Experimental and numerical investigation of secondary flow structures in an annular LPT cascade under periodically wake impact – Part 2: numerical results

Benjamin Winhart, Martin Sinkwitz, David Engelmann, Chair of Thermal Turbomachinery, Ruhr-Universität Bochum, Bochum, Germany
Ronald Mailach, Chair of Turbomachinery and Flight Propulsion, Technische Universität Dresden, Dresden, Germany

Long Abstract

Introduction and Theory

In the course of cost and weight reduction of aero engines, (ultra-) high-lift turbine blade profiles were developed allowing engine operation with reduced blade count. The remaining - heavy-loaded - blades are exposed to increased pressure gradients, affecting in particular near wall flow that is prone for separation anyway. Augmented probability of boundary layer separation at end-walls and on the profile suction side result in pronounced secondary flow systems. These in turn are attributed to high loss and main flow perturbation [1]. Different models of secondary flow have been proposed, extended and modified, resulting in a basic, broadly accepted, secondary flow model. It is mainly built up of passage vortices (PV), horse shoe vortices (HSV), tip leakage vortex (TLV), corner vortices (CV) and a vortex street that is shed at the blade trailing edge. A few of the models incorporate yet another vortex structure originating from the separated suction side boundary layer, named concentrated shed vortex (CSV) [2]. It is a consequence of end-wall boundary layer fluid (PV) impinging on the blade suction side and leading to separation of the suction side boundary layer itself close to the end-wall.
Analysis and potential reduction of these vortex systems are complicated by the multistage environment in turbomachinery, superimposing the impact of rotor stator interaction, including transport and shedding of blade wakes and vortices. An extremely non-uniform, distorted and time-dependent flow field is resulting. Thus, it is sophisticated to separate distinct interacting flow structures from each other and to determine their degree of influence on aerodynamic loss generation mechanisms.
Numerous tests have been conducted under simplified conditions in linear cascades. To add the influence of periodically unsteady incoming wakes shed by upstream rotor blades in linear cascades, linear wake generators have been developed, that use cylindrical bars to simulate wakes [3, 4, 5, 6, 7, 8, 9]. However, study of secondary flow with help of linear cascades neglects several essential influences present in real turbomachinery flow.
In this study an experimental setup for time-resolved analysis of wake-stator interaction is presented that incorporates the influence of curvilinear end walls, non-uniform, radially increasing pitch and radial flow migration. This is achieved by making use of an annular geometry instead of a linear cascade. Incoming wakes are generated by a variable-speed driven rotor disk equipped with cylindrical bars.

Results reported in this two-part paper discuss the impact of periodically unsteady wakes on a modified T106 profile LPT stator row. Special emphasis is put on wake-induced time-dependent dilatation of individual components of the vortex system. Furthermore, the interaction between wake and boundary layer flow and so potential separation along the blade suction surface is studied.

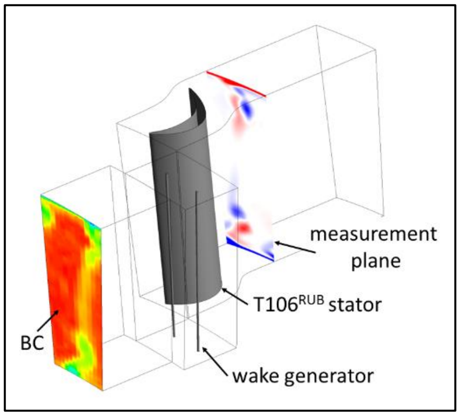
In Part 2 of this paper, numerical results achieved through 3D Unsteady Reynolds-Averaged Navier-Stokes (URANS) simulations are validated against stationary and time resolved experimental results by means of 2-dimensional field data and pressure signals located at blade surface and end-walls. The advantage of high spatial resolution of the obtained numerical data is then used to precisely locate the origins of secondary flow structures and the time-dependent interactions between those and the incoming wakes.

1. Numerical Setup

The numerical analysis conducted in this investigation is done using the commercial flow solver ANSYS CFX v17.0 release. In order to provide accurate boundary conditions (BC) a highly resolved 2D-traverse of total pressure, total temperature and the velocity components was measured in front of the wake generator and interpolated onto the numerical grid at the inlet.

An extensive timestep and grid influence study was conducted to assure the sufficient resolution of all important flow pheneomena, such as wakes and secondary flow structures. The final grid consists of 3.3 mio elements resulting in a non-dimensional wall distance of $y^+ \approx \mathcal{O}(1)$ along the blade surface as well as hub and shroud walls.

The numerical domain including the interpolated inlet BC is shown in Fig. 1 (left) together with the final mesh of investigated T106^{RUB} stator (right).



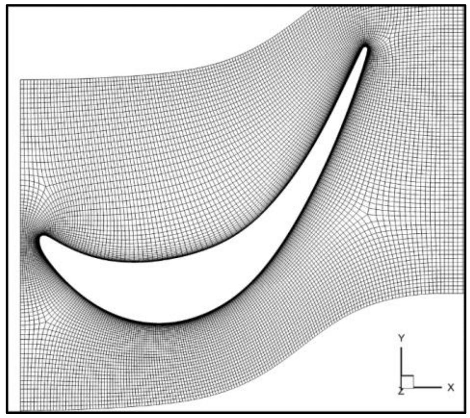


Fig. 1: Numerical domain and inlet BC (left); Mesh of investigated T106^{RUB} stator (right).

2. Numerical Results

The numerical results are in good accordance to the experimental data. Fig. 2 shows the distribution of pressure coefficient $c_p = \frac{p(x)-p_{s2}}{p_{t2}-p_{s2}}$ along 50% span wise coordinate compared to the measured data.

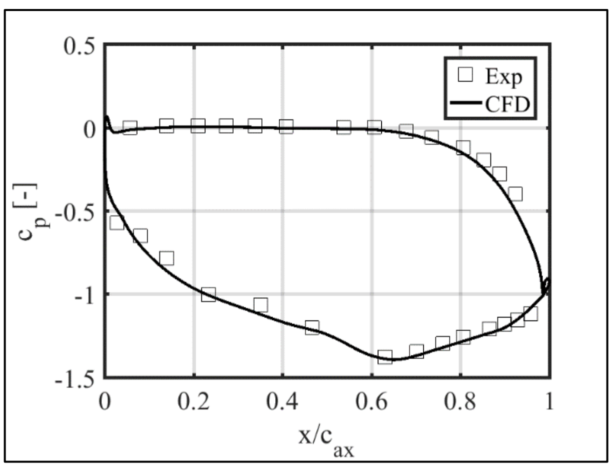


Fig. 2: Distribution of pressure coefficient c_p along 50% span wise coordinate

Unsteady CFD- and measurement data revealed that the incoming wakes generated by the rotating bars have significant influence on the development of the secondary flow system occurring in the T106^{RUB} stator passage. For illustration the distribution of total pressure loss coefficient $\zeta_p = \frac{p_{t1}-p_t(y,z)}{p_{t,1}-p(y,z)}$ is shown in Fig. 3 for different phase angles ϕ of wake generator passing. It can be stated that there is a strong impact of incoming wakes on the loss mechanisms caused by the secondary flow structures. This is due to the fact that incoming wakes periodically enhance and damp different components of the vortex system which are interacting. The unsteady behavior of these phenomena will be discussed in the final paper as well as the connection to the interaction between wakes and boundary layers. Therefore the unsteady simulations were carried out at different operating points by varying flow coefficient φ and Strouhal number *Sr.*

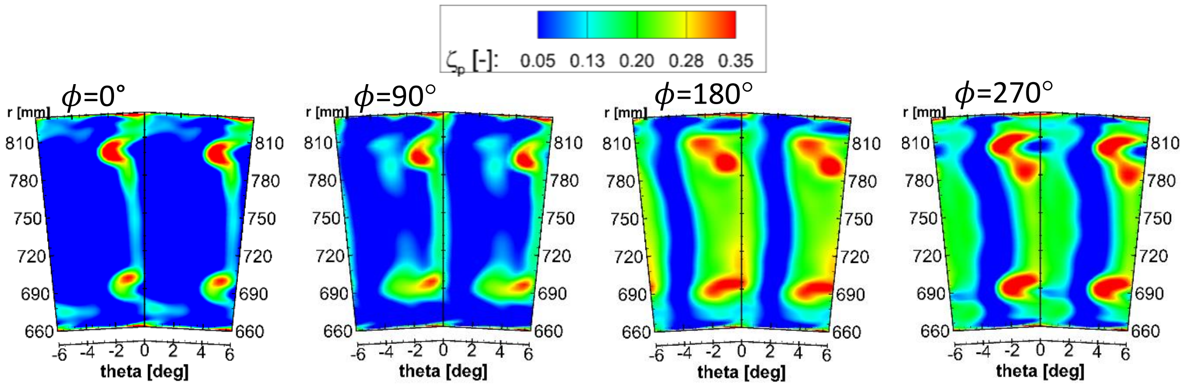


Fig. 3: total pressure loss coefficient ζ_p at different passing phase angles (Sr = 2.7, φ = 0.95)

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