Generating Gradients for Turbomachinery Applications using the Discrete Adjoint Method

Georgios Ntanakas*†and Marcus Meyer*

*Rolls-Royce Deutschland, Blankefelde-Mahlow, 15825, Germany

†School of Mechanical Engineering, National Technical University of Athens, Athens, 15780, Greece

The steady adjoint method is already efficiently and actively employed for gradient-based CFD optimization problems in many industrial applications.[3,8,10,11,13] In almost all of those examples, the steady state assumption is used in order to reduce the computational cost of the optimization. However, the recent increase in the availability of compute power is currently leading to a paradigm shift: The use of unsteady simulations in time scales compatible with industrial design cycles is now becoming feasible.

Especially in turbomachinery applications, where the flow is inherently unsteady due to the interaction of stationary and rotating blade rows, unsteady simulations are necessary to avoid the simplifying assumption of the so-called mixing plane coupling[14,15] between blade rows. Instead, a sliding plane coupling is used to increase the model accuracy.[1,2]

In order to enable efficient gradient-based optimization of these unsteady models, it is thus necessary to develop an unsteady adjoint capability: The URANS flow equations are solved using a dual time-stepping technique until a periodic solution is obtained. The objective function of interest is usually defined as the mean of a scalar value of interest (for example the efficiency of the compressor or turbine under consideration) over the period T of the periodic flow solution. The length of the period is defined by the blade count of the blade rows and the rotational speed, from which the dominating frequencies that occur in the model can be calculated. The approach described in this paper can also be applied to non-periodic flows but for the scope of this work and without loss of generality, periodicity of the solution is assumed. Storing the primal flow is essential, since the adjoint solver needs the primal flow during the backwards-in-time marching of the adjoint solver. In the present paper, an overview of the discrete unsteady adjoint method is presented. The final equations are derived and the connection with the steady equations is discussed. Moreover, the additional disk-storage and time cost that is introduced by the unsteadiness is evaluated. The method is applied to testcases to show its capability to enable the efficient optimization of unsteady turbomachinery models.

References

[1] D. Amirante, N. J. Hills, and C. J. Barnes. A moving mesh algorithm for aero-thermo-mechanical modelling in turbomachinery. *International Journal for Numerical Methods in Fluids*, (October 2007):601–629, 2008.

[2] M. Burgos, J. Contreras, and R. Corral. Efficient Edge-Based Rotor/Stator Interaction Method. *AIAA Journal*, 49(1):19–31, jan 2011.

[3] C. Frey, H.-P. Kersken, and D. Nürnberger. The Discrete Adjoint of a Turbomachinery RANS Solver. *ASME Conference Proceedings*, 2009(48883):345–354, 2009.

[4] M. B. Giles and N.A. Pierce. An Introduction to the Adjoint Approach to Design. pages 393–415, 2001.

[5] M.B. Giles. On the use of Runge-Kutta time-marching and multigrid for the solution of steady adjoint equations. 2000.

[6] L. Hascoët and V. Pascual. The Tapenade Automatic Differentiation tool: Principles, Model, and Specification. *ACM Transactions On Mathematical Software*, 39(3), 2013.

[7] A. Jameson, S. Shankaran, and L. Martinelli. Continuous adjoint method for unstructured grids. *AIAA Journal*, 46(5):1226–1239, May 2008.

[8] N. Kroll, N. R. Gauger, J. Brezillon, R. Dwight, . Fazzolari, D. Vollmer, K. Becker, H. Barnewitz, V. Schulz, and S. Hazra. Flow simulation and shape optimization for aircraft design. *Journal of Computational and Applied Mathematics*, 203(2):397 – 411, 2007.

[9] K. Mani and D.J. Mavriplis. Geometry Optimization in Three-Dimensional Unsteady Flow Problems using the Discrete Adjoint. 2013.

[10] A. C. Marta, S.m Shankaran, and A. Stein. Blade Shape Optimization using a RANS Discrete Adjoint Solver. *2nd International Conference on Engineering Optimization*, pages 1–10, 2010.

[11] M. Meaux and M. Cormery. Viscous aerodynamic shape optimization based on the discrete adjoint state for 3d industrial configurations. m:1–19, 2004.

[12]E. J. Nielsen, B. Diskin, and N. K. Yamaleev. Discrete adjoint-based design optimization of unsteady turbulent flows on dynamic unstructured grids. *AIAA Journal*, 48(6):1195–1206, Jun 2010.

[13]E. M. Papoutsis-Kiachagias and K. C. Giannakoglou. Continuous adjoint methods for turbulent flows, applied to shape and topology optimization: Industrial applications. *Archives of Computational Methods in Engineering*, pages 1–45, 2014.

[14]S. Rodrigues and A. Marta. Discrete adjoint mixing-plane formulation for multi-stage turbomachinery design. *Congresso de Metodos Numericos em Engenharia*, 2015.

[15]D. X. Wang and L. He. Adjoint Aerodynamic Design Optimization for Blades in Multistage Turbomachines-Part I: Methodology and Verification. *Journal of Turbomachinery*, 132(2):021011, 2010.

Acknowledgements

This work was supported by the *AboutFlow* project (`http://aboutflow.sems.qmul.ac.uk`), funded by the European Commission under FP7-PEOPLE-2012- ITN-317006.