Applied Soft Computing 12 (2012) 3627–3635

Contents lists available at SciVerse ScienceDirect

Applied Soft Computing

journal homepage: www.elsevier.com/locate/asoc

Using genetic algorithms to improve the thermodynamic efficiency of gas turbines designed by traditional methods

Jose M. Chaquet [a,*], Enrique J. Carmona [b], Roque Corral [a]

[a] Technology and Methods Dep., Industria de Turbo Propulsores S.A., Avda de Castilla 2, 28830, San Fernando de Henares, Madrid, Spain
[b] Dpto. de Inteligencia Artificial, Escuela Técnica Superior de Ingeniería Informática, Universidad Nacional de Educación a Distancia, Madrid, Spain

ARTICLE INFO

Article history:
Received 15 July 2011
Received in revised form 25 April 2012
Accepted 4 June 2012
Available online 30 June 2012

Keywords:
Gas turbine
Thermodynamic efficiency
Genetic algorithm
Throughflow
Number of airfoils

ABSTRACT

A method for optimizing the thermodynamic efficiency of aeronautical gas turbines designed by classical methods is presented. This method is based in the transformation of the original constrained optimization problem into a new constrained free optimization problem which is solved by a genetic algorithm. Basically, a set of geometric, aerodynamic and acoustic noise constraints must be fulfilled during the optimization process. As a case study, the thermodynamic efficiency of an already optimized by traditional methods real aeronautical low pressure turbine design of 13 rows has been successfully improved, increasing the turbine efficiency by 0.047% and reducing the total number of airfoils by 1.61%. In addition, experimental evidence of a strong correlation between the total number of airfoils and the turbine efficiency has been observed. This result would allow us to use the total number of airfoils as a cheap substitute of the turbine efficiency for a coarse optimization at the first design steps.

1. Introduction

The *Low Pressure Turbine* (LPT) module has a major contribution in gas turbine engines with one third to the total weight and up to 20% to the total cost [12]. The LPT design process is a very challenging task. A lot of different constraints must be taken into account and usually the final decision on the particular optimum configuration needs a trade-off among different requirements.

The extraction of work from the fluid is done by means of several aerodynamic surfaces called *airfoils* that are placed in an annular way to form *rows*. A turbine *stage* consists of two consecutive rows, called *stator* and *rotor*. Stator airfoils are called *vanes*, whereas rotor airfoils are called *blades*. The stator is attached to the casing and directs the flow towards the rotor, whereas the rotor transmits the power to the turbine *shaft*. The number of airfoils in a row is called *NumberOff*.

In the literature related to this area, few works have been focused on the importance of the *NumberOffs*. For instance, work [21] investigates the influence of blade height and blade number on the performance of low head axial flow turbines for micro-hydro applications. The study concluded that the influence of blade number is higher than the blade height and that the choice of blade number should be carefully made. Other work where the number of airfoils is optimized can be seen in [13]. In that contribution the objectives were to simultaneously minimize the total pressure loss, maximize the total aerodynamic loading and minimize the number of airfoils for a turbomachinery cascade. Several constraints were taken into account, as fixed mass flow rate, fixed axial chord, fixed inlet and exit flow angles, etc.

Regarding the optimization process, the usual approach modifies the airfoil shapes, but without modifying the *NumberOffs*. For instance in [8] we can see the aerodynamic optimization of highly loaded turbine cascade blades for heavy duty gas turbine applications. The main target was the reduction of the total pressure losses, which is equivalent to increase the thermodynamic efficiency. Other works have been reported where airfoil shape optimization is performed not only for gas turbine engine airfoils [13,17] but as well for Micro-Air-Vehicle airfoils [6], propellers [7], wind turbine blades [11] and steam turbine airfoils [19].

In order to obtain performance variables such as thermodynamic efficiency, pressure losses, power, etc., the Navier–Stokes equations must be solved in the fluid domains. This is done with Computational Fluid Dynamics (CFD) solvers. One specific type of CFD solver for turbomachinery applications is the so called *throughflow* code [20,22], which computes the flow variables along all the rows. Navier–Stokes equations are circumferentially averaged solving the 2D flow field over a meridional plane. Using *throughflow* models in the optimization process is appealing because they can produce a fast design avoiding expensive full 3D CFD simulations [9,23,18]. *Throughflow* models have been used not only for airfoil optimization, but as well for other geometry optimization as we

* Corresponding author. Tel.: +34 91 207 9147.
E-mail addresses: jose.chaquet@itp.es, jose.chaquet@gmail.com (J.M. Chaquet), ecarmona@dia.uned.es (E.J. Carmona), roque.corral@itp.es (R. Corral).

1568-4946/$ – see front matter
http://dx.doi.org/10.1016/j.asoc.2012.06.009

can see in [14], where entropy minimization (or efficiency maximization) optimizes hub and shroud geometries and inlet and exit flow-field for each blade row of a two-stage axial flow gas turbine. Although *throughflow* codes could give accurate solutions, in some cases *throughflow* and 3D CFD solutions must be linked [5].

Several techniques have been used for Aerodynamic optimization, such as gradient-based schemes. These methods require knowledge about the aerodynamic derivatives for each parameter, which are normally expensive to compute. Furthermore, gradient-based methods cannot be applied to problems where there are discontinuities in the design space because the derivatives in these regions are not defined [15]. In such cases genetic algorithms (GAs) have demonstrated good performance. Multidisciplinary airfoil optimization (aerodynamic and acoustic) can be seen in [16] where a parallel GA was used to generate a family of aerodynamically efficient, low-noise rotor blade designs which represent the Pareto optimal set. The multiple objectives of that work were to maximize lift-to-drag of a rotor airfoil shape and to minimize an overall noise measure, including the effects of loading and thickness noise of the airfoil. More recently [6], a GA for optimizing the shape of low Reynolds number airfoils for generating maximum lift for Micro-Air-Vehicle (MAV) applications has been developed where the GA computational efficiency has been significantly enhanced with an artificial neural network (ANN). The authors showed that the combined GA/ANN optimization technique is capable of finding globally optimal airfoils accurately and efficiently. Another example of coupling a GA with an ANN can be seen in [11], where wind-turbine blades are optimized for generating maximum lift to drag ratio.

Regarding thermal system engineering, several recent works have shown that GAs can be successfully employed in the optimization of real power generation systems based on gas turbines. In this way, [4] presents the simulation and multiobjective optimization of a gas turbine power plant with preheater, [1] reports the optimization of a combined heat and power plant for cogeneration purposes, [2] makes a thermodynamic and exergoeconomic modeling and optimization of a gas turbine plant, and [3] gives an exergy, exergoeconomic and environmental analysis and optimization of several combined cycle power plants. Among other important parameters, the gas turbine isentropic efficiency is investigated as design parameter. It can be appreciated that improving the design of several key components (as the compressor, turbine or combustion chamber) important savings can be obtained in the complete cycle, not only from the thermodynamic point of view, but as well from other dimensions such as the environmental impact or the monetary costs. These complex systems usually require a trade-off between different requirements, so multiobjective optimization must be employed. Evolutionary algorithms such as GAs have proved to be very efficient for solving this type of problems.

This paper presents a method for optimizing the thermodynamic efficiency of a turbine while a set of geometric, acoustic and aerodynamic restrictions are fulfilled. The optimization problem at hand involves seeking a solution which maximizes the turbine efficiency fulfilling at the same time several constraints. In this context, the function to optimize is not guaranteed to be continuous. Therefore, it is not recommendable to use gradient-based methods. Moreover, we are interested in finding global optimum in a problem which naturally is multimodal due to the high dimensionality and complex relationship among the control variables. The large size of the search space makes direct methods such as exhaustive or random search impracticable [10]. Therefore the use of Evolutionary Computation (EC) paradigms is more suitable to that type of problems: a smooth continuous and derivable optimization fitness function is not required, and the use of a population of candidate solutions facilitates the global optimum finding. The ability of evolutionary algorithms to maintain a population of potential solutions not only provides a means of escaping from one local optimum; it also provides a means to manage large and discontinuous search spaces. As it will be shown in the next section, our initial constraint satisfaction problem can be reduced to optimize a real valued function of integer variables. This fact makes the use of a genetic algorithm (GA) more appropriated than other EC paradigms such as Evolutionary Strategies, more suitable for functions of real variables.

Unlike other approaches in the literature, the main control parameter used in this work for optimizing the efficiency is the number of airfoils for each row. This approach is applied to a turbine that has already been designed using a classical methodology. Fluid variables are computed using a *throughflow* solver. The approach adopted to solve the optimization problem uses a genetic algorithm (GA). The particular optimization performed considers the fluid variables as constant, so *throughflow* models are not updated until the GA run is finished. This approach saves computational time and makes the algorithm more robust. Since the GA geometry modification affects the flow field, there must be an iterative process between the *throughflow* and the GA. Convergence is achieved in only 2 or 3 global iterations in the given case studies.

In summary, the main contributions of the present work are the following:

- Improving the thermodynamic efficiency of an already designed by traditional methods aeronautical LPT using an evolutionary algorithm.
- Demonstrating that, for a given number of airfoils, it is possible to fulfill all the geometric constraints with a correct election of other design parameters such as chords and gaps between rows.
- Showing that a GA can successfully deal this type of constrained optimization problems.
- Showing the importance of reducing the total number of airfoils to improve the turbine efficiency, giving some possible recommendations for speed-up in the first steps of the design process.

In this article, first a description of the problem to solve is presented (Section 2). Then the GA approach (Section 3) and how the algorithm interacts with other design tools (Section 4) are described. The results obtained in the optimization of a real 13 row aeronautical gas turbine are presented for two different sets of constraints (Section 5). Finally, some conclusions and future works are given (Section 6).

2. Problem description

The problem consists of optimizing the thermodynamic efficiency of an LPT for a given flow-path (Fig. 1a) and aerodynamic exit angles. The optimization process has to fulfill a set of aerodynamic, acoustic and geometric restrictions that may be reduced to a set of explicit analytical expressions. As a consequence, the restrictions are extremely fast to evaluate.

In order to parametrize the problem, simplified geometry will be used to approximate each row to a rectangle (Fig. 1b). For a turbine of M number of rows, each row is defined with only 5 parameters: NumberOff (N_i), gap (g_i), chord (c_i), span (S_i) and mean radius (R_i) where i goes from 1 to M. The chord c_i for a given row i is defined as the axial length between the leading and the trailing edges, and the span S_i is the length of the row in radial direction. The mean radius is the distance from the middle point of the row to the turbine axis. There must also be one global variable L, which is the total axial length of the turbine. The turbine inner and outer annuli are supposed to be optimized in an outer loop and in this work are kept constant. Therefore the mean radius and the span of all the