**ΕΘΝΙΚΟ**
**ΜΕΤΣΟΒΙΟ**
**ΠΟΛΥΤΕΧΝΕΙΟ**
ΣΧΟΛΗ ΜΗΧΑΝΟΛΟΓΩΝ ΜΗΧΑΝΙΚΩΝ

Α.Π. :
Αθήνα,

ΚΟΣΜΗΤΟΡΑΣ

**Προς τα Μέλη ΔΕΠ της**
**Σχολής Μηχ/γων**
**Μηχ/κών**

## ΠΡΟΣΚΛΗΣΗ

Σας προσκαλούμε στην παρουσίαση της Διδακτορικής Διατριβής του Υ.Δ. **κ. Βασιλόπουλου Ηλία** του Χρήστου, κατόχου Διπλώματος Μηχανολόγου Μηχανικού, την οποία εκπόνησε στον Τομέα **Ρευστών** . Η παρουσίαση θα πραγματοποιηθεί την *Τετάρτη 27 Μαΐου 2020* , ώρα 11:00π.μ διαδικτυακά. Ο ελληνικός τίτλος της Διδακτορικής Διατριβής είναι ο εξής :

«*Αεροδυναμική Βελτιστοποίηση Μορφής Πτερυγώσεων Στροβιλομηχανών με τη Συζυγή Μέθοδο, με και χωρίς χρήση CAD*»
Και ο Αγγλικός ως εξής:
«*CAD-based and CAD-free Aerodynamic Shape Optimization of Turbomachinery Blade Rows using the Adjoint Method*»

Όποιος ενδιαφέρεται να την παρακολουθήσει παρακαλείται να στείλει email (kgianna@mail.ntua.gr) ώστε να του δοθεί πρόσβαση.

**Ο Κοσμήτορας της Σχολής**

**Ν. Μαρμαράς**
**Καθηγητής Ε.Μ.Π**

National Technical University of Athens
School of Mechanical Engineering
Fluids Section
Laboratory of Thermal Turbomachines
Parallel CFD & Optimization Unit

# CAD-based and CAD-free Aerodynamic Shape Optimization of Turbomachinery Blade Rows using the Adjoint Method

# Αεροδυναμική Βελτιστοποίηση Μορφής Πτερυγώσεων Στροβιλομηχανών με τη Συζυγή Μέθοδο, με και χωρίς χρήση CAD

***Ilias C. Vasilopoulos***

*Academic Advisor*: Kyriakos C. Giannakoglou, Professor NTUA
*Industrial Advisor*: Marcus Meyer, PhD, CFD Methods, Rolls-Royce Deutschland

## PhD Thesis Abstract

This PhD thesis deals with the gradient-based aerodynamic shape optimization of 3D turbomachinery blade rows, where the sensitivity derivatives of the objective functions with respect to (w.r.t.) the design variables are computed by coupling a new discrete adjoint CFD solver with a differentiated CAD model. First, to increase the efficiency of the Rolls-Royce in-house Hydra adjoint code, an implicit iterative solution scheme is developed (replacing the pre-existing explicit one) and the resulting implicit adjoint solver accelerates the convergence significantly. Then, a node-based CAD-free parameterization as well as alternative CAD-based approaches for computing geometric sensitivities (and, thus, making the shape optimization steps fully compatible with the CAD model) are tested and evaluated according to industrial design requirements (such as geometric constraints' imposition). All the developed tools are incorporated into gradient-based optimization workflows, which are demonstrated on the examined applications (cases A–C; listed below). Finally, to be able to optimize w.r.t. more than one objectives, a new multi-objective optimization method is developed, which traces the Pareto front in an efficient way using Hessian approximations computed by the BFGS iterative scheme.

The Hydra steady flow/primal solver discretizes the compressible RANS equations with the Spalart-Allmaras turbulence model, and then solves them using a Runge-Kutta pseudo-time-marching scheme, accelerated by a geometric multigrid technique. This flow solver is validated in this work against measurements on case A. The discrete adjoint method is formulated for turbomachinery-related objectives (e.g. total pressure losses, exit flow angle, capacity) and the derived system of equations is solved using a consistent adjoint Runge-Kutta scheme. Algorithmic differentiation (AD) is employed to compute the adjoint right-hand-side terms. For the development of the implicit adjoint solver, the block-diagonal explicit preconditioner matrix is replaced by the first-order Jacobian and its inversion is applied by solving a linear system, using either the ILU-preconditioned Richardson or the GMRES method. This new adjoint solver is tested on various turbomachinery applications (cases A–C, including a 3-row turbine) and a convergence speed-up of ~ 8 times is gained in comparison to the explicit solver. Grid sensitivities are computed via the Hydra mesh-adjoint post-processor, where adjoint surface sensitivities are obtained by applying the reverse operation of a spring-based grid deformation algorithm to the volume sensitivities.

To perform a CAD-free shape optimization, the node-based parameterization is considered. In terms of grid deformation (to update the volume grid according to the shape deformation during the optimization), a pre-existing elastic medium analogy implementation is selected and enriched with additional functionalities needed for turbomachinery applications (e.g. a sliding capability allowing boundary nodes to move along the casing during a rotor's tip deformation). Smoothing of the noisy adjoint surface sensitivities is applied using an approach based on the Sobolev gradient projection. These required tools are integrated within a CAD-free optimization framework, which is demonstrated on case A by omitting any geometric constraints.

To keep the parameterized geometry within the optimization loop, a feature desired in industrial design processes, the following four alternative CAD-based approaches are implemented, tested and evaluated.

- *CAD Design Velocities*: This already established approach allows the computation of geometric sensitivities in case commercial (closed-source) CAD packages are used. In particular, these sensitivities are obtained by applying finite differences (FD) between discrete representations of the CAD geometry before and after a parameter perturbation. Here, an interface is created for coupling geometric sensitivities w.r.t. native CAD parameters in Siemens NX with the surface sensitivities obtained by the adjoint solver.
- *FD Outside the CAD*: A similar FD approach is implemented to compute geometric sensitivities in case a grid generation tool providing structured grids with fixed topology (e.g. PADRAM) is available. The computation is performed outside the CAD tool, where the perturbed geometries are re-meshed (fine CFD grids are generated here; in contrast to the relatively coarse triangulations used for the projections/FD in the previous approach, whose fixed topology allows tracking of the nodes). Due to re-meshing for each design variable, this approach can be time-consuming.
- *FD Inside the CAD*: To avoid using re-meshing loops, an alternative FD geometric sensitivity computation is implemented inside Parablading, the Rolls-Royce in-house blade design tool, by exploiting the NURBS analytical description and keeping the node parametric coordinates fixed. This approach still scales with the number of design variables, but is more efficient than the previous one.
- *AD of the CAD*: A CAD-based parameterization for compressor blades is differentiated in forward AD mode using an operator-overloading technique and, thus, exact geometric sensitivities w.r.t. compressor design parameters are computed. The results are found to match very well those computed by the third approach with a lower, though, computational cost.

To deal with the solution of multi-objective optimization problems (typically encountered in industry and, usually, tackled using evolutionary algorithms), a new adjoint-based method is developed. It relies on an iterative prediction-correction algorithm for efficiently tracing the Pareto front. The main difference from other continuation techniques exists in the formulation of the KKT conditions, where a distance function is treated as the objective to be minimized. The BFGS technique is properly embedded into the method to approximate the Hessian information required at each prediction step of the algorithm.

Overall, the turbomachinery applications presented in detail include:

- Case A: Compressor stator (outlet guide vane) with high turning.
- Case B: Turbine nozzle guide vane with a trailing edge cooling slot.
- Case C: Turbine rotor with a winglet feature.

CAD-based sensitivity derivatives of capacity and total pressure losses are computed and verified against FD for cases B and C, respectively. Case A is primarily used, throughout this thesis, to perform optimizations utilizing the developed workflows. Three optimization problems are defined for case A; an unconstrained CAD-free optimization, a constrained multi-point (three operating points) CAD-based optimization and a constrained bi-objective CAD-based optimization. Moreover, the optimal stator from the second optimization was manufactured using 3D printing and its performance is validated from experimental measurements conducted by the Technical University of Berlin in a wind tunnel.

Part of this work was conducted under the IODA ITN, a 3-year Research Fellowship Programme of the European Commission funded by Marie Skłodowska-Curie Actions.

**Keywords**: Computational Fluid Dynamics, Discrete Adjoint Method, Shape Optimization, Turbomachinery Blade Rows, Computer Aided Design, Algorithmic Differentiation, Geometric Sensitivities.

Athens, 2020