Turbocharger Design Optimization by Adjoint Method Coupled with CHT Analysis

Abstract

The thesis deals with the problem of the multidisciplinary design optimization of thermally stressed turbomachinery components, with focus on a turbocharger radial turbine impeller for automotive applications.

Thermal analyses are usually excluded from standard optimization frameworks because of their high computational cost. Therefore, significant engineering margins are applied to the design process, in order to avoid any unexpected failure related to thermal events appearing during the component validation phase. The shortcoming about this practice is related to the highly constrained problem the optimizer is requested to deal with, resulting in reduced opportunities of identifying the truly optimal solution. Hence, the work herein is devoted to the introduction of thermal analyses within the scope of the optimization of complex geometries, by the development of a computationally affordable framework based on the discrete adjoint method.

The first part of the manuscript addresses the problem of the thermo-mechanical stresses that develop in the turbomachinery components operating in steady state conditions. The thermal Fluid-Structure Interaction phenomenon is numerically described by the Conjugate Heat Transfer (CHT) method. In particular, a partitioned coupling technique is adopted to separately solve the fluid and the solid domains with dedicated meshes and specialized solvers. The conjugate coupling is based on the heat transfer Forward Flux Back (hFFB) method, which offers stability properties particularly suited to the turbine impeller problem investigated in the present work.

The interaction between the fluid and the solid domains is established by the development of an interface, aimed at allowing the exchange of information between a multiblock structured mesh and an unstructured grid of second order tetrahedral elements. A distance-weighted interpolation technique is adopted herein because of its robustness in treating meshes of any complexity, as well as cases of locally overlapping grids. The original procedure is revised by multiple improvements addressing the accuracy and the memory footprint of the method.

A heat transfer model based on a FEM linear solver is developed for the evaluation of the energy balance within the solid. Concerning the fluid side, the in-house CFD solver available in CADO is integrated in the present framework. The solid temperature field returned by the iterative hFFB process is transferred to a FEM linear mechanical solver in order to compute the thermal strains in the material, contributing to the prediction of the thermo-mechanical stresses. The latter represents the cost function of the problem, which is seeded for its introduction in an adjoint workflow aimed at computing the sensitivities of the maximum von Mises stress w.r.t. the fluid and the solid grid points coordinates.

The adjoint framework is developed by the manual differentiation of the primal workflow in reverse mode through an Algorithmic Differentiation approach, with the goal of optimizing its memory footprint. In this respect, the perturbations to the state variables are propagated throughout the workflow by walking the primal development in opposite direction, till the original location of the grids generation routines. During the evolution in reverse mode, the relevant adjoint variables are exchanged at the interface of the two domains, and the grid sensitivities are accumulated at any call to the fluid and the solid solvers. Finally, those gradients, once multiplied by the sensitivities of the grid coordinates w.r.t. the CAD parameters, are transferred to a Sequential Quadratic Programming algorithm.

The framework is successfully applied to a turbine rotor test case previously optimized under the assumption of adiabatic walls. Hence, it is demonstrated that the thermal evaluations are a necessary means to improve the structural robustness during the design optimization of such components.

The second part of the thesis expands the outreach of the thermal analysis to unsteady conjugate problems with the aim of optimizing the Thermo-Mechanical Fatigue (TMF) lifetime of components experiencing cyclic operations. The transient phenomenon is numerically described by a quasi-dynamic approach leading to the decomposition of a transient manoeuver in separate stretches, each one analyzed by an iterative hFFB approach. The loose coupling framework developed for steady state problems is revised for the scope of the analysis of transient operations by introducing an unsteady FEM non-linear heat transfer solver interfacing with the in-house steady state CFD solver. The mutual exchange of information between the two domains is iterated at each stretch of the manoeuver till the achievement of convergence of the conjugate coupling. The resulting transient temperature field is transferred to an unsteady FEM linear mechanical solver for the evaluation of the solid thermo-mechanical response along the manoeuver. A set of constitutive equations is included in the prediction of the unsteady displacements field in order to capture any accumulation of local plasticity, under the assumption of the operations in the small-strains region. The evolution of the strains and the stresses in the solid is finally conveyed to the Morrow model, a strain-life method aimed at computing the fatigue lifetime under cyclic conditions.

The durability of the component represents the new cost function, which is seeded to kick off the adjoint workflow. Consistently with the development in steady state conditions, the primal workflow is manually differentiated by a reverse Algorithmic Differentiation technique, and the adjoint variables are propagated in opposite direction.

The novel framework is evaluated in the case of a radial turbine impeller experiencing different transient manoeuvers, and proves its effectiveness in capturing the impact of the thermal non-equilibrium during the unsteady computations, thus leading to the development of thermal strains and thermal stresses not present in steady state operations. Finally, the adjoint framework returns the sensitivities of the component lifetime, providing the directions for the perturbations of the grid coordinates necessary to enhance the impeller TMF resistance.