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INVESTIGATION OF 3D FLOW STRUCTURES IN A LINEAR BLADE CASCADE WITH STEREO PARTICLE IMAGE VELOCIMETRY

Šnábl P.[*], **Procházka P.**[**], **Uruba V.**[***], **Pešek L.**[†]

Abstract: *In most experiments and numerical calculations of flow through blade cascades, there is a tendency to reduce the problem to 2D. This is understandable due to the design of the experimental rigs and measurement methods, as well as the very long computation times of 3D numerical flow simulations. In reality, however, 3D flow structures such as streamwise vortices begin to appear in wakes behind profiles even for 2D geometry even at low Reynolds nubers. They can create force variations acting along the blade span, which can be represented on average by the 2D measurement and simulation and give a correct result, e.g. for the total lift and drag of the profile. However, when investigating dynamic aeroelastic instabilities such as flutter, local variations in aerodynamic forces can greatly influence the overall behaviour, e.g. by inducing stall flutter.*

Keywords: Experimental flow dynamics, blade cascade, 3D flow structures, stereo PIV.

1. Introduction

The aeroelastic stability of blade cascades is a very complex fluid-structure interaction phenomenon. In real turbomachinery there is a very complex 3D geometry with non-homogenous flow under rotation where gravity, centrifugal forces, Coriolis effect, etc. play their role, and so far it is impossible to numerically calculate the non-stacionary fluid-structure interaction on a full scale model. In the Institute of Thermomechanics of the CAS we have used reduced order structure models with Van der Pol model to describe the instabilities (Pešek et al., 2023a,b) and also the reduced order flow models (Prasad and Pešek, 2019; Prasad et al., 2023).

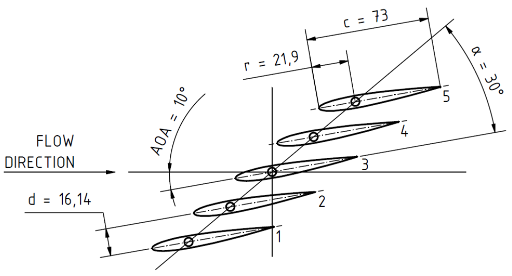

Fig. 1: The geometry of the blade cascade.

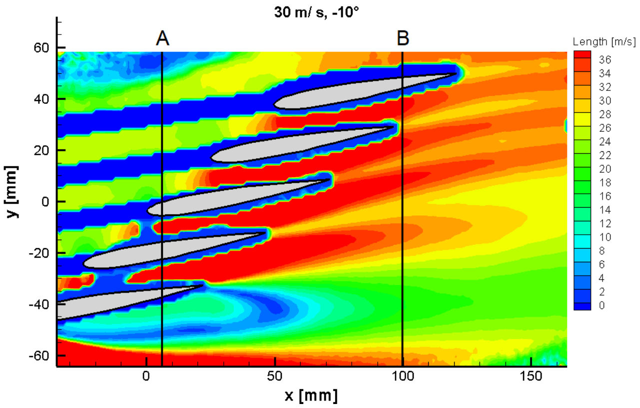

Fig. 2: 2D PIV measurement of the blade cascade.

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[*] Ing. Pavel Šnábl: Institute of Thermomechanics of the CAS, Dolejškova 5; 182 00, Prague; CZ, snabl@it.cas.cz

[**] Ing. Pavel Procházka, PhD.: Institute of Thermomechanics of the CAS, Dolejškova 5; 182 00, Prague; CZ, prochap@it.cas.cz

[***] Prof. Ing. Václav Uruba, CSc.: Institute of Thermomechanics of the CAS, Dolejškova 5; 182 00, Prague; CZ, uruba@it.cas.cz

[†] Ing. Luděk Pešek, CSc.: Institute of Thermomechanics of the CAS, Dolejškova 5; 182 00, Prague; CZ, pesek@it.cas.cz

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In order to study the aeroelasticity in a blade cascade experimentally, simplifications have to be made in order to make any measurements possible. Most researchers therefore use linear cascades: parallel blades with constant cross-sections. Although linear cascades lack some key features such as rotational periodicity and variation of parameters in the radial direction, it is still possible to obtain and study aeroelastic couplings. However, even though all the perpendicular cross sections along the blade span are the same and thus the geometry can be considered as 2D, the flow field does not necessarily have a 2D structure. In particular, corner vortices can emerge at the corners where the sidewalls and blade ends meet (Moon and Koh, 2001; Liu et al., 2016) and streamwise vortices in wakes start to appear appear at low Reynolds numbers (Procházka and Uruba, 2019).

To assess the significance of such 3D vortex structures on a linear blade cascade, which has been used in the past to study aeroelastic phenomena such as flutter (Šnábl et al., 2021, 2022), an experimental setup with the same geometry, shown in Fig. 1, was prepared. The prismatic NACA 0010 blades with a span of 100 mm fill the entire width of the test section channel with a cross-sectional dimension of 250×100 mm.

2. Methods

The experimental investigation of 3D flow structures within the cascade geometry was performed by using 3D Particle Image Velocimetry (PIV). Unlike standard 2D PIV, where a single fast camera is positioned perpendicular to an laser-illuminated plane, the 3D PIV measurement method incorporates two PIV cameras that are pointed at the illuminated plane under an angle from both sides. This enables to capture motion of the illuminated particles not only in the illuminated plane, but also through the plane. When the captured data from both cameras are handled by the post-processing software, all three velocity components of the flow in the plane of measurement (PoM) are calculated.

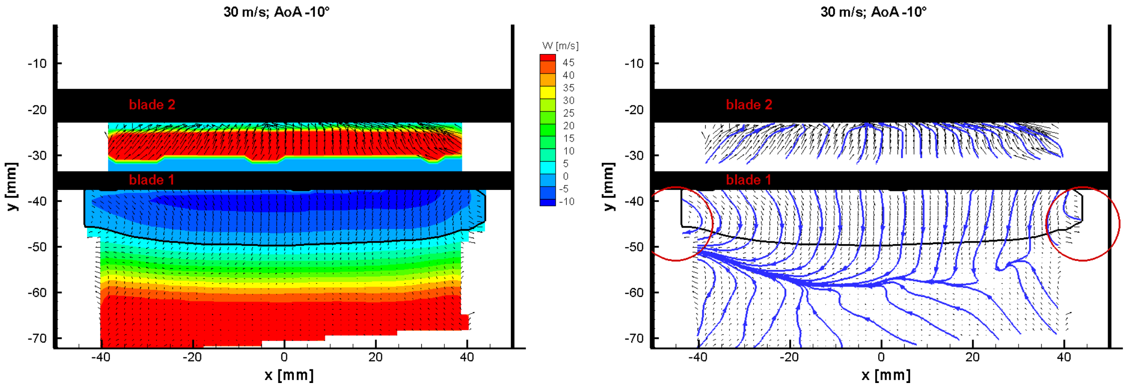
Our measurement system consists of a NewWave Pegasus laser to create the laser sheet and consequently illuminate the seeding particles. Two NanoSense MKIII cameras (1280×1024 px, 1024 Hz) are mounted on Scheinpflug adapters to correct for distortion as the camera lens plane is not parallel to the image plane. A special calibration procedure is also desirable to dewarp the images and evaluate the correct values of the velocity signal.

The cascade was exposed to a wind speed of 30 m/s that gives $Re = 140\ 000$ with respect to the blade cord; the angle of attack of all fixed blades was set to -10°. Two independent PoM A and B, perpendicular to the free stream and located 6 mm and 99 mm respectively downstream of the origin of the coordinate system, were selected and are shown in Fig. 2, where the flow field through the central plane of the cascade measured by 2D PIV is shown. The PoM A targets the large separation area under blade 1 and the channel between blades 1 and 2. The PoM B targets the wake region behind blades 1 and 2 further downstream.

3. Results

There is a distribution of time-averaged streamwise velocity component (W) in PoM A shown in Fig. 3a). The channel region between blade 1 and 2 is characterised by the occurrence of high velocity region (up to 60 m/s). The area describing the flow separation is more important - there is a black line marking the region of backflow (in terms of the W-component). Note that this region does not extend over the whole width of the channel, but fills about 80 % of the width. This is due to the presence of secondary (corner) vortices. These vortices were not fully captured; however, their presence is evident from the streamlines in Fig. 3b) – marked by red circles. Fig. 4a) reveals two individual time instants of the flow below the blade 1. Based on the vector lines, we can observe fully 3D and dynamic nature of the flow with a large amount of coherent structures; pseudo-periodic corner vortices are still visible.

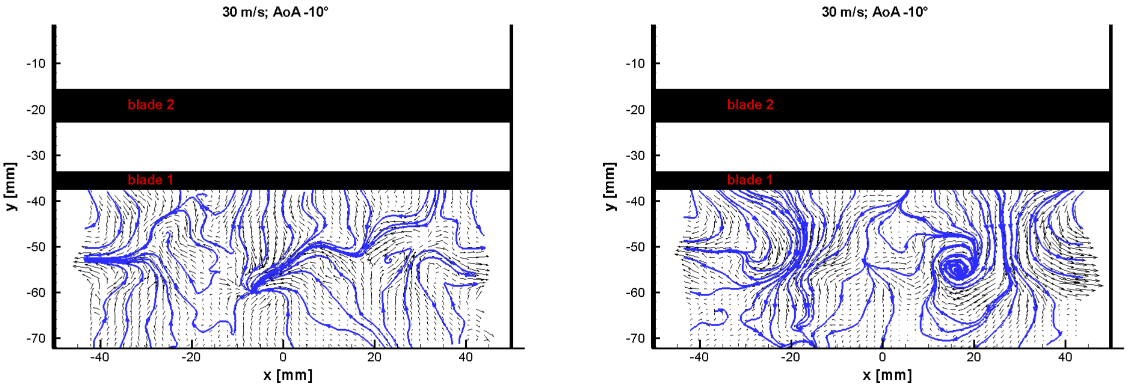
The PoM B mainly covers the wake behind blade 1 and partly 2. The wake extension is large (green moderate velocity in Fig. 5a)), but it is in good agreement with the previous 2D PIV measurement shown in Fig. 2. The wake width is more than 30 mm. Fig. 5a) and Fig. 5b) are supplemented by dashed lines indicating the projection of the trailing edges well in front of the measurement plane. Just behind the trailing edge of the second blade there is a location of higher velocity (close to 30 m/s) - however this is not a contradiction as the actual wake region of the second blade is a little higher (as can be seen in Fig. 2). The flow rises in the whole area (Fig. 5b)) because it is deflected by the inclined blades. As in the previous case, there are two snapshots in time (0.15 s step) in Fig. 6, proving that the flow field behind the blade cascade is not only composed of spanwise oriented vortex structure, but mainly of streamwise oriented vortices, which



a) With contours of streamwise velocity component.

b) With streamlines in the PoM.

Fig. 3: Time-averaged velocity in PoM A located 6 mm downstream the origin.



a) Time 0.04 s

b) Time 0.36 s

Fig. 4: Two snapshots; streamlines mapping the structures in PoM A 6 mm downstream the origin.

play a crucial role in influencing the following blades. These streamwise vortices have a vortex axis parallel to the blade chord and occur mainly for larger values of AoA, when their vortex strength is significant compared to the case without flow separation.

4. Conclusions

The aim of this work was to measure 3D flow structures using 3D stereo PIV in order to map the vortex structures that could play an important role in the aeroelastic stability of the blade cascade. Two measurement planes were chosen; PoM A intersecting the inter-blade channel between blades 1 and 2, and PoM B located in the wake region far downstream of the blades.

The time averaged results show a fairly uniform velocity distribution which would correspond to the 2D case. The separation spanwise vortex fills about 80 % of the channel width and the corners are filled with streamwise corner vortices. However, the streamwise vortices emerge randomly in instantaneous flow field snapshots in the large separation bubble under blade 1 and then spread downstream. These vortices do not appear in a time-averaged image, nor could they even be shown in the 2D representation (in the streamwise plane).

In the research of aeroelastic stability of blade cascade, such local 3D flow structures can have impact on blade cascade stability and their importance will be further studied.

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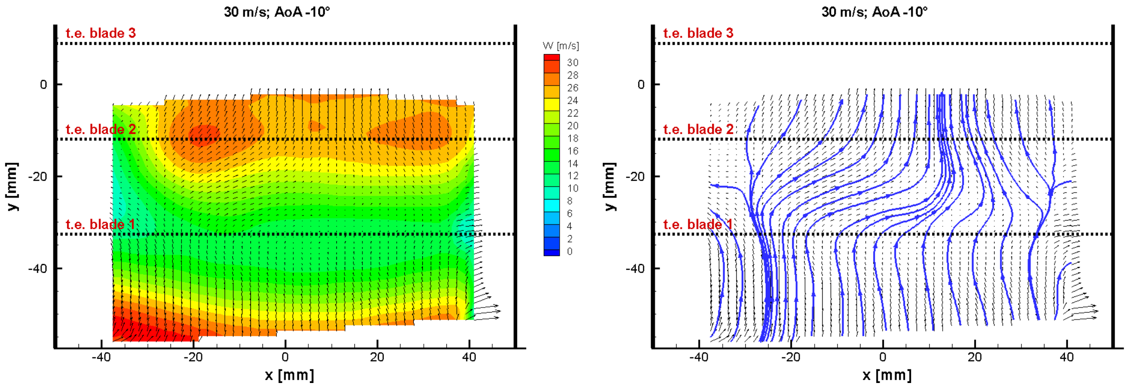
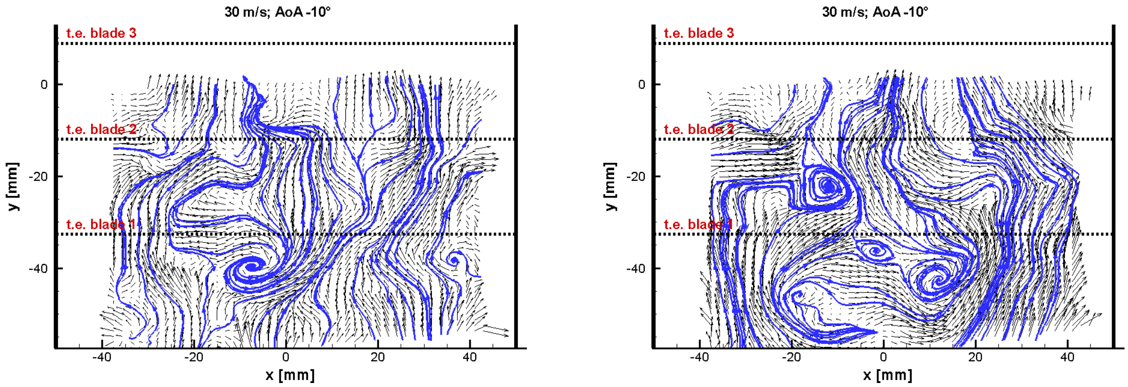


a) With contours of streamwise velocity component.

b) With streamlines in the PoM.

Fig. 5: Time-averaged velocity in PoM B located 99 mm downstream the origin.



a) Time 0.02 s.

b) Time 0.17 s.

Fig. 6: Two snapshots; streamlines mapping the structures in PoM B 99 mm downstream the origin.

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