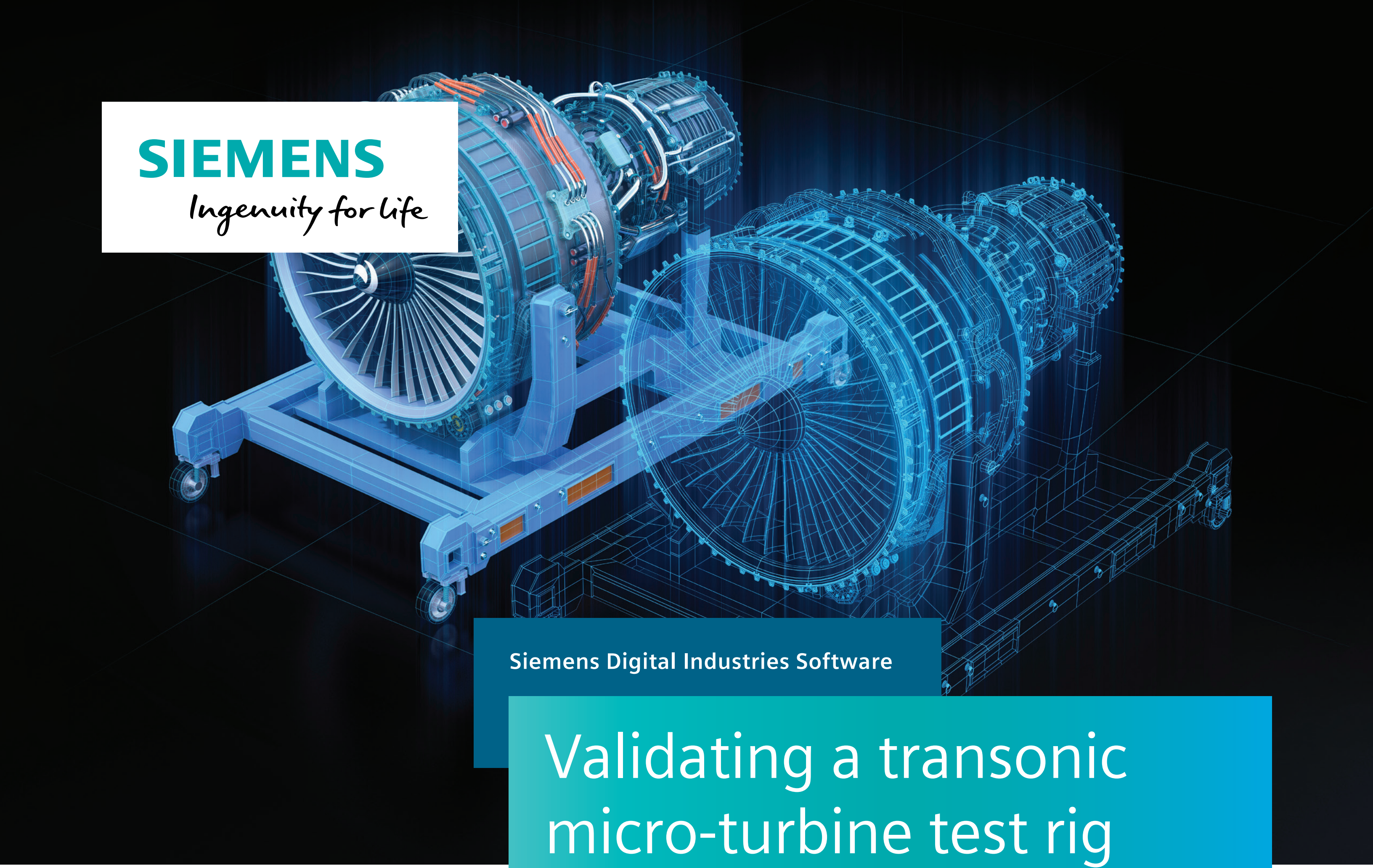

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Validating a transonic micro-turbine test rig

Technion uses Simcenter FLOEFD simulations to give researchers confidence their test rig will perform as expected

Executive summary
The ability to investigate turbine profile performance has been an area of interest for both academia and industry for a long time. Although there is a relatively large number of existing test rigs, Technion is using a unique closed-loop continuous transonic turbine cascade design that offers potential benefits that existing rigs do not.

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Abstract

The goal of the planned rig is to create a platform for a versatile test-aided design of compressor stators and turbine nozzle guide vanes that will significantly reduce the turnaround time between different experimental setups. This will provide researchers with a reliable tool that can simulate aero-thermal parameters relative to micro-turbomachinery. Over time, this will produce a large empirical database that can be used for validating computational fluid dynamics (CFD). These capabilities are geared toward providing convenient aerodynamic performance studies, including improved transonic loss correlations as well as evaluation of heat transfer characteristics in a broad range of thermal management (cooling) techniques.

Technion Transonic Linear Cascade

The Technion Transonic Linear Cascade (TTLC) differs from existing facilities in several ways. The facility is designed to provide effortless modification of incidence and stagger angles (in the range of ±20°), absent of any alterations to the test section. Furthermore, the considered vane geometry can be easily replaced, allowing a quick swap design that permits the cascade to be re-bladed without manufacturing or reassembling other components. At the exhaust, the cascade outlet can accommodate a large range of flow-turning angles to address the needs of both compressor and turbine stators.

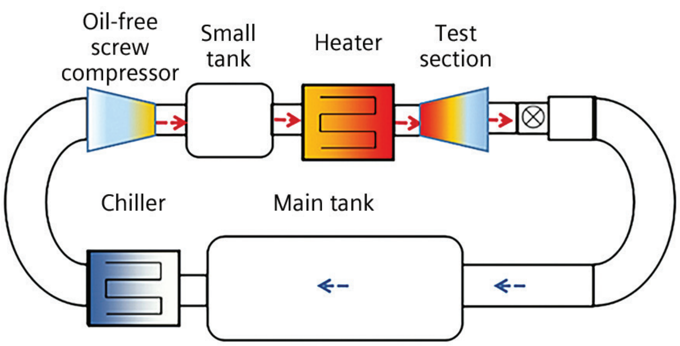

Figure 1: Closed-loop TTLC facility layout.

The test rig is also expected to operate continuously, providing periodic conditions over at least two passages surrounding an airfoil. Due to mass flow limitations, a finite number of blades was implemented in the TTLC. Typical axial turbomachinery profiles can be effectively imitated by a set of individual blades.

Since it is nearly impossible to design a fixed-framed cascade for different sized vanes, similarity principles are used to scale the dimensions of the components by preserving the Re and M numbers. By independent control of these two dimensionless quantities, different aerodynamic conditions can be simulated. Heat transfer characteristics of the hot gas section are also preserved to retain the gas at a solid temperature ratio. Therefore, TTLC is required to maintain an independent M-Re-T ratio.

The cascade features a modular design that is able to accommodate a wide range of compressor stator and turbine vane configurations. The main test section subassemblies and the reference frame used are presented in figure 2. The subsections include: (1) an inlet, (2) flow straightener and turbulence grid, (3) controllable main frame frontboards, (4) bladed test section, (5) optical access window, (6) rotating disks, (7) controllable main frame tailboards and (8) an outlet. Technion used Simcenter™ FLOEFD™ software, which is part of Xcelerator, the comprehensive and integrated portfolio of software and services from Siemens Digital Industries Software, to optimize the design of the inlet, frontboards and tailboards.

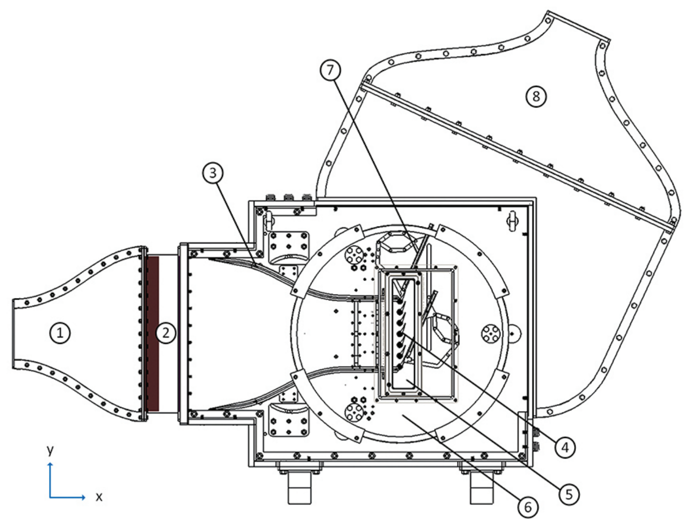

Figure 2: TTLC test section layout and reference frame.

Inlet flow characteristics are a crucial factor for the test section performance. The flow enters the test rig through a standard 6-inch diameter flange, and the cross-sectional area is reduced by 28 percent in a linear fashion to provide flow in a high aspect ratio rectangular slot. The inlet is designed to produce attached uniform flow with minimal boundary layer thickness. This is achieved by the bellmouth shape with zero gradient solid boundary conditions where the air is expanded in the XY plane while contracting in the XZ plane.

In this configuration, the Bell-Mehta guidelines describe the contraction plane profile, while the expansion shape is dictated by the linear area change. The design was tested using Simcenter FLOEFD. It uses a modified k-epsilon (k-e) two-equation turbulence model – where turbulence intensity (I) is 2 percent and turbulence length scale (L) is 2 millimeters) – in association with an immersed boundary Cartesian meshing technique, coupled with a two-scale wall function treatment. The average dimensionless wall distance (y+) was 125. Since the entry length of the input pipe is less than 5 diameters, the incoming flow was assumed to be uniform. The simulation results are presented in figure 3, and no observable separation is present in the flow path.

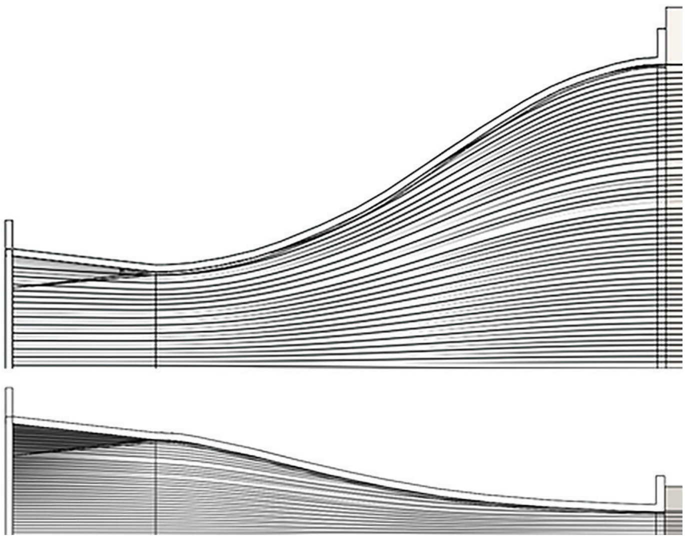

Figure 3: Flow lines across the inlet XY (top) and XZ (bottom) cross-sections.

Honeycomb is a typical component for most wind tunnel designs as it can negate cross-flow vortices, which are typically created due to upstream geometrical changes. Due to lateral turbulence inhabitance and pressure loss considerations, the implemented honeycomb design consists of 3.2 millimeters (mm) hexagonal aluminum cells with a size to length ratio of 10. Lastly, in a typical turbomachine, different components have varying turbulence intensity levels. The first compressor stage usually has a small amount of turbulence, whereas the last turbine stage experiences much higher levels due to the upstream combustor and stages. Therefore, in order to mimic the turbulence intensity of various engine relevant conditions, the cascade includes a modular turbulence grid situated downstream of the honeycomb. A representative turbulence grid is depicted in figure 4, simulating typical first turbine rotor vane turbulence intensity of 5 percent.

The test section of the rig is mounted on a rotating disk to allow the blade positioning to have a variable incidence angle ± 20° (figure 5).

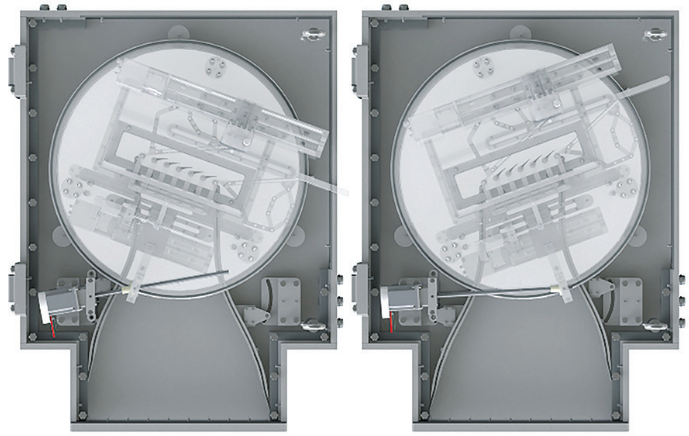

Figure 5: Disks rotation mechanism set to ± 20°.

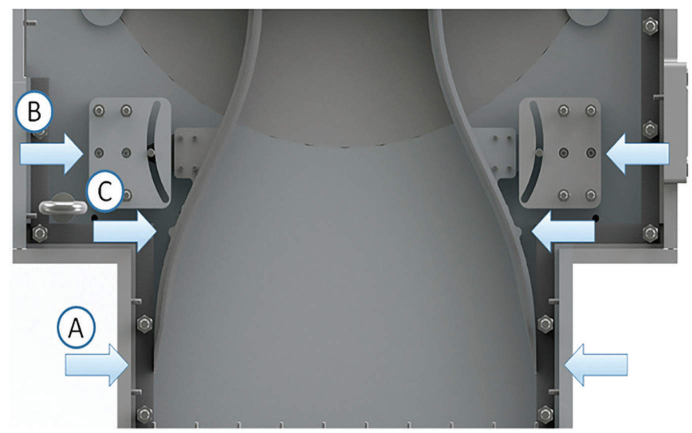

Figure 6: Frontboards sealing and support mechanisms.

As a result of the disk rotation, the frontboards are to be maintained sealed and parallel for all incidence angles (figure 6). Three modules keep the walls leak-proof and aligned for all conditions. Movable Teflon seals (A) keep the walls leak-proof, while the positioning mechanism (B) and leaf springs (C) translate the circular motion of the disks to parallel movement of the boards.

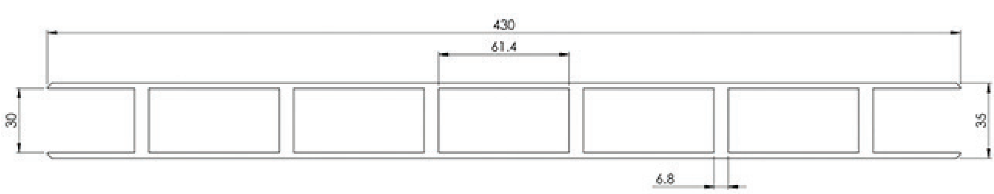

Figure 4: Turbulence grid design [mm].

Two distinct configurations were considered during the frontboard design process: bellmouth curved and straight shaped. The simulation results are presented in figure 7 for both shapes. Based on the reduced boundary layer development, the bellmouth configuration was selected as the frontboard design choice.

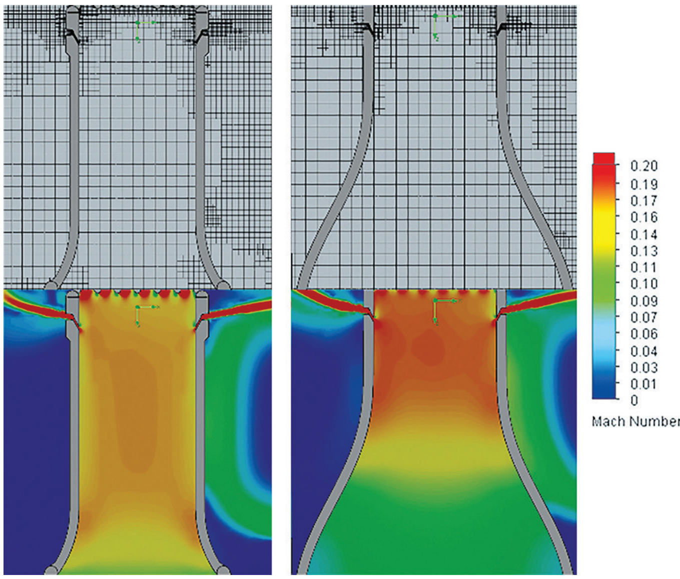

Figure 7: Frontboard XY flow simulation – mesh and results for straight frontboards (left) and bellmouth shaped frontboards (right).

Nevertheless, the frontboards boundary layers may cause partial blockage of the far side test section passages so they no longer contribute to periodicity. An additional simulation was conducted to quantify the boundary layer thickness in the XY and XZ planes (figure 8). At three chords upstream of the test section, the boundary layers in the XY plane cover 12 percent of the pitch in the two far most passages. In order to overcome this issue, a slanted boundary layer suction mechanism is implemented at the end of the frontboards before the test section at two chords upstream of the test section. The air is ingested (up to 4 percent of overall flow rate) through a thin slot, the mass flow of which is regulated by an external valve. This mechanism can effectively purge the entire momentum deficit. However, it is challenging to suck the boundary layer in the XZ direction while preserving the total air mass in the closed system. Nevertheless, at the immediate upstream of the test section, the top and bottom boundary layers cover 30 percent of the total span, resulting in 2D flow in the remaining 70 percent of the blade height. Hence, the cascade is suitable for investigating aero-thermal of various 2D airfoil profiles.

The flow behavior and the validity of the experimental data are heavily influenced by the span-wise flow characteristics upstream and downstream of the test section. The inlet boundary layer suction maintains relatively uniform 2D pressure and velocity distributions across all six passages. Together with exit tailboard actuation, the final design can achieve downstream periodicity in all stagger and incidence angle configurations. According to Simcenter FLOEFD simulations under nominal design conditions, figure 9 depicts flow trajectories colored by local Mach and total pressure distributions over the two middle passages. Periodicity is expected to be achieved within 5 percent in M distributions.

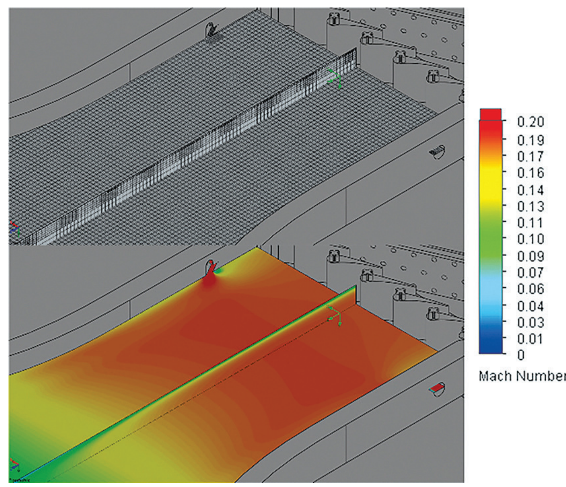

Figure 8: Frontboard 3D flow simulation – mesh and results for bellmouth-shaped frontboards.

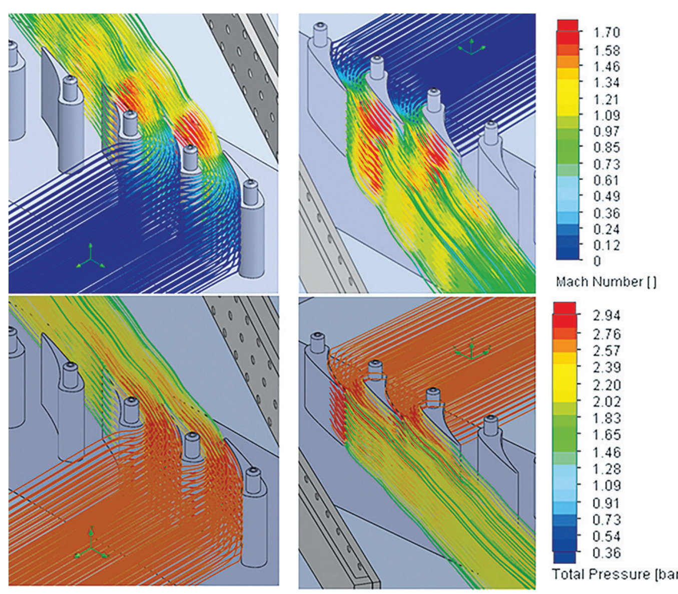

Figure 9: Mach number (top) and total pressure (bottom) distribution in the streamlines.

Conclusion

These Simcenter FLOEFD simulations give the researchers at Technion confidence their test rig will perform as expected and when complete will be able to provide validation for future CFD simulations. This in turn gives design engineers confidence in their simulations of evolutionary design changes in micro-turbomachinery.

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