NUMERICAL INVESTIGATION OF 3-D FLOW PHENOMENA IN INTERBLADE CHANNEL WITH TIE-BOSS


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ABSTRACT
The paper is concerned with the numerical investigation of the 3-D flow field in a last stage rotor blading in a steam turbine of large power output. The mid-span section of 1220 mm long blade is equipped with a stabilization device called tie-boss, two variants of which have been investigated. The tie-boss presents a considerable disruption to the flow field and is the reason of loss of efficiency and the origin of vortices. The investigation has been conducted using Ansys CFX. A detailed investigation determined the origins of the vortical structures and identified flow separations, which have a non-negligible effect on the aerodynamic performance of the blade cascade. The research allows the comparison of the quality of the flow field of both tie-boss variants. The results show that the tie-boss with a round trailing edge causes lower losses and higher exit flow angle than the variant with tailored trailing edge.

KEYWORDS: VORTICES, LONG TURBINE BLADE, TRANSONIC, TIE-BOSS

NOMENCLATURE
\[ \alpha \] inlet angle
\[ a^* \] critical speed of sound [m·c⁻¹]
\[ C \] chord length [m]
\[ L \] span of the blade [m]
\[ M \] Mach number [1]
\[ M^* \] dimensionless speed, \[ M^* = \frac{v}{a^*} \] [1]
\[ p \] pressure [Pa]
\[ Re \] Reynolds number [1]
\[ T \] temperature [K]
\[ \zeta \] kinetic energy loss coefficient [1]
\[ q \] blend factor [1]
\[ x \] coordinate parallel to the chord [m]
\[ z \] coordinate along the height [m]

Subscripts or superscripts
1 in front of the cascade
2 at the exit of the cascade
in inlet
is isentropic
out outlet
s static
tot total

INTRODUCTION
For the next few decades, the steam turbines of large power output can be expected to remain a major source of electrical power. One of the developments of the turbines are ever longer last stage blades. Very long last stage blades enable the turbine to manage higher mass flow and thereby reducing the exit kinetic energy increasing thus the turbine efficiency. In the right circumstances, prolongation of the last stage blade can lead to the reduction of the number of low-pressure cylinders and hence lowering the costs of the entire turbine. The prolongation of the blades brought with it the need for stabilization and damping of very thin, high aspect ratio, non-prismatic blades. The natural frequencies need to be outside the operational frequencies of the machine and the modes need to be within the mechanical tolerances. The implemented solution consists of two stabilizing elements,
both of which utilize the untwisting of the non-prismatic blade during loading. The blade tips carry an integrated shroud and in the middle of the blade, there is the tie-bosses Novak, et al. (2019). Measurements on whole turbine, which was not specifically aimed at tie-boss Hoznedl, et al. (2016) showed, that significant changes of the flow field occur in the vicinity of the tie-boss. Numerical investigation of part-span connector was carried out by Brüggemann, Schatz, Vogt, & Popig (2017), which show that various configurations of the connectors always lead to formation of vortices and to decrease of aerodynamic performance of the blade cascade. Similar part span connector has been investigated by Häfele, et al. (2015) and experimental investigation along a numerical simulation on fine mesh by Häfele, et al. (2014) and by Brüggemann, Schatz, Vogt, & Popig, (2019). The investigation showed that the connector induced vortices and losses into the flow field. However, all of the part-span connector investigations had been carried out at subsonic speeds, while need of transonic investigation for turbines of large power output remains. Investigation of a different mid-span connector of GE blade Mistry, et al. (2011) showed, that vortical structures are present in transonic blades. However, this simulation has been carried out on much coarser mesh. It is apparent that significant vortical structures and blade performance decrease can be expected. A numerical simulation and comparison of different part-span connector position in transonic flow field was conducted by Li & Li, (2014). The simulation with equilibrium steam model and coarser mesh also showed that major vortical structures formed around the connector, and that they are affected by the cylindrical flow in simulated bucket.

The tie-boss was designed regarding its mechanical properties and damping and stabilizing function. As the blade untwists, the abutment surfaces of the tie-boss come into contact and at approximately 70% of its operational revolutions, the force becomes strong enough to practically form a ring of solid material at mid-span. This solution is an evolution with respect to stabilizing lacing wires that were utilized in the past. Two variants of tie-bosses were considered for the blade design, see Figures 1 and 2. Both the designs are in use on Doosan Skoda Power turbines. The design of the tie-boss takes into consideration the requirement of even mass distribution to avoid asymmetrical loading in the blade. Since the aerodynamics of the tie-bosses was not fully assessed during the design phase. Additional research aiming at a better understanding of the flow phenomena and their effect on the flow field was deemed necessary.

Figure 1: Tie-boss type I. Figure 2: Tie-boss type II.

Figure 1 and Figure 2 present side views of both types of tie-bosses. The type I tie-boss has an ovoid cross section while the type II has a tailored trailing edge with sharp edges and flat rear face. The reference cascade is the mid-section of a Doosan Skoda Power 1220 mm long last stage steam turbine rotor.
**PRECEDING WORK**

The numerical simulations, presented later in this paper, were preceded by an experimental investigation of a blade cascade equipped with tie-bosses and by a less precise numerical investigation. A full account of those investigations is reported Radnic, et al., (2018). The experiments were carried out in the aerodynamic laboratories in Nový Knín. The laboratory is equipped with indraft type high speed wind tunnel. Diagram of this tunnel is shown in Figure 3.

A cascade of 8 blades was mounted in the test section. Aspect ratio of the blade was 2, solidity of the cascade was 0,73. Inlet Mach number was set to $M_1 = 0,33$ and outlet $M_{2i5} = 1,44$. The inlet angle was $\alpha_{in} = 30,9^\circ$ and the Reynolds number was $Re \approx 1,6 \cdot 10^6$. The experimental investigation comprised pneumatic and optical measurements. The pneumatic measurements consisted of traversing a 5-hole conical probe in a plane parallel to the plane of trailing edges. Schlieren photography and interferometric pictures were taken on a reference cascade without tie-bosses. A blockage of the flow channel was tested using numerical simulation of the reference cascade and a cascade of infinite width with tie-boss. The examination showed the blockage had negligible effect on the position of the sonic plane Radnic, et al., (2018).

![Figure 3: Layout of the wind tunnel Radnic, et al. (2018): 1 - Silica-gel dryer; 2 - Particle filters; 3 - Entrance nozzle; 4 - Deformable inlet nozzle; 5 - rotating test section; 6 - Settling chamber; 7 - Control nozzle; 8 - Quick acting valve; 9 - Diffuser; 10 - Vacuum chamber.](image)

![Figure 4: Distribution of kinetic energy loss coefficient in a tie-boss equipped cascade.](image)

![Figure 5: Interferogram of reference blade cascade with red curve representing $M=1$ highlighted.](image)
These experiments already showed that the tie-boss caused significant changes in the flow field as demonstrated in Figure 4, which presents the distribution of the kinetic energy loss coefficient $\zeta$, defined as:

$$\zeta = 1 - \left(\frac{M^*}{M_{is}^*}\right)^2. \quad (1)$$

Besides the effect on the losses, it was found that the presence of the tie-boss also caused a shift of the cascade exit angle. Previous numerical simulations also already revealed the existence of at least two major vortices originating from the tie-boss type I. The existence of vortices at mid-span blade connectors was also found by Mistry et al. (2011). These authors identified two distinct vortices at the intersection of the connector with the pressure side of the blade. The vortices then stuck to the trailing edge of the connector and subsequently to the suction side of the blade. These observations proved the need for further, more detailed numerical simulation.

MORE PRECISE NUMERICAL SIMULATIONS

As mentioned before, numerical investigations of the tie-boss were conducted earlier on a relatively coarse mesh and less precise geometry Radnic, et al. (2018). The main motivation for a more elaborate simulation was the assumption that additional vortices originated at the joint of the two parts of tie-boss. The main difference between the previous and current simulation model was the modelling of the fine mesh in the vicinity of the blade and tie-boss surface.

The computational domain was 160 mm wide, corresponding to the wind tunnel. Periodical boundary conditions were assumed on top and bottom of the domain, so that the computational domain resembles an infinitely long cascade with interacting interblade channels. The sides of the domain were assumed as adiabatic no slip walls, as were the blades and tie-boss bodies themselves. The inlet total pressure was set to $p_{tot} = 10^5 \, Pa$ and the static temperature $T_s = 298 \, K$. The previous simulation used an experimentally validated wind tunnel inlet boundary profile. In the present simulation the inlet boundary was not modelled. The inlet turbulence intensity was set to 1%. The direction of the inlet flow was set axial to the cascade. The outlet average static pressure was set to $p_{s,ave} = 3 \cdot 10^4 \, Pa$, assuming a blend factor of $q_{blend} = 0.05$. The outlet pressure corresponds to an outlet Mach number $M_{2is} = 1.44$. The solver used the BSL EARSM turbulence model and a high-resolution advection scheme Barth & Jespersen (1989).

![Computational domain](image)

Figure 6: Computational domain: 1 - Inlet; 2 - Outlet; 3 - Periodic sides; 4 - Blade and tie-boss.
Overview of the computational domain is shown in Figure 6. The domain was modelled with respect to inlet and outlet angle of the blade cascade. The mesh for both cases was made with non-homogenous interfaces. Both meshes were modelled using Ansys ICEM. The vicinity of the tie-boss body was modelled with an unstructured tetrahedral mesh generated by the Octree algorithm with pentahedral boundary layer refinement. The first grid line was set to \( y_1 = 0.006 \text{mm} \) for an expected value of \( y^+ = 1 \). The evaluation showed that \( y^+ \) was between 0.8 and 3. The interface was shaped specifically to allow perpendicular cells in the area of the boundary layer. The remaining area was meshed using structured mesh. The structured mesh was desirable wherever it could be modelled. The complicated shape of the tie-boss body prevented generating a structured mesh in its vicinity, so an unstructured mesh had to be used. The connection between the meshes is shown in Figure 7 both tie-boss types were modelled similarly.

In case of the type I tie-boss, the inner, unstructured mesh was composed of roughly 3.1 million elements. The outer, structured mesh was composed of 10.1 million elements in the side regions of the domain and 1.6 million of elements in the region in front of and behind the tie-boss. The mesh was composed of 164 span-wise and 57 pitch-wise elements and of 179 elements along the surface of the blade.

![Figure 7: Non-homogenous mesh interface](image)

**Figure 7: Non-homogenous mesh interface**: 1 - Succiton side of the blade; 2 - Pressure side of the blade; 3 - Frontal non homogenous interface; 4 - Rear non homogenous interface

**RESULTS AND DISCUSSION**

**Identification of vortex structures**

The interpretation of the numerical results shall focus on the identification of the vortical structures in the flow field. A side-view of the visualization of all vortices associated with the type I tie-boss is shown in Figure 8. The second invariant of tensor of velocity gradient, called Q-criterion, was utilized for the visualization (ANSYS).
There are three major vortices in the wake of the tie-boss. They have been labelled (a), (b) and (c). The vortex (a) originates at the intersection of the tie-boss with the pressure side of the blade. Vortex (b) originates at the top edge of suction side part of the tie-boss. The top edge has a sharp ending into the round trailing edge of the tie-boss itself. The third vortex (c) emerges at the trailing edge of the tie-boss. There are two more vortices at the base of the tie-boss, but they were not visible enough in the core visualization, because the of the visualization based on Q-criterion. The Q-criterion will show shear stress layer in the vicinity of a no-slip surface; therefore, the core of the vortex is not distinct in the vicinity of any surfaces.

![Diagram of vortices](image)

**Figure 8: Tie-boss type I vortical cores visualization.**

The Figures 8, 9 and 10 present the flow field in 3 successive planes approximately normal to the main flow direction at the cuts A, B, and C. Figure 9, representing the flow at cut A, shows clearly two vortical cores in the wake of the upper part of the tie-boss. Both vortices were visualized as a single core (a) in the Figure 8, yet clearly, they are separate. There is also a clear beginning of vortex (b), that appears just above the lower part of the tie-boss.

![Flow field visualization at cut A](image)

**Figure 9: Flow field visualization at cut A.**

At cut B in Figure 10, two small vortices, marked (d) and (e), are clearly visible at the base of the tie-boss and one major vortex (b) in the middle of the section. The vortex (c) is not visible in this

![Flow field visualization at cut B](image)

**Figure 10: Flow field visualization at cut B.**
because it is not perpendicular to this particular plane. This is also an indication of a change of the flow angle with respect to the tie-boss.

Finally, at cut C in Figure 11, the flow visualization clearly pictures 4 vortices. The flow is now relatively far from the tie-boss and is more homogenous so that this section is roughly perpendicular to all parts of the flow. Thus, all vortices are clearly visible. It is also clear that the vortex (b) is diminishing, while the other vortices seem to get bigger and more distinguished. This is considered to be mutual effect of the counter rotating pair of vortices (c) and (d) and pair (c) and (e).

Contrary to the vortices in case of the type I tie-boss, designated by letters, the vortices in case of the type II tie-boss are designated by numbers. The vortical structures behind the type II tie-boss are, as expected, much more complicated due to the tailored trailing edge. To facilitate the understanding two views of the evolution of the vortical cores have been provided, a side view in Figure 12 and a view from downstream in Figure 13. Five vortices have been identified. Vortex 4 originates at the joint between the upper and lower parts of tie-boss. The geometry of the joint was not modelled in the earlier simulations, the surface was flattened; hence, its effect was only suspected so far. Vortices 2, 3 and 5 originate at the tailored trailing edge while vortex 1 originates at the intersection of the tie-boss with the suction side of the blade.
The side-view in Figure 12 shows that the vortical structures are much more massive than those caused by the type I tie-boss. Note that the vortex 1, does not appear in this view, because as mentioned before, the value of Q-criterion similar in the boundary layer of the blades as in the vortex core, which is preventing vortex 1 from being visualized.

Figure 14-Figure 16 present the flow field in planes approximately normal to the main flow direction at the cuts A, B and C. In the first plane at cut I, Figure 14, the vortices 1 and 4 are clearly visible. This is less the case for the vortices 2 and 3 which do not form closed streamlines. As in the case of tie-boss type I, this is caused by the turning of the flow induced by the transverse pressure gradient of the low momentum fluid in the tie-boss wake. This is also the case for vortex 5. The Mach number distribution shows that this plane is still in the wake of the tie-boss and the flow is not perpendicular to the plane in that region.

The flow field in the second plane at cut B in Figure 15 shows very clearly the vortices 4 and 5. The vortex 5 has moved to the edge of computational domain and the vortex 4 moved to the right, away from the body of the tie-boss. On the contrary, vortices 2 and 3 are not clearly visible. The transverse pressure gradient behind the trailing edge of the tie-boss has shifted the flow in the direction of suction side of the blade, hence
the vortices 2 and 3 moved closer to the bottom edge of the image. Finally, in the third plane at cut C, Figure 16, the vortices 2, 3 and 4 are clearly visible. They are now completely adjacent to the suction side of the blade. The flow is now more homogenous, so the plane is perpendicular to most of it.

![Figure 17: Distribution of loss coefficient along the height of the blade.](image)

**Impact of vortical structures on span-wise loss distribution**

As mentioned before in the chapter “PREDENDING WORK”, the effect of the tie-boss on the cascade performance was measured by downstream pitch-wise pressure probe traverses over the entire blade span. The experimental data in Figure 17 are the same as those in Figure 4 but for comparison reasons with the numerical predictions they are plotted on a larger scale. The losses present the pitch-wise integrated kinetic loss distribution along the span as evaluated with the data reduction method by Amecke & Šafařík (1995). The measurement plane is parallel to the trailing edge at a distance of 0.275 \( \cdot \) \( C \).

The numerical calculations confirm the significant increase of the losses caused by the tie-bosses. There is also a clear relation of the loss coefficient to the position of the identified vortices. As regards the tie-boss I, the vortices (b) and (c) clearly cause the spike of the loss coefficient at approximately \( z/L = 0.5 \) (P1). The reason for this spike is the significant increase of the shear stress in the vortex region. The wake of the tie-boss enlarges this peak. The vortex (e) is responsible for the spike at \( z/L = 0.56 \) (P2) and the vortex (d) seems to cause the spike at \( z/L = 0.43 \) (P3). Compared to the type I tie-boss, the vortices of the type II tie-boss are much more spatially distant than in the case of the type I tie-boss. This is also clearly visible in the distribution of the loss coefficient. There are 4 distinctive peaks and one smaller peak. The loss peaks associated with the vortices 1 and 4 are visible at \( z/L = 0.4 \) (P4) and \( z/L = 0.65 \) (P5). The vortices 3 and 5 are very similarly span-wise positioned and thus they form the peak at \( z/L = 0.55 \) (P6). The vortex 2 forms a peak at the left side of the wake.
of tie-boss peak, which is approximately at $z/L = 0.5$ (P7). It is also clear that the measured loss coefficient has trends very similar to the numerical simulation, particularly in the case of type II tie-boss. There is a minor discrepancy between the measured data and data provided by numerical simulation. However, the trends are very similar, and the discrepancies can be attributed to the lower accuracy of the measurement compared to the results of the numerical simulation. The accuracy of the measurement was limited by the size of the conical probe used, but it is clear that the tie-boss model had a similar impact on the integral flow field parameters. Discrepancies between the experiment and the numerical simulation near the sidewalls ($z/L \rightarrow 0$ and $z/L \rightarrow 1$) are due to the fact that the inlet sidewall boundary layer was not considered in the current simulation.

A noteworthy observation is that the area of significant kinetic energy loss spans quite far into the free stream region of the cascade and is not limited to the wake of the tie-boss. This phenomenon proves that the vortices are contributing a significant part to the losses caused by the tie-boss.

Finally, it is worthwhile mentioning that measurements on the real turbine also showed significant changes in the wetness of the steam in the last stage, that could clearly be attributed to the tie-boss Hoznedl, et al. (2016). Discussion is on-going whether the vortices do cause multiphase changes in the flow field.

**CONCLUSION**

In continuation of the work by Radnic et al (2015), the present work provides valuable insight into the flow phenomena induced by tie-bosses. The investigation aimed at the identification of significant vortical structures in the flow and their consequences on the blade performance. Two cases of tie-bosses were investigated and their vortical structures are described. The vortices of type I tie-boss stayed in proximity to the wake of the tie-boss, while the type II tie-boss caused the vortices to spread. The ovoid shape of the type I tie-boss caused smaller vortices which in turn caused smaller peaks of the kinetic loss coefficient than the type II tie-boss with the tailored trailing edge and the flat rear face. It is also notable that both tie-bosses cause significant turning of the flow and a significant wake loss.

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