PhD proposal DynFluid Laboratory, Arts & Métiers ParisTech

Robust 3D optimization of ORC turbine expanders

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Duration : 3 years ; Start October/November 2016

Required skills

The ideal candidate has at least a master degree level in mechanical/aeronautical engineering or applied mathematics, with a background in the fields of computational fluid dynamics. A reasonably good knowledge of one or more programming languages (fortran, C, C++, python) is mandatory.

Le candidat idéal est titulaire d'un diplôme d'ingénieur et/ou d'un diplôme de master recherché en mécanique, génie mécanique, génie énergétique, génie aéronautique, et possède des compétences dans le domaine de la mécanique des fluides numérique. Une connaissance adéquate d'un ou plusieurs langages de programmation (fortran, C, C++, python) est indispensable.

Research subject

Dense gases are defined as single phase vapors, characterized by complex molecules and moderate to large molecular weights. The use of dense gases as working media in turbomachinery, referred to as Organic Rankine Cycle (ORC) turbines, is proposed as a method of recovery of variable energy sources such as waste heat from industrial processes. Whereas a traditional Rankine Cycle operates with water vapor as the working fluid, ORC turbines use an organic fluid such as hydrocarbons, silicon oils or other organic refrigerants. The low critical temperature, high density and elevated heat capacities of these fluids result in high suitability for low temperature operation, even as low as 80℃ [1]. Furthermore, the slope of the saturated vapor line for organic fluids eliminates the risk of condensate at the turbine outlet, without heating the working fluid into the superheated vapor region. ORCs represent a promising technology for the development of widely distributed, small yield (from 5 kW to 1 MW) thermal energy conversion devices [2,3]. Proposed heat sources for ORC turbines typically include variable energy sources such as solar thermal collectors or waste heat from industrial processes. As a result, to improve the feasibility of this technology, the resistance to variable input conditions must be taken into account at an early stage of the development process.

Robust design has been developed to improve the product quality and reliability in industrial Engineering. The concept of robust design was introduced by Taguchi in the late 1940s and his technique has become commonly known as the Taguchi method or robust design [4,5]. Since 1980s, the Taguchi method has been applied to numerical optimization, complementing the deficiencies of deterministic optimization. This newly developed method is often called robust optimization and it overcomes the limitation of deterministic optimization that neglects the effect of uncertainties in design variables and/or design parameters. The robustness is determined by a measure of insensitiveness with respect to the variations. To consider the robustness, statistics such as mean and variance (or standard deviation) of a response are calculated in the robust optimization process. Hereafter, "statistics" imply mean and variance. Currently, there are significant difficulties associated with calculation of statistics, especially in Aerodynamics, where each single evaluation of the cost functions requires solving a complex nonlinear problem with many degrees of freedom.

In recent years, several robust optimization techniques for aerodynamic problems have been proposed [6,7,8]. In most cases, applications have been limited to simple problems, like flow around airfoils. Some applications to 2D compressor blades have also been investigated [9,10]. Nevertheless, most of these studies remain still generic and none of them have really addressed robust optimization of realistic ORC turbine expanders, taking into account real-world operation conditions. Moreover, robust optimization still remains very costly for fluid flow problems.

As part of a preceding research project (ORCHID+, cofounded by Enertime and ADEME and ANR TRENERGY *-TRain ENergy Efficiency via Rankine-cycle exhaust Gas heat recovery-*) the DynFluid

Laboratory developed fast 2D design tools for supersonic ORC injectors and rotor blades [11] and carried out preliminary investigations of the feasibility and the benefits of robustly optimized turbine expanders for ORC applications [12]. On the other hand, the research team explored more accurate and efficient robust optimization techniques for real-world applications [13].
The objective is to seek for a compact, highly efficient turbine expander with stable performance under highly variable operating conditions. The choice of the "stability" criteria requires specific sensitivity studies. The approach should lead to efficient 3D designs of the blades and to stable performance, specifically under highly variable operating conditions. A major difficulty for the application of automatic optimization tools to realistic 3D ORC turbine blades is the high computational cost of objective function evaluations. These are obtained by running a 3D CFD simulation per each design evaluated (for standard optimization), or multiple evaluations per design for robust optimization, multiple simulations being necessary for evaluating the averages and standard deviations of the objective functions.
The robust optimization approaches studied in the literature often combine evolutionary optimization algorithms, like genetic algorithms (GA) and an uncertainty quantification (UQ) technique. The GA may require several function evaluations before a converged solution is obtained. On the other hand, the UQ methodology may also require several function evaluations (i.e. CFD computations), according to the number of uncertain parameters and the UQ approach in use. Recently, our team investigated a promising, non intrusive, Kriging-based robust optimization technique was developed by coupling a Kriging uncertainty quantification method with a Kriging surrogate of the fitness functions, along with an automatic enrichment strategy. This approach was applied to the optimization of 2D ORC turbine blades and provided accurate solutions of the optimization problem with a minimal amount of cost-function evaluations and, consequently, a moderate computational cost, at least for problems characterized by a moderate (i.e. O(10)) number of uncertain parameters and design variables [14]. However, further research is required to make robust optimization feasible for complex 3D problems of industrial interest, like the ORC turbine under consideration in this project.

In this work we plan to couple a high-fidelity 3D CFD model for an ORC turbine blade with an advanced UQ method and an optimizer, in order to obtain robust 3D designs over a range of operating conditions. A crucial issue for the project is the development of an efficient robust optimization strategy for real-life problems, allowing to get a satisfactory solution by using a minimal amount of cost function evaluations, i.e., CFD runs. An efficient way for reducing the number of function evaluations required by the UQ method is to use information from the first and, possibly, second-order sensitivity derivatives to approximate the statistics of the cost functions by means of a Taylor-series development, albeit at the cost of lower accuracy. The computational cost of this UQ approach corresponds to one CFD calculation plus the solution of two linear equations. Moreover, the computational cost is nearly independent on the number of uncertain parameters taken into account (see, e.g. [15] for a discussion). This kind of approach, called a moment method, has been successfully explored in the context of the robust optimization of quasi-1D nozzles [16]. Applications to 2D ORC turbine cascades have been presented in [13]. One drawback of the method is that it is intrusive, i.e. requires modifications of the flow solver. As an alternative, information about the derivatives could also be integrated to Kriging response surfaces to improve the overall accuracy without increasing the number of samples. Finally, the information on the sensitivity derivatives can also be efficiently employed to speed-up the convergence of the optimization algorithm. Possible improvements to existing robust optimization techniques, in terms of both accuracy and efficiency, will be investigated. Gradient-based algorithms, hybrid gradient/evolutionary algorithms and surrogate-based approaches (see [17]) will be specifically investigated in the framework of ORC turbine design. In addition, multi-fidelity techniques, based on the mixed use of high-fidelity, costly models and low-fidelity unexpensive ones for cost function evaluations, like the one presented in [18] will be also investigated. The improved technique will be applied again to the design of the turbine expander, and compared to the previous results to measure the gains in computational efficiency and performance criteria.

The expected deliverables of the PhD are the following:

- An efficient UQ model for 3D ORC turbine simulations
- An efficient robust optimization strategy
- An optimization loop readily available to be used by the industrial partner in its design chain
- A 3D blade design for a specific application case

Tentative schedule:

- First year: bibliography, learning of the simulation code (DynHOLab) and of the UQ and optimization codes already existing at DynFluid. Implementation of some UQ techniques, validations, comparisons, selection of a few promising UQ strategies for robust optimization.
- Application of some existing optimization methods to a simplified ORC turbine configuration. Validations, comparisons. Development of an efficient robust optimization strategy.
- Further development of the robust optimization strategy, application to industrial cases. Preparation of the final manuscript.

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Enertime

Enertime is a company offering innovating energy solutions based on thermodynamics for energy efficiency and production of heat and power with renewable resources. In particular, Enertime designs, develops and implements Organic Rankine Cycle modules (ORC) to convert waste heat or heat produced with renewable resources into CO_2-free electricity. Enertime also develops high-temperature heat pumps and ad hoc turbomachines. Its headquarters are situated in Courbevoie, near Paris.

The DynFluid Laboratory and the Aerodynamics team

The DynFluid (Fluid Dynamics), created on January the 1st 2010 is recognized by the French Ministry of Higher Education and Research as *Equipe d'Accueil* 92. The laboratory belongs to the Ecole Nationale Supérieure d'Arts et Métiers (ENSAM), one of the most ancient and prestigious Engineering schools in France, and to Cnam (Conservatoire National des Arts et Métiers). The team has a recognised expertise in the development of numerical methods for compressible flows, numerical simulation and analysis of turbulent compressible flows, computational aeroacoustics, and their applications of internal and external high-speed flows.
The position is opened in the framework of a long-term collaboration between DynFluid and Enertime.

Workplace
The DynFluid Laboratory is located in the city centre of Paris, 13e Arrondissement. Part of the work (1/3 to ½ of the whole time) will be conducted at Enertime Headquarter in Courbevoie.