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A NEW BLADE CASCADE FOR FLUTTER STUDIES

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Abstract: *In this paper, a new blade cascade, developed in the Institute of Thermomechanics, is presented. The geometry of the cascade was modified so now the stall flutter can occur. It has some major construction improvements over the original cascade which now allow more precise and reliable measurements. The stability of the new blade cascade with five NACA 0010 profiles with rotational degree of freedom is assessed by Travelling Wave Mode approach and Aerodynamic Influence Coefficient approach.*

Keywords: Blade cascade, stability, travelling wave mode, aerodynamic influence coefficient.

1. Introduction

In 2019, an experimental blade cascade with five NACA 0010 profile blades with rotational degree of freedom was built. The dimensions (cord length, blade distance, stagger angle) on this cascade were taken from former blade cascade with translational degree of freedom of the blades. The shafts of the blades were held in ball bearings, free rotation of the blades was restricted by torsional springs and the excitation was provided by linear shakers of our own design. The motion of the shaker was transmitted through piezoelectric force cell and then transformed from linear to rotational via rod and arm. More detailed information about the original cascade design and measurements can be found in (Šnábl et al., 2021) and (Šnábl et al., 2022).

Controlled flutter experiments were conducted under the project of Czech Science Foundation: GA20-26779S, *"Study of dynamic stall flutter instabilities and their consequences in turbomachinery application by mathematical, numerical and experimental methods"* on that original cascade to study the flutter phenomenon and provide data for tuning reduced-order models (Prasad and Pešek, 2020) and (Prasad et al., 2021). During the experiments, two main flaws of the cascade appeared:

1. **Stall flutter did not occur.** The experiments have shown flutter instabilities but the studying of the flow field by particle image velocimetry (PIV) revealed that there was no flow separation (stall) on the inner blades of the cascade and that the instability was of the classical flutter type.
2. **The mechanical part of the cascade wasn't good enough for precise force measurements.** The mechanical design was easy to manufacture, included conventional parts, such as ball bearings and torsional springs, and instrumentation that was available in our institute. The cascade performed well for observation of the flow field with or without forced harmonic excitation. Sadly, the measurement of the aerodynamic moments by the force cell connecting the shaker and the rest of the mechanism proved to be nearly impossible due to nonlinearities and high damping. Those unwanted effects were mostly caused by the ball bearings, friction between the coils of torsional springs, clearances in the connection of rod with arm etc. The piezoelectric force cells used for the measurement were small and lightweight but had a disadvantage that they could only measure dynamic force, not a static force.

In 2021, based on the experience gained during the measurements on the original cascade, it was decided to design and build a new cascade that will not suffer by the above mentioned flaws.

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2. New blade cascade design

2.1. Modification of the geometry

An experiment with three static blades with a possibility of changing the blade distance was created. The blades were observed with PIV camera and we searched for such blade distance for specific angle of attack (AOA), where separation of the flow occurs on the middle blade. On the other hand, we searched for the lowest distance possible to keep the aeroelastic coupling between the blades as strong as possible. The optimal distance was found to be 35mm. At this distance, for turbine configuration (negative AOA), the separation of the flow at the middle blade started to occur at around AOA -10°. Figure 1 shows the separated flow at AOA -11°.

The final geometry of the new blade cascade with five blades and blade distance 35mm is shown in figure 2. It has fixed stagger angle 60°and the angle of attack is changed by rotation of the whole cascade around blade 0's rotational axis. The cascade is placed in rectangular test-section of the open-loop wind tunnel 280mm high and 600mm long. The width of the test section is 100mm and the blade span is little lower with minimal clearance to the side-walls.

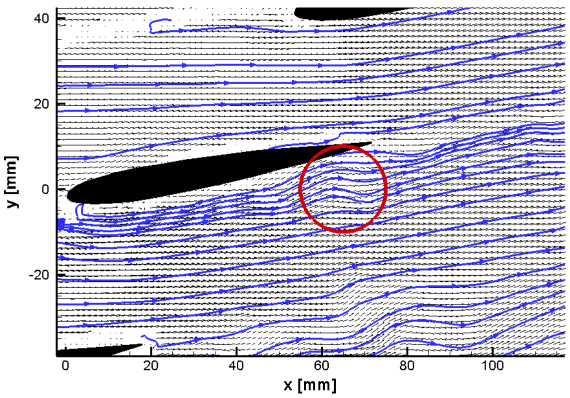

Fig. 1: Instantaneous vector streamlines of the three-blade testing cascade with designation (red circle) of separation of the flow under the middle blade. AOA -11°, velocity 30m/s.

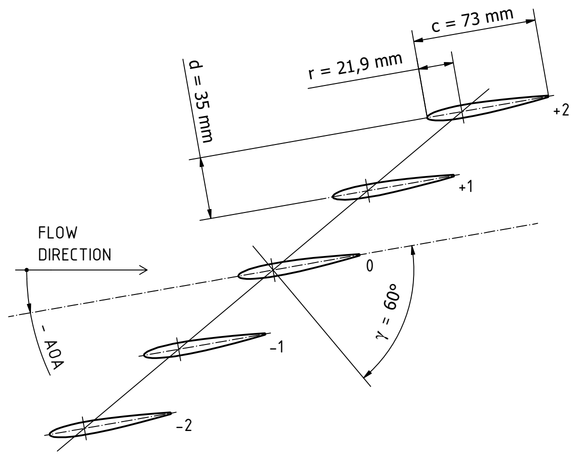

Fig. 2: Schematic picture of the new blade cascade geometry.

2.2. New suspension, excitation and measurement systems

The purpose of the suspension system is to fix the blade elastically in its rotational axis and restrict the motion in all other degrees of freedom. In the new cascade design there was a goal to avoid bearings and winded torsional springs, if possible, to reduce the damping of the suspension system. A flat spring suspension system that satisfies this goal was developed. It uses four thin flat sheets made of spring stainless steel that are arranged into a cross. Those sheets are on one side clamped into part that is fixed to the frame and on the other side clamped into a moving part that is connected with the moment-measuring shaft, coils of the torsional shakers and with the blade. The flat spring suspension system can be seen in figure 3. The design of the suspension element allows changing of the stiffness by selecting different thickness of the flat springs.

On the original cascade, linear shakers were used to excite the blades. In that case, however, there is a need of mechanism to drive the blades. Additionally the linear shakers have their own suspension springs. Better solution is to use actuators that directly actuate rotational motion. Moreover, there is no mechanical connection between the static and moving parts of the actuator so the actuation is basically contactless. The 3D printed coils can be seen on the prototype in figure 3.

The last but not the least part of the new blade assembly is the moment-measuring shaft equipped with strain-gauges that connects the suspension system with the coils and the blade. In such configuration, the

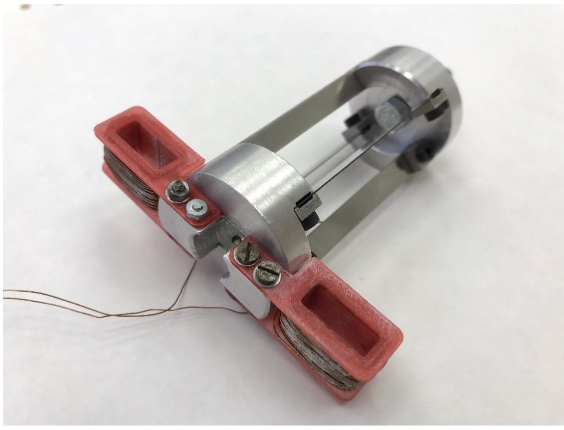

Fig. 3: Prototype of flat spring suspension system with mounted coils for torsional excitation.

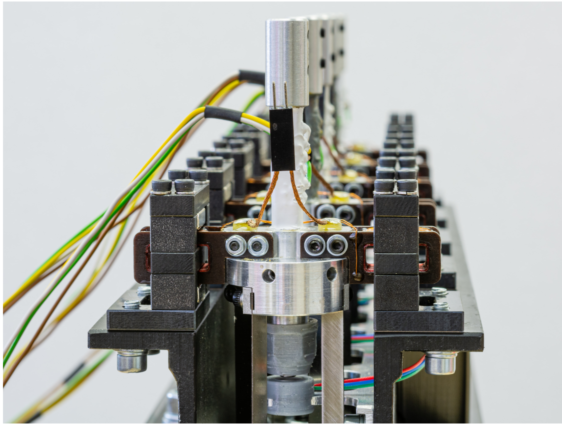

Fig. 4: Assembly of the suspension, excitation and measurement system for the new five-blade cascade.

moment-measuring shaft separates the blade from the suspension and only the aerodynamic moment and dynamic moment of the blade are measured.

The complete assembly of the suspension systems, torsion-excitation and moment-measuring shafts for the new cascade is shown in figure 4.

3. Measurements of the cascade stability

In this paper, motion-induced controlled flutter is considered only. According to (Vogt, 2005), two testing methods exist: aerodynamic influence coefficient (AIC) approach and travelling wave mode (TWM) approach. Both approaches were used and compared on our new cascade.

In TWM approach, all blades in a row oscillate with same frequency and amplitude with various inter-blade phase angles (IBPAs). The response is measured only on the reference blade. With this approach, several measurements for different IPBAs are needed to construct the stability S-curve. This method well represents the reality but the complexity of the experimental setup is high and more measurements are needed.

On the other hand, AIC uses single oscillating blade and principle of linear superimposition of aerodynamic influence responses measured on all blades in a cascade. The influence is calculated both in terms of magnitude and phase and the result of one single measurement can be used for estimation of aerodynamic damping for any IBPA.

The test case chosen for this paper is AOA -8°, wind speed 25m/s, amplitude of oscillation 1° and variable frequency of the forced vibration in the range from 10 to 50Hz. At this AOA, there is no separation of the flow except for the suction side of the blade “-2” so at this configuration the flutter is of a classical type. The reference blade for both TWM and AIC is the middle blade of the cascade marked “0”. The blades “-2” and “+2” were fixed and not considered in the stability evaluation.

The resulting stability curves are plotted in figure 5. For TWM, only discrete points corresponding to measured IBPAs are plotted while AIC allows to evaluate the stability parameter value at any IBPA. The TWM results respect the real cascade stability while AIC results for our 5-blade cascade are more of an approximation because AIC was derived for infinite cascade. Even though our cascade is far from infinite, the agreement of both approaches is very good. The positions of maxima and minima, the trend of increasing stability with increasing frequency - it is well captured by AIC approach. Only the maximal and minimal values of aerodynamic damping parameter are underestimated by AIC in most of the cases.

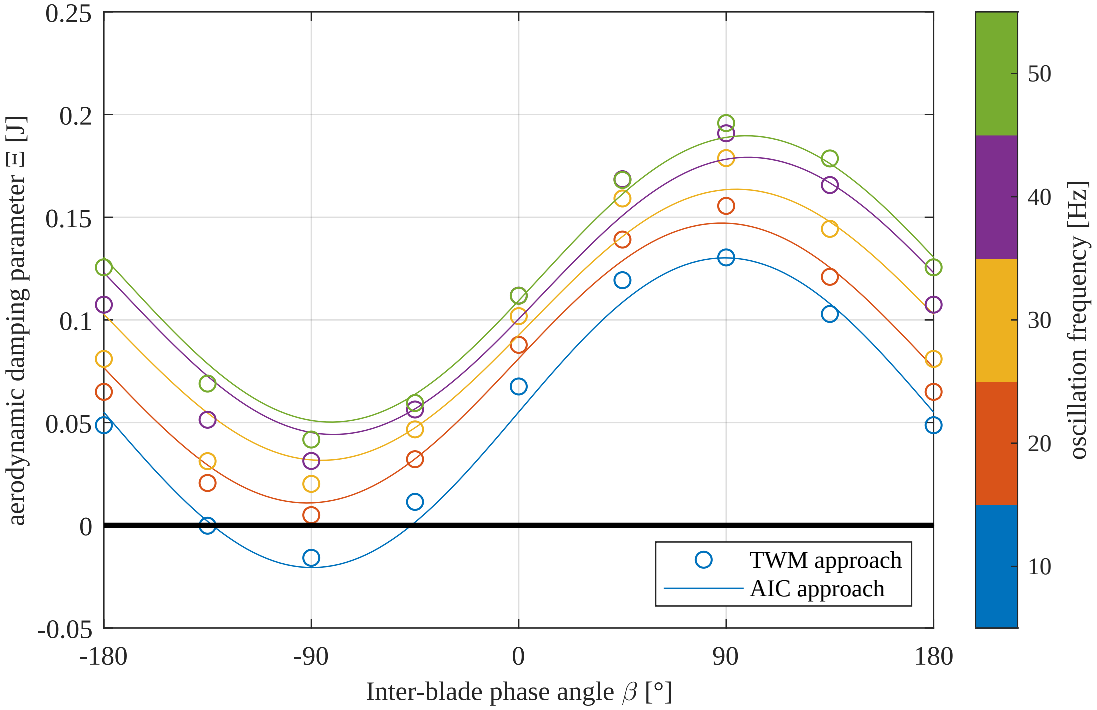

Fig. 5: Stability diagram of the new cascade for different oscillation frequencies evaluated by both TWM and AIC approaches. AOA -8°, wind speed 25m/s.

4. Conclusions

In this paper, a new, upgraded, blade cascade design was briefly introduced. The gap between the blades was increased and that will allow studying of stall flutter that was not possible on the original cascade. Based on the experience from the original cascade, the mechanical parts, including blade suspension, excitation and instrumentation, were completely reworked to minimize blade damping and improve the precision of the measurements on the new cascade.

One of the first results measured on the new cascade, a parametric study focused on the effect of blade oscillation frequency on the cascade stability, was shown. Two approaches, TWM and AIC, were used for the stability evaluation. The results have shown very good agreement of both approaches, even though AIC was derived for infinite cascade and our cascade has only five blades. Increase of the oscillation frequency helps to stabilise the system.

Acknowledgments

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