iv) variable fidelity models, where an hierarchy of physical models is used. The first category is focused in this paper.

Often the constructed metamodel itself is of prime importance for the user when it is meant for utilization without further callings to the costly model.

In this context, this paper presents the metamodel construction, and with this, to obtain optimal results of the flow field variables into the compressor. The goal is to maximize the isentropic efficiency, with the design variables: the geometric variation of the meridional channel. For metamodel construction, RBF (Radial basis Function) interpolation multiquadrics was used (Silva et al., 2012).

The use of surrogate models, in this case, facilitates the analysis of efficiency, quickly and efficiently, because otherwise, using classic techniques coupled with optimization of complex models for calculating the flow in turbomachines (3D-CFD) would make this approach extremely computationally expensive.

2. INTERPOLATION BY RADIAL BASIS FUNCTIONS (RBF).

The RBF methodology was originally developed by Hardy (1971) in the beginning of 1971 to produce excellent fits to irregular contour of both deterministic and stochastic functions. More recently, many authors (Jones, 2001 and Regis and Shoemaker, 2005) have been used different kinds of radial basis functions such as circular hyperboloids, circular paraboloids, and circular ellipsoids, combined with factorial and Monte Carlo designs as metamodeling technique in engineering.

The RBF is a function in which their values points depend only on the distance from the origin point, called center, and its standard definition is symbolically defined as follows:

$$\phi\left(\|\vec{x}\|\right): R^n \rightarrow R \tag{1}$$

where any function ϕ that satisfies the property (1) is a radial function. Where $\|\ \|$ is the Euclidian norm, defined as $\|\vec{x}\| = \sqrt{x_1^2 + x_2^2 + \ldots x_n^2.}$. By considering the Eq. (1), the metamodeling definition by using the RBF can be mathematically defined as follows:

$$u(x) = \sum_{i=1}^{n} \alpha_i \phi\left(\|x - y_i\|\right) \tag{2}$$

where $u(\boldsymbol{x})$ is the approximate function, and y_i represents the input vector for the i-th run of the simulation, and α_i are real coefficients to be determined.

In this present paper the metamodel construction is made with multiquadric radial basis functions with shape parameter c equal 1.0.

$$\phi(r) = \sqrt{r^2 + c^2} \tag{3}$$

The Full Factorial experiment was adopted for the initial points. The number of variables (k) in this study is restricted to two. The choice these variables has major influence in the compressor efficiency. The numbers of experiments (m) are obtained varying the levels (n_{lev}). Is expressed as follows: $m = n_{lev}^k$

3. CENTRIFUGAL COMPRESSOR DESIGN.

The preliminary design of a centrifugal compressor is based on the classic methodologies dimensional (1-D) for the determination of geometric and kinematic characteristics of the rotor, which estimates the rotor diameter, number of blades, blade angle of inlet and outlet are defined. The 1-D study is largely based on empirical data (Came, 1999), which have great importance in the design process. According to Xu (2006), the approach of this methodology (1-D) has a high reliability due to having large number of experimental tests, which are obtained through the semi-empirical correlations.

Vavra (1970) established a 1-D design methodology for high-speed centrifugal compressors that have radial blades at the discharge and the absolute inlet velocities are in the axial direction operating with ideal gases.

A computational program based on Vavra's methodology was developed and adapted to include the backsweep at the discharge and the effect of real gases. For a particular design it is necessary to know the mass flow rate, total inlet temperature, total inlet pressure, pressure ratio and the gas composition (CH_4).
As a measure of the rotor performance quality, Vavra (1970) defined through the isentropic efficiency.

$$\eta_w = \frac{h_{2s} - h_u}{h_2 - h_u}, \quad h_u = h_1 + \frac{U_2^2 - U_1^2}{2} \tag{4}$$

A centrifugal compressor stage was designed for CH4 gas pipeline with a pressure ratio of 1.5, mass flow of 74 kg/s, p_{01} = 6,470,730 Pa, T_{01} = 307 K and the value efficiency design η_R considered 0.90. In the impeller outlet it was obtained p_2 = 8.6 MPa, T_2 = 332K, p_{02} = 10.8 MPa and T_{02} = 347 K.

4. THE IMPELLER PARAMETERISATION

The meridional channel was parameterized using two Bezier curves, representing the hub and shroud respectively. The rotor was placed in a cylindrical coordinate plane (r, θ, z), which were fixed radial direction and circumferential angle theta in the physical plane. Slight modifications in the meridional direction in the plane z were introduced as shown in Fig. (1).

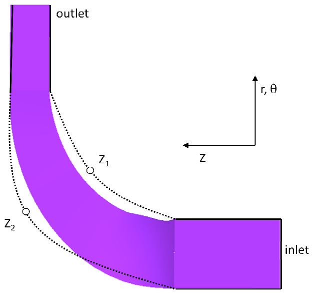

Figure 1. Sketch of the impeller parameterisation on the meridional plane.

Based on the principal dimensions of the compressor centrifugal, a *script file* was constructed with editing commands written in Tcl/Tk language, interpreted by the commercial software ICEM-CFD®. This methodology allows the automatic construction of the geometric and parameterized mesh. The periodic channel has been generated containing a single blade, since the geometry is perfectly regular and all surfaces are of revolution. For this simplification is appropriate to use the *Single Rotating Frame* SRF model, helping to reduce the computational cost (CFX®, 2006). Figure 2 shows the channel of the runner with the boundary conditions such as: inlet, outlet, blade-wall and periodic interfaces, hexahedrical mesh (1.373.049 elements**)** and the geometry of the channel periodically replicated.

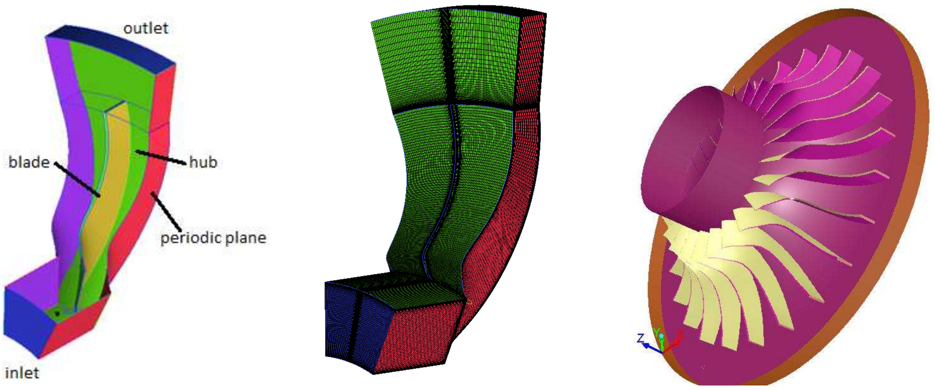

Figure 2. Periodic channel of centrifugal compressor, generated automatically from the *script file*.

5. PRELIMINARY RESULTS.

For the construction of metamodels were used a factorial plan with four levels and two variables (z_1, z_2) resulting in 16 experimental points. Table 1 shows the variation of z_1 and z_2, and the efficiency values calculated with CFX-CFD® in the DOE.

Table 1 – Plan of the Experiments.

Number Exp	z_{1} (m)	z_{2} (m)	Efficiency isentropic
1	-0.0624	-0.0374	88.034
2	-0.0624	-0.0374	88.034
3	-0.0624	-0.0364	88.067
4	-0.0624	-0.0359	88.080
5	-0.0618	-0.0374	88.088
6	-0.0618	-0.0364	88.100
7	-0.0618	-0.0359	88.113
8	-0.0612	-0.0374	88.102
9*	-0.0612	-0.0364	88.140
10	-0.0612	-0.0354	88.179
11	-0.0606	-0.0364	88.165
12	-0.0606	-0.0364	88.165
13	-0.0606	-0.0354	88.213
14	-0.0600	-0.0364	88.168
15	-0.0600	-0.0354	88.217
16	-0.0600	-0.0374	88.130

* Original design point

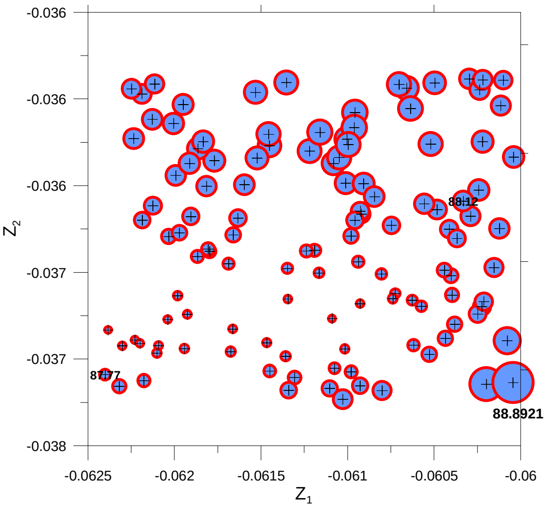

Figure 3. Historical of convergence with metamodels

These results (Table 1) are then used to build the metamodel through interpolation by radial basis functions (RBF). The metamodel is then used to calculate the isentropic efficiency of the centrifugal compressor. For this calculation were used 40(n +1) data points generated randomly. The Figure 3 shows a representation of bubble charts the historical of convergence with 120 points based on response surface.

For a final analysis, it is important to verify that the response of the efficiency obtained through the metamodel is also validated with the physical model quantified through the CFD.

These results are then used to build the metamodel through interpolation by radial basis functions (RBF). The metamodel is then used to calculate the isentropic efficiency of the centrifugal compressor. For this calculation were used 40(n +1) data points generated randomly. The Figure 6 shows a representation of bubble charts the historical of convergence with 120 points based on response surface.

Table 2 shows the calculated result with the response surface and CFD-CFX, may be noted that the metamodel was able to find a better efficiency better than that found in the original design point 9 (See table1). Other hand, Table 3 shows the excellent results reported by the metamodel and through the solution for direct CFX with the same values of z_1 and z_2. There is still the metamodel has an increase in efficiency isentropic.

Table 2 – Best results obtained with metamodels

z_{1} (m)	z_{2} (m)	Efficiency isentropic Metamodel	Efficiency isentropic CFD-CFX
-0,0600	-0,0373	88,8921	88,7812

6 CONCLUSIONS

This methodology has to be appropriate for applications where the turbo machinery flow calculation (3D) using CFD become extremely complex and high computational times become classical optimization applications unfeasible. In this sense it is important to build metamodels through interpolation with radial basis functions or higher order polynomial functions. To obtain numerical solution of the flow field in centrifugal compressor using CFX, was approximately one hour with an i7 processor (Core (TM) i7-2600 CPU 3.40GHz, 16.0 GB (RAM), Operational System 64-bit). The time it would take without the use of metamodels, with 120 points to consider would be approximately 120 hours or 5 days processing uninterrupted, considering as criteria for convergence in the transport equations of 10 -4 using CFX. As future work we intend to make a comparison of the efficiencies calculated by the use of metamodels and classical optimization.

7 ACKNOWLEDGMENTS

This work was supported by FAPEMIG and PROCAD/CAPES agencies.

8. REFERENCES

Came, P. M. And Robinson, C. J., 1999. “Centrifugal compressor design”. Proc. Instn Mech. Engrs, Part C, Journal of Mechanical Engineering Science.

Forrester, A. I. J., Sóbester, A. and Keane, A. J., 2008. “Engineering Design via Surrogate Modelling - A Practical Guide”, John Wiley & Sons Ltd.

Hardy, R. L., 1971. “Multiquadrics. A scattered data approximation scheme with applications to computational fluid-dynamics, II. Solutions to parabolic, hyperbolic and elliptic partial differential equations”. Computers Math Appl., 19(8-9), 147-161.

Jones, D. R., 2001. “A taxonomy of global optimization methods based on response surfaces”. Journal of Global Optimization, 21 (4), pp. 345–383.

Praveen, C. and Duvigneau, R., 2007. “Radial Basis Functions and Kriging Metamodels for Aerodynamic Optimization”, RR-6151, INRIA, France, 40 p.

Regis, R. G. and Shoemaker, C. A., 2005 “Constrained global optimization using radial basis functions”, Journal of Global Optimization, Vol. 31, pp. 153–171.

Vavra, M., 1970. “Basic elements for advanced design of radial flow compressors”. Agard Lecture Series N. 89 on Advanced Compressors.

Xu, C., 2006. “Design experience and considerations for centrifugal compressor development”. Proc. Instn Mech. Engrs, Part J, Journal of Aerospace Engineering .

Da Silva, E. R., Manzanares-Filho, N., Ramirez Camacho, R. G., 2012. “Metamodelling approach using radial basis functions, stochastic search algorithm and CFD – application to blade cascade design”. International Journal of Mathematical Modelling and Numerical Optimisation (IJMMNO). Vol3 – Issue 1/2, pp 87-92.