Verification tests of a new blade flutter research facility

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Abstract. Long term strategic changes in power generation approaches will require more flexibility for large power generating turbines as an unavoidable consequence of the increasing share of power generated by alternative energy sources. Demanded flexibility for the power turbine output will augment undesired flow phenomena in the low-pressure turbine module, which will consequently enhance blade flutter problems of long slender blades in turbine last stages. In order to advance the understanding of blade flutter onset conditions, the Institute of Thermomechanics of the Czech Academy of Sciences instigated an advanced research program on blade flutter research in high-speed turbomachines. A new innovative test facility for Blade Forced Flutter research was designed and built in the High-Speed Laboratory of the Institute of Thermomechanics. The concept of the new test facility is based on extensive experience with an older Transonic Flutter Cascade facility operated at the NASA Glenn Research Center in Cleveland, Ohio. At present, the first phase of verification tests of the new facility is in progress. The ongoing steady-state tests are intended for exploration of a newly proposed quasi-stationary method to investigate instigating flow conditions leading to an onset of intense blade flutter. Results of some opening tests under steady flow conditions are presented in the paper. The blade drive mechanism for unsteady tests with oscillating blades has not yet been installed in the facility. The presented paper is a work-in-progress report on the ongoing research of complex blade flutter problems.

1 Introduction

A new advanced test facility for Blade Forced Flutter research (BFF) was designed and built in the High-Speed Laboratory (HSL) of the Institute of Thermomechanics (IT) at the Czech Academy of Sciences (CAS) [Lepicovsky et al., 2020]. The concept of the new test module is based on extensive experience with an older Transonic Flutter Cascade (TFC) facility operated at the NASA Glenn Research Center in Cleveland, Ohio [Boldman & Buggele, 1978; Shaw et al., 1986]. Both, the BFF as well as TFC facilities are dedicated to flutter research on linear blade cascades. The new BFF facility features several advanced

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modifications, namely an independent mechanical drive for each blade and improved instrumentation of tested blades using less expensive miniature commercial pressure transducers. Further, the new facility has provision for blade torque measurements and it will enable installation of optical windows on both test-section side walls for interferometer investigations of the cascade flow field. The BFF blade chord is 120 mm as opposed to 90 mm of the TFC blades, which permits more detailed blade instrumentation. On the other hand, a disadvantage of the BFF cascade is that it consists of 5 blades only versus the 9-blade TFC cascade [Lepicovsky et al. 2002]. The smaller number of blades is dictated by the size and the flow-rate capacity of the IT CAS wind tunnel. Consequently, the BFF cascade tuning for acceptably uniform flow periodicity will be more demanding due to a smaller number of blades

At present, two sets of blades have been fabricated and are being prepared for testing. The first set of blades consists of simple planar blades (FLA). This blade row is intended for exploration of a newly proposed quasi-stationary method modeling the distribution of cascade blade loadings caused by incidence of a single blade at steady-state flow. Data will be used as an initial computational input to predict evolution of flutter oscillations of the remaining blades in a cascade. The purpose of these tests is to generate a reliable experimental dynamic data base needed for better understanding of the onset conditions leading to dangerous blade flutter oscillations and for further refinement of the prediction computation codes.

2 Test facility status

The aim of this paper is to report an ongoing progression of the BFF facility build-up as well as to present some initial experimental data acquired up-to-date. The BFF research facility is in the first phase of its development and built-up. Only steady-state flow tests with no blade oscillations are being performed at present. The test section case with the investigated cascade has been completed and is installed in the modular suck-down wind tunnel [Luxa, 2001; Luxa et al., 2002] in the IT laboratory in Novy Knin (Fig. 1). The tunnel consists of an inlet nozzle (A), located behind a silica gel drying bed, and followed by a transition segment (B) from a circular to a rectangular cross-section flow path. The new cascade test section (C) is located past the transitional segment. Tailboards placed in the exit module (D) are provided for fine tuning of the cascade operation regime. A downstream transition piece (E) connects the entire test section to an exit duct leading to an underground vacuum chamber. The main flow regulator and a shut-off valve, which are not shown in the figure, are located in the main exit duct (F). An enlarged view of the test section is in Fig. 2; the side walls of the exit module (D) are removed to allow installation of the tailboards. A suitable setting angle of the tailboards can to a degree improve flow uniformity in the tested cascade [Lepicovsky et al., 2000; Lepicovsky et al., 2002].

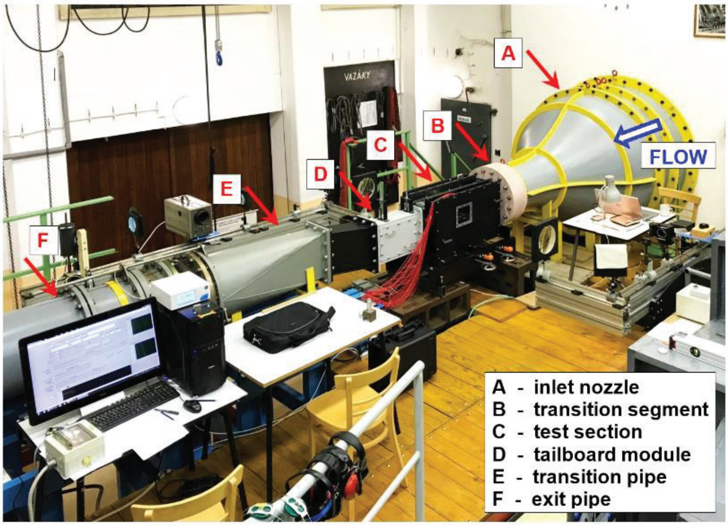

Fig. 1. Blade forced flutter research test facility in the high-speed laboratory of IT CAS.

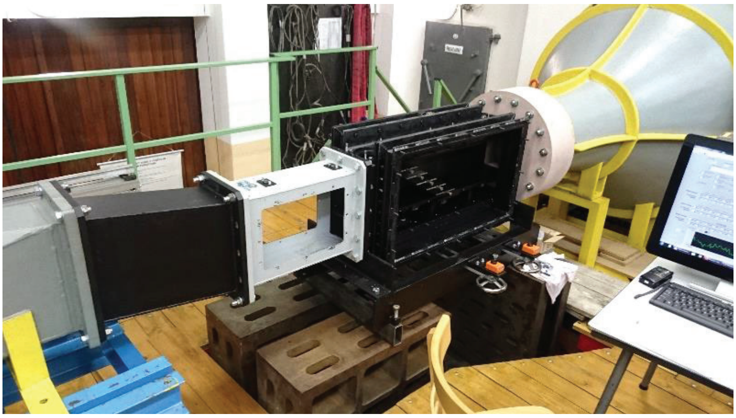

Fig. 2. Enlarged view of the BFF test module.

A detail sketch showing the cascade test section (CTS) inner arrangement is in Fig. 3. The test section is provided with two blade-supporting bridges located outside of the section flow path walls. The blades, provided with pinions on both ends, are inserted into the slide bearings in both bridges. This arrangement allows setting the blades to a desired incidence angle and around the pinion axis to simulate the blade torsional flutter motion. The right side of the test section, in the flow direction, is labeled the driver side, whereas the left side is labeled the instrumentation side. From an operational perspective it is preferable to separate the blade driven side from the blade instrumented side in particular for easier mutual exchange of test blade installation in the cascade. In the NASA TFC facility the driver and the blade instrumentation was constructed from the same blade side which proved to be cumbersome and very labor intensive for any test cascade reconfiguration. A view of the CTS driver side is in Fig. 4. Blade drive pinions protrude through the CTS flow path inner wall. The driving mechanism has been completed, however has not yet been mounted on the CTS side wall. The driver crankshaft will be affixed to the hexagon tip of the blade pinion. Ends of flat blades can also be seen protruding through the cut-outs in the flow path wall. View of the section instrumentation side with the inner wall removed is in Fig. 5. Five flat blades are visible here. The adjustable flow floor can be also seen in this figure.

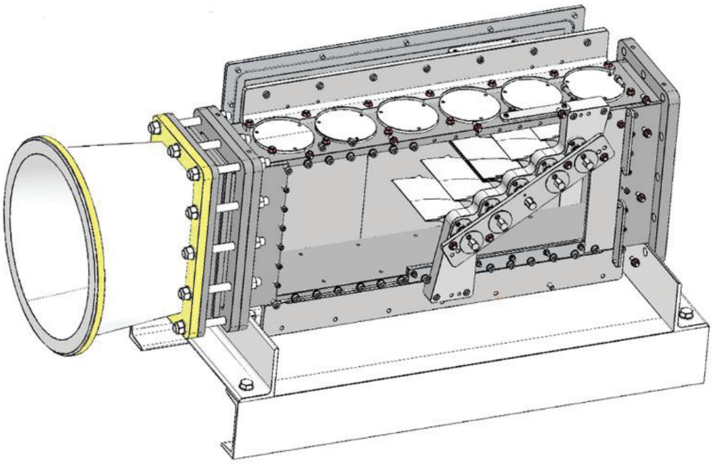

Fig. 3. View of the cascade arrangement and the bridge supporting blades in the BFF test module.

Fig. 4. View of the test module driver side with blade pinions protruding through the cascade inner wall.

The middle blade is set at an incidence angle offset of 3 deg. This blade is instrumented with 10 surface pressure static ports; the connection tubes stick out from the blade body. The second blade above the floor is affixed with six channels ready for miniature high-frequency pressure transducers to be inserted in the blade for the upcoming dynamic testing.

The flow-path inner side wall on the CTS left side is instrumented with a row of wall static taps upstream of the cascade and a similar row of the wall taps downstream of the blade cascade. A bundle of pressure tubing connected to the taps in the section inner wall is shown in Fig. 6. The distribution of the wall static taps and blade suction side taps for the FLA cascade are shown in Fig. 7. Some of the main dimension are also included in the same figure for a better idea about the cascade size. The red tubes connect wall static taps upstream and downstream of the cascade, whereas the white tubes are connected to the middle blade surface pressure taps. The bulkhead passage seal in the lower left corner secures the tubing connection out of the test module to the data acquisition equipment. Not all the tube connections are active for a given test run due to a limited number of reading pressure ports.

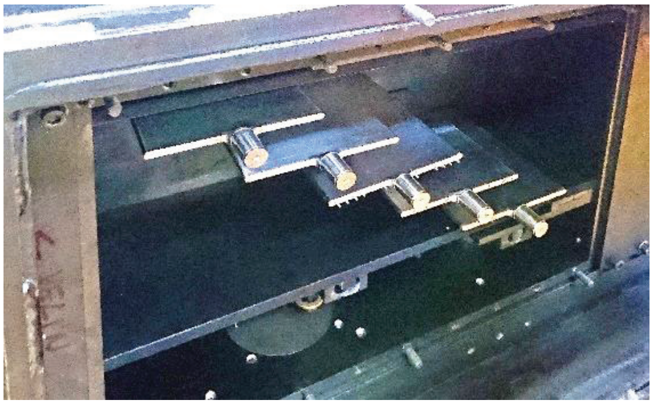

Fig. 5. View of blade cascade instrumentation side with removed section inner wall.

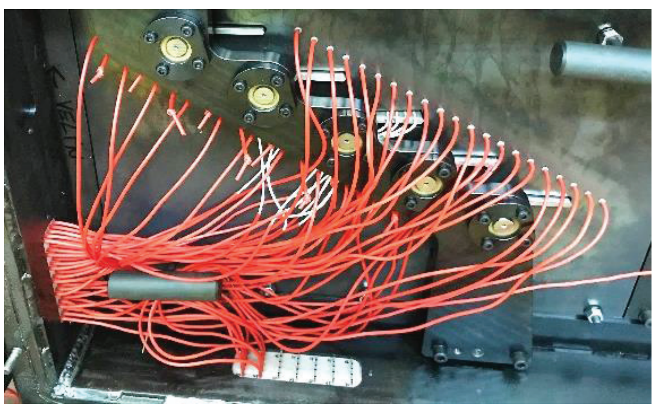

Fig. 6. Routing of connecting tubes from wall pressure taps to a pressure scanner.

3 Experimental results

Cascade inlet and exit Mach numbers as well as the overall cascade pressure ratio were determined during the initial sets of experiments. The average values of the inlet total pressure, measured by a single probe past the inlet nozzle in the channel center, and averages of wall static pressures measured upstream and downstream of the cascade (see Figs. 6 and 7) were used to determine cascade operation conditions. The cascade inlet and exit Mach numbers are isentropic values calculated from the above-mentioned data. A linear cascade (FLA) comprised of five flat blades was used initially. The FLA blade cascade exhibits features of a turbine blade row. A quick glance over data in Figs. 8 and 9 confirms this remark. The flow Mach number increases and the pressure decreases while passing through the cascade.

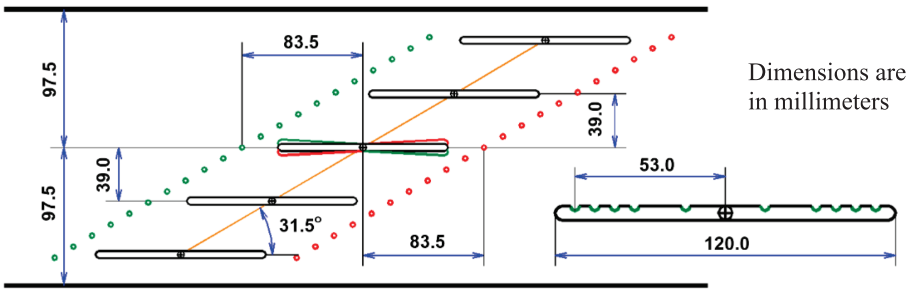

Fig. 7. Locations of side wall pressure taps upstream and downstream of the cascade.

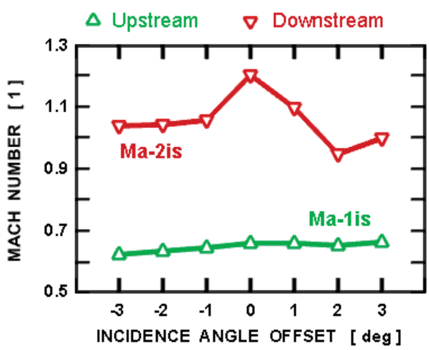

Fig. 8. Effects of middle blade incidence angle offset on FLA cascade peak performance.

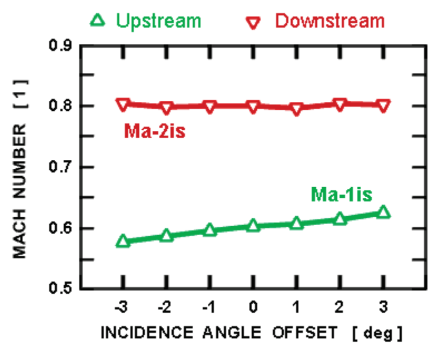

Fig. 9. Effects of middle blade incidence offset on FLA cascade inlet flow at exit Mach number of 0.8.

The effects of changing the incidence angle offset (ICO) of the cascade middle blade are depicted in the above-mentioned Figs. 8 and 9. The incidence angle offset of the middle blade was gradually adjusted from -3 deg to +3 deg in steps of 1 deg while the the tunnel control valve was opened to the maximum through-flow rate. As seen in Fig. 8 the inlet Mach number (Ma-1) is practically not affected by the incidence angle change, rising very mildly from the level of 0.62 up to 0.66, whereas the average exit Mach number (Ma-2) first increases from a level of 1.04 at the incidence angle offset of -3 deg, then peaks up to 1.2 at the zero-incidence offset and eventually drops down to 0.99 for the incidence angle offset of +3 deg. Data presented in Fig. 9 shows results of similar investigations when the exit Mach number was kept constant at a level of 0.8. The inlet Mach number was steadily rising for this operation regime from a level of 0.58 to 0.63 while the incidence offset angle varied from an angle of -3 deg up to the level of + 3 deg.

The effects of the middle blade variations of the incidence offset (BIO) on the static wall pressure levels upstream of the FLA cascade appear to differ noticeably between the lower and the upper halves of the cascade as can be seen in Figs. 10 and 11. The ratios of local pressures and the total inlet pressure are plotted here for the cascade upstream and downstream positions. The position of the blade pin axes are marked by small black circles in the figures.

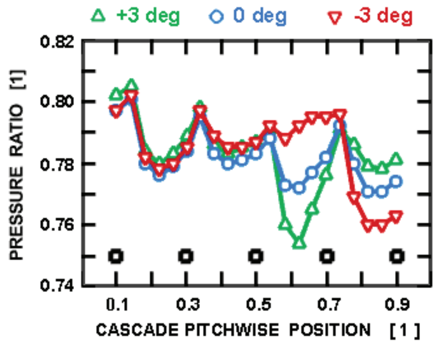

Fig. 10. Effects of middle blade incidence angle offset on wall pressure distribution upstream of FLA blade cascade (Ma-in = 0.6).

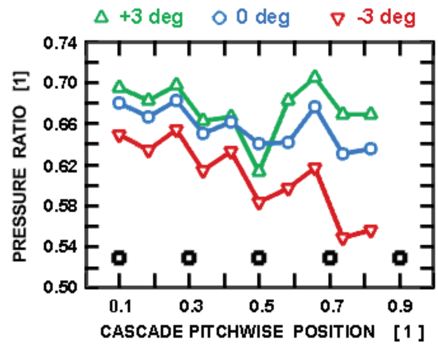

Fig. 11. Effects of middle blade incidence angle offset on wall pressure distribution downstream of FLA blade cascade. (Ma-in = 0.6)

As can be seen in Fig. 10, the incidence offset of blade 3 in the cascade (middle blade) has no effect on the wall pressure distribution for the lower cascade half (blades 1 through 3). On the contrary the upper half of the cascade span between blades 4 and 5 is overwhelmingly affected by the blade 3 incidence offset. In the blade channel 3-4 the pressure level rapidly plunges for the incidence angle offset upturn and it rapidly increases for the incidence angle offset decline below the nominal value. The incidence angle offset effects on the wall static pressure distribution in the channel 4-5 are just reversed to the changes in the blade channel 3-4. The effects of varying offset angle setting for blade 3 are noticed downstream of the cascade along the entire span of the blade row. These changes are stronger over the entire span of the cascade, albeit the changes are again more pronounced for the upper cascade half (blades 3 through 5) than for the lower cascade half (blades 1 through 3).

At present, the test blades are being instrumented with static taps as well as with miniature high-frequency pressure transducers [Lepicovsky, 2005]. The blade instrumentation is not yet completed. To date, only one FLA blade is instrumented with static taps. The blade is instrumented on one side only. However, thanks to the blade symmetry, the blade can be turned by 180 deg in the cascade and consequently the surface pressure distribution can be eventually obtained on both sides of the blade. The blade loading distributions are presented in terms of pressure coefficients as usually defined for compressible flow:

$$C_p = \frac{p_i - p_1}{0.5 \cdot k \cdot p_1 \cdot M_1^2}$$

where p_1 is the average static pressure as measure upstream of the cascade, p_i is a local pressure measured at a given location on the blade surface, k is the ratio of specific heats, and M_1 is the inlet Mach number calculated from the measured upstream data.

The measured pressure coefficient distributions on both surfaces of the middle FLA blade #3 are shown in Figs. 12 through 14. Data shown in these figures are for the blade incidence angle offsets of -3 deg, 0 deg, and +3 deg, respectively. Data reveals huge changes in the blade pressure coefficient values even for such relatively small changes of the blade incidence angle offsets. Acquisition of unsteady data for the blade pressure side as well as the blade loading of the adjacent blades was not competed at the time of writing this paper. Therefore no substantiated judgment of the entire blade loading can be stated at present. The same set of data is replotted in Figs. 15 and 16 where the pressure coefficient distributions are plotted separately for the upper and lower side of the cascade middle blade. The effects of the blade incidence offset angle variations are clearly demonstrated here. Nevertheless, partial data in Figs. 12 through 16 strongly indicate that the changes in the blade loading during the flutter oscillations will be significant and strong enough to modify the instant flow pattern not only in the blade vicinity but even in an extended range of the entire cascade. Consequently, fast flow pattern changes will affect the loading on the adjacent blades in the row and will excite the flutter oscillations of additional blades in the cascade.

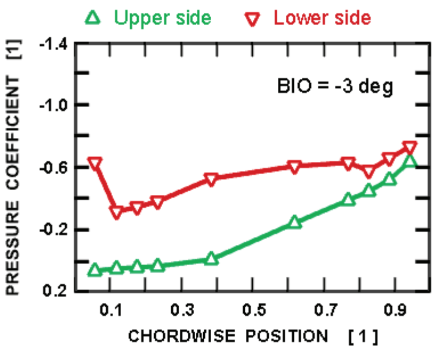

Fig. 12. Distribution of surface pressure coefficient on blade #3 for an incidence angle offset of -3 deg.

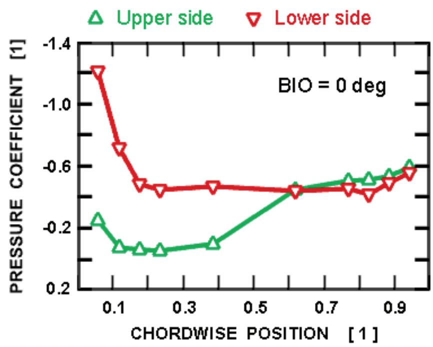

Fig. 13. Distribution of surface pressure coefficient on blade #3 for no incidence angle offset.

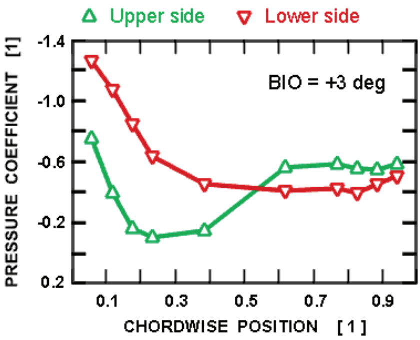

Fig. 14. Distribution of surface pressure coefficient on blade #3 for an incidence angle offset of +3 deg.

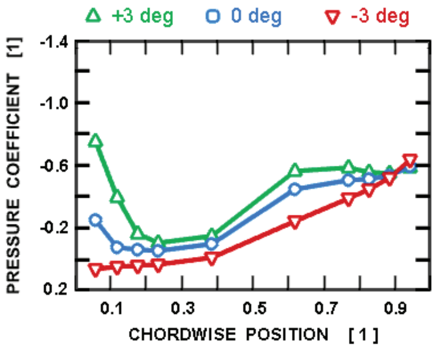

Fig. 15. Effects of middle blade incidence angle offset on pressure distribution on the upper side of the middle blade in cascade (Ma-in = 0.6).

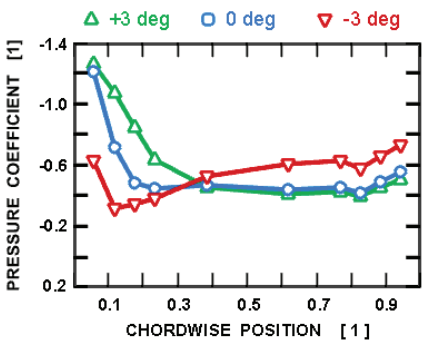

Fig. 16. Effects of middle blade incidence angle offset on pressure distribution on the lower side of the middle blade in cascade (Ma-in = 0.6).

A computational study of the effects of varying cascade middle blade incidence angle offset is being performed in parallel with the experimental effort. The aim of this complex project is to verify validity of the proposed alternative quasi-stationary approach to blade flutter onset research. This method is based on a phased-out stationary measurements of blade loadings at a range of blade incidence angle offsets, which can be determined more easily and efficiently than collecting data from a blade under flutter vibrations.

4 Conclusions

The presented paper is a work-in-progress report on the initial phase of the ongoing research on complex blade flutter problems. Nevertheless some conclusions may be already drawn based of the few preliminary results.

- The modular arrangement of the entire test section enables easy and fast reinstallation of this test module in the wind tunnel frame depending on the wind tunnel test section availability and operation schedule.
- The newly built test section proved to be well suited for advanced research of a single or multiple blade incidence angle "misalignment" effects on cascade performance characteristics under steady flow conditions. Setting the incidence angle offsets for individual blades can be arranged from the outside of the test section and is easy and fast.
- The test section is provided with adjustable floor and ceiling in front of the cascade and adjustable tailboards downstream of the cascade. The initial tests were performed for fixed positions of these adjustable articles. Data in Figs. 10 and 11 indicate that some adjustment may be needed to improve the uniformity of the flow periodicity in the cascade. Boundary layer suction upstream of the tested cascade is intended, albeit not available yet. Common experience is that boundary layer suction is the most effective way for flat cascade flow periodicity improvement [AGARD-AG-328, 1983, Song & NG, 2007].

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References

1. AGARD-AG-328, "Advanced Methods for Cascade Testing", Linear Cascades, Chap. 2, pp. 13-73, Neuilly sur Seine, (1983).
2. Boldman, D.R. and Buggele, A.E.: "Wind Tunnel Tests of a Blade Subjected to Mid-chord Torsional Oscillations at High Subsonic Stall Flutter Conditions", NASA TM-78998,(1978).
3. Luxa, M.: "Budovani noveho aerodynamickeho tunelu v Novem Knine", Symposium o anemometrii, ISBN 80-238-7138-2, Praha (2001) (in Czech)
4. Luxa, M., Jonas, P., and Safarik, P.: "Eintrittentwurf des WindKanals", Fluid Mechanics and Thermodynamics Symposium, ISBN 80-902714-9-9, Praha (2002) (in German).
5. Lepicovsky, J., McFarland, E.R., Chima, R.V, and Wood, R.V.: "On Flow Periodicity in the NASA Transonic Flutter Cascade, Part-I, Experimental Study", ASME 2000-GT-0572, (2000).

6. Lepicovsky, J., McFarland, E.R., Capece, V.R., and Senyitko, R.G.: “Methodology of Blade Unsteady Pressure Measurement in the NASA Transonic Flutter Cascade”, NASA/TM-2002-211894, (2002).
7. Lepicovsky, J.: “Effects of Transducer Installation on Unsteady Pressure Measurements on Oscillating Blades”, ASME-2005, DOI:10.1115/GT2005-6900, (2005).
8. Lepicovsky, J., Sidlof, P., Simurda, D., Stepan, M., and Luxa, M.: “New Test Facility for Forced Blade Flutter Research”, XIX International Conference Power System Engineering PSE 2020, p. 20, Pilsen (2020).
9. Shaw, L.M., Boldman, D.R. Buggele, A.E., and Buffum, D.H. “Unsteady Pressure Measurements on a Biconvex Airfoil in a Transonic Oscillating Cascade”, J. of Eng. for Gas Turbines and Power, Vol. 108, pp. 53-59, (1986).
10. Song, B. and Ng, W.F.: “The Role of AVDR in linear cascade testing”, Journal of Aerospace and Power, Vol. 22, No. 6, (2007).