Experimental and numerical investigation of secondary flow structures in an annular LPT cascade under periodically wake impact – Part 1: experimental results

Martin Sinkwitz, Benjamin Winhart, 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 1 of this paper, the measuring concept for an in-depth analysis of the described unsteady flow phenomena is presented and results from highly resolved time-averaged and time-resolved experimental investigations are discussed. The distinction between time-averaged and time-resolved analysis of secondary flow phenomena and the importance of time-resolved measurement is stressed. By relating measurement data of two-dimensional flow field traverses, end-wall passage pressure distributions as well as blade profile pressures to each other, a profound interpretation of the complex interaction between wake, boundary layer and secondary flow is facilitated. By altering both bar pitch and bar circumferential velocity independently of one another, the sole influence of flow coefficient and Strouhal number (reduced frequency of flow perturbation) can be quantified. It is evaluated how these variables can contribute to a time-dependent homogenization of stator exit flow and a consequent loss reduction in the present configuration.

1. Experimental Test Facility

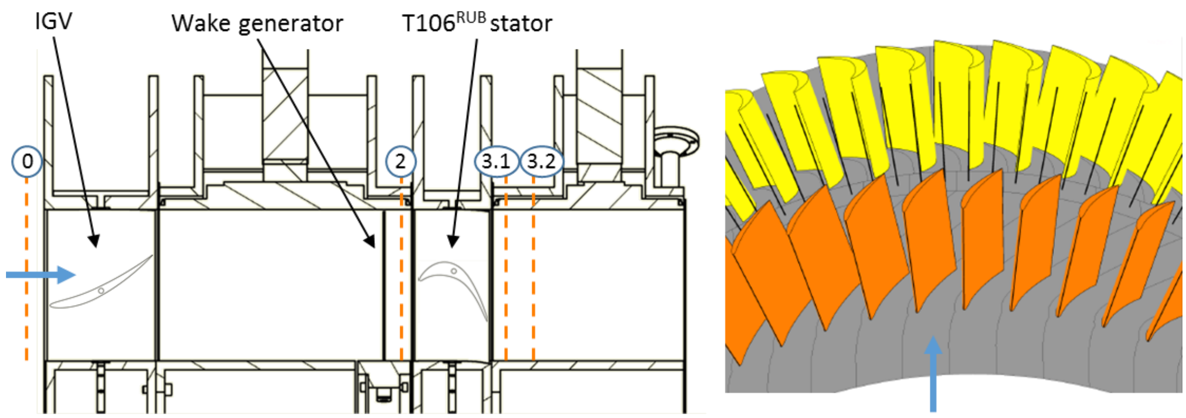

Fig 1. Experimental Test Facility.

For this study an existing large scale, full annular, axial flow turbine test rig was retrofitted to allow highly resolved measurements of unsteady wake stator flow interaction. The test facility is operated continuously in an open circuit, with air at ambient conditions as the working medium. Flow is induced by a 150 kW variable-speed engine coupled to a radial blower capable of $\dot{m}$ = 13 kg/s. The large dimensions of the flow channel allow detailed flow measurements with negligible blockage and perturbation.

The aft-loaded blade profile under investigation is a modified T106 LPT blade, specified as T106^{RUB}. It is characterized by a cylindrical geometry, chord length of C = 0.1 m and an aspect ratio of H/C = 1.7. An Inlet Guide Vane (NACA 8408 profile) was installed for ensuring proper inflow angles to the stator. The IGV row was developed for correct flow turning whilst perturbing the T106^{RUB} inflow as few as possible with additional wakes and secondary flow structures.

For generating simulated blade wakes the rotor disk was equipped with radially stacked steel bars. This allows to isolate velocity defect and increase of turbulence of rotor blade wakes without the additional secondary flow system, associated with flow turning. The wakes are generated in a plane parallel to the stator leading edges, located at an axial distance of 0.33 C upstream of the LE, which represents a typical axial gap width in a LPT. The investigations discussed in this paper were carried out for three different values of bar pitch resulting in total pressure loss coefficients between 2.2 % and 6.5 %. The rotor shaft is driven by a 15 kW AC engine controlled by a frequency converter.

2. Measurement Techniques

For this study two-dimensional (in radial and circumferential direction), time-averaged and time-resolved flow field traverses have been carried out. For time-averaged traverses miniature 5HP were employed. Hot wire anemometry measurements (CTA mode) provided time-resolved traverse data and were conducted with a combination of two different types of Split Fiber Probes (SFP). Measurement data of both SFP is post-processed for obtaining time-resolved, three-dimensional flow vectors.

For determination of the immediate structure of periodically generated wakes the axial gap between bars and stator LE was traversed (plane 2, see Fig **1**). Finally two additional planes downstream of stator TE (planes 3.1 and 3.2) were traversed for quantifying wake impact on the downstream secondary flow system.

Furthermore time-averaged and time-resolved measurements of passage end-wall pressures and turbine blade profile pressures have been conducted.

For all investigations theoretical exit Reynolds number was kept constant at $Re_{exit,th}$ = 200,000 (based on T106^{RUB} chord length and theoretical exit velocity $c_{exit,th}$).This is a typical value for LPT operation at high altitude where suction-side separation can occur.

Flow coefficient φ and Strouhal number Sr have been identified as the main dimensionless quantities for characterizing unsteady flow disturbances [3]. To study the effect of different periodically unsteady inflow conditions (disturbance by incoming wakes) they have been varied in wide ranges including values for typical LPT operation. As the axial velocity is approximately held constant, Sr and φ are modified by altering bar speed u_B (circumferential velocity) and/or bar pitch g_B. By changing bar pitch, Sr and φ can be altered independently from one another.

3. Experimental Results

In combination with the acquired flow-field traverses, a link can be established between passage flow (on profile and near end-wall) and resulting secondary flow structures downstream of the stator. Analysis of combined time-resolved measurement data in the time-domain allows examination of periodically unsteady flow phenomena of the secondary flow system. By comparison of both measurement planes downstream of the stator, the mixing behavior of individual vortices under different Strouhal number and flow coefficients is discussed.

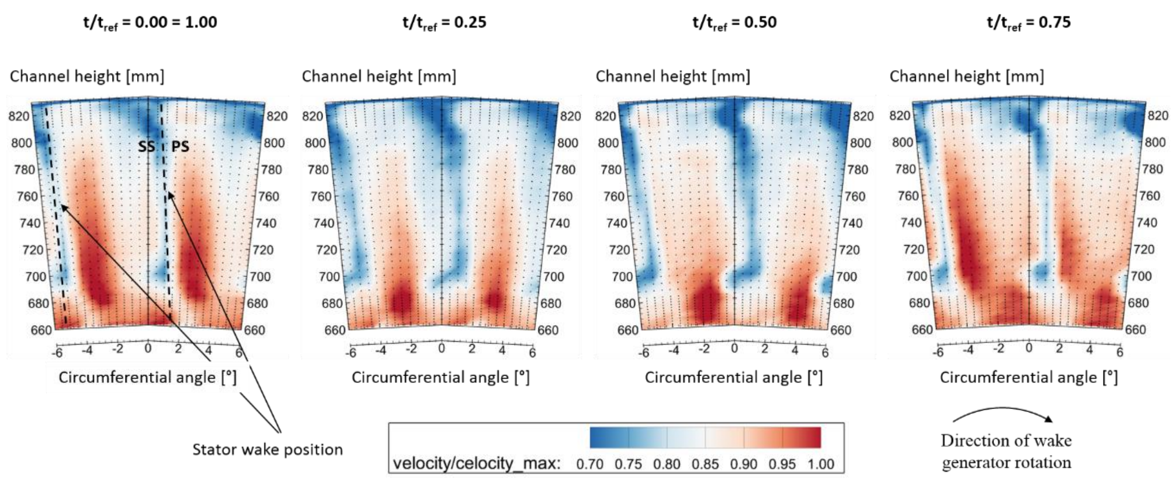

Fig 2. Time-resolved results in stator exit plane. Temporal evolution of non-dimensional velocity for one bar passing, divided into 4 time steps.

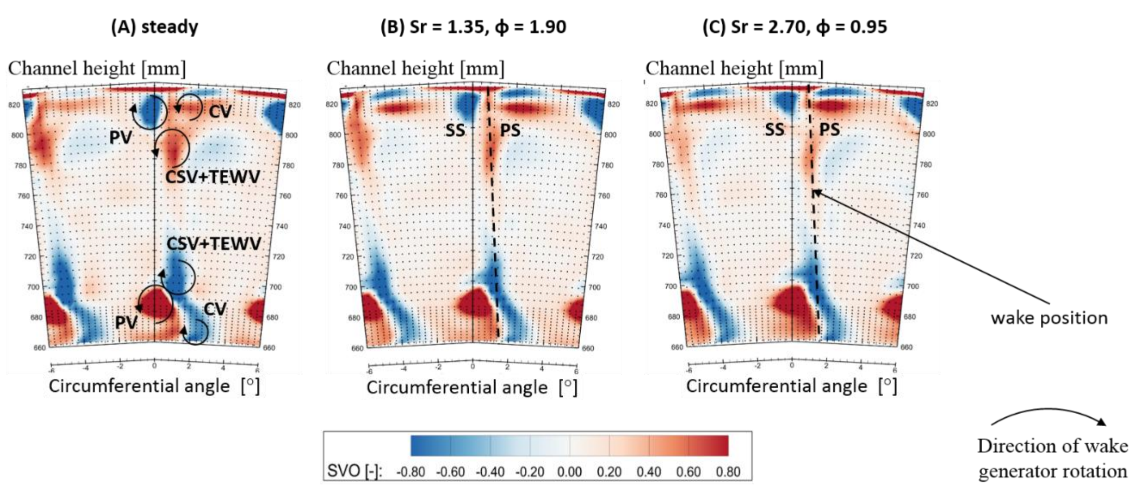

Fig 3. Time-mean results in stator exit plane. Vorticity for undisturbed case (left, A) and for two cases disturbed by bar wakes (mid, B and right, C).

References

[1] P. Puddu, C. Palomba and F. Nurzia, "Time-Space Evolution of Secondary Flow Structures in a Two-Stage Low-Speed Turbine," in *Proceedings of ASME Turbo Expo 2006: Power for Land, Sea, and Air, May 8–11, Barcelona, Spain*, Paper No. GT2006-90787.

[2] S. Kang and C. Hirsch, "Three Dimensional Flow in a Linear Compressor Cascade at Design Conditions," in *Proceedings of ASME 1991 International Gas Turbine and Aeroengine Congress and Exposition, June 3-6, Orlando, Florida, USA*, paper No: 91-GT-114.

[3] R. Ciorciari, I. Kirik and R. Niehuis, "Effects of Unsteady Wakes on the Secondary Flows in the Linear T106 Turbine Cascade," *ASME J. Turbomach,* no. 136(9), pp. 091010-091010-11, 2014.

[4] A. Krug, P. Busse and K. Vogeler, "Experimental Investigation Into the Effects of the Steady Wake-Tip Clearance Vortex Interaction in a Compressor Cascade," *ASME J. Turbomach,* no. 137(6), pp. 061006-061006-10, 2015.

[5] R. J. Volino, "Effect of Unsteady Wakes on Boundary Layer Separation on a Very High Lift Low Pressure Turbine Airfoil," *ASME J. Turbomach,* no. 134(1), pp. 011011-011011-16, 2011.

[6] Q. Lei, Z. Zhengping, L. Huoxing and L. Wei, "Upstream Wake-Secondary Flow Interactions in the Endwall Region of High-Loaded Turbines," *J. Comput. Fluids,* no. 39(9), pp. 1575-1584, 2010.

[7] H. P. Hodson and W. N. Dawes, "On the Interpretation of Measured Profile Losses in Unsteady Wake–Turbine Blade Interaction Studies," *ASME J. Turbomach,* no. 120(2), pp. 276-284, 1998.

[8] M. Berrino, D. Lengani, D. Simoni, M. Ubaldi and P. Zunino, "Dynamics and Turbulence Characteristics of Wake-Boundary Layer Interaction in a Low Pressure Turbine Blade," in *Proceedings of ASME Turbo Expo 2015, June 15-19, Montreal, Canada*, paper No: GT2015-42626.

[9] D. Infantino, F. Satta, D. Simoni, M. Ubaldi, Z. P. and F. Bertini, "Phase-Locked Investigation of Secondary Flows Perturbed by Passing Wakes in a High-Lift LPT Turbine Cascade," in *Proceedings of ASME Turbo Expo 2015, June 15-19, Montreal, Canada*, paper No: GT2015-42480.