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On the Influence of a Five-Hole-Probe on the Vibration Characteristics of a Low Pressure Turbine Rotor while Performing Aerodynamic Measurements

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For many reasons it is essential to know and assess the flow field and its characteristics up- and downstream of a turbine stage. For these purpose measurements are conducted in test rigs such as the STTF-AAAI (subsonic test turbine facility for aerodynamic, acoustic, and aeroelastic investigations) at the Institute for Thermal Turbomachinery and Machine Dynamics at Graz University of Technology. A low pressure turbine is operated in engine relevant operating conditions. The turbine is experienced high mechanical loads and is excited to vibrate (forced response). In the rotor design process forced response predictions and structural assessments are performed. However, it is not common to include instrumentation (e.g. total pressure and temperature rakes, five-hole-probes, fast response aerodynamic pressure probes) in these forced response predictions. But, these measurement devices are essential and therefore this paper investigates the influence of such an instrumentation onto the vibrational behaviour of a low pressure turbine rotor of the STTF-AAAI. Several vibration measurements at distinct circumferential and radial positions of the five-hole-probe in the flow channel are conducted. These measurement results are compared to measurements performed without a five-hole-probe in the flow channel. A clear influence of the five-hole-probe on the vibration level is shown.

1 Introduction

Aerodynamic investigations of turbine stages are the main part of every turbomachinery research. After the design and numerical predictions of the flow through turbine stages and its mechanical and dynamical behaviour it is indispensable to perform measurements in test rigs especially if the design is at the limits of the known and established design space. Since many years the Institute for Thermal Turbomachinery and Machine Dynamics at Graz University of Technology has been operating a test rig to investigate sound propagation and blade vibrations. For sure, instrumentation is a necessary and essential part of the test rig. The influence of the instrumentation and measurement devices should be as less as possible, but it is still there. This is true for the flow itself but also for the excitation of blade vibrations. Within a national funded project AdMoNt a sensor telemetry system is used in the subsonic test turbine facility for aerodynamic, acoustic and aeroelastic investigations (STTF-AAAI) in order to measure blade vibrations by means of strain gauges on the blade surfaces in the rotating frame of reference. These investigations have been conducted under engine representative conditions. (Schönleitner, 2016) investigated blade vibrations due to the potential effect of different turbine exit casings (TEC) and due to the downstream effect of the upstream low pressure turbine stator vane row. He has shown a clear evidence of both effects. Also, due to blade-vane interaction the vibrational characteristics of the rotor is affected. This is true for the rotor blades and rotor disc.
Because of the small axial distance between rotor and TEC and hence a small distance between the five-hole-probe (shaft diameter 7mm) and the rotor blades the influence of this probe onto the blade vibrations is determined. Blade vibrations have been measured for different circumferential and radial positions of the probe.

2 Literature Survey

Public experimental data of vibrations of low pressure turbine blades under engine relevant operating conditions are limited. A lot of numerical data can be found in literature, also analytical data and literature about the development of methodology is available. Also, a lot of theoretical work dealing with flutter, forced response and mistuning can be found. Experimental data is mostly obtained in cascades due to the simpler test set up and easier measurements. These tests however neglect essential 3D phenomena and effects that occur. Thus they cannot be simulated in linear cascades.

(Bell, et al., 2000) show the influence of the tip leakage onto the blade vibration of a oscillating blade in a linear cascade. (Huang, et al., 2006) investigated the effect of the tip leakage vortex onto the flutter behaviour of turbine blades. The authors conducted their experiments also in a linear cascade. Shock induced vibrations has been investigated by (Urban, et al., 2000) in a linear cascade utilising flexible supported blades. (Nowinski, et al., 2000) did experiments with low pressure turbine blades and showed some aspects of flutter occurrence in an annular cascade. (Vogt, et al., 2007) reported the influence of negative incidence on the mode shape of oscillating blades. Also these authors conducted their experiments in an annular cascade. The influence of mistuning on aerodynamic damping of an oscillating low pressure turbine blade was shown by (Glodic, et al., 2011). In the same cascade (Vogt, et al., 2007) showed that the influence of a vibrating blade is limited to the adjacent blades. (Kielb, et al., 2001) give detailed insight into the effect of damping of a turbine. The authors showed that aerodynamic damping is inversely proportional to the square of the rotational speed.
There have been no publications found in open literature dealing with low pressure turbine blade vibration measurements in the rotating frame of reference under engine representative operating conditions. Also, there is no literature available that shows the influence of the upstream stator vane row (downstream effect) on the blade vibration excitation and the influence of the downstream turbine exit casing (upstream effect). Therefore, within the project AdMoNt (Schönleitner, 2016) created a novel database with data obtained in the rotating frame of reference under engine representative conditions in order to support the development of future innovative low pressure turbine stages. Main focus was on the upstream effect of different turbine exit casings on the forced response of low pressure turbine blading combined with the downstream effect of the stator vanes.
Also investigations in order to identify and clarify the influence of a five-hole-probe on the blade vibrations during a measurement campaign has been conducted and are reported in this paper.

3 Experimental Facility and Instrumentation

3.1 Subsonic Test Turbine Facility for Aerodynamic, Acoustic and Aeroelastic Investigations (STTF-AAAI)

Figure 1 shows the meridional section of the subsonic test turbine facility. Figure 1 a) illustrates the leaned TEC configuration while in b) the measurement plane is depicted. Air, delivered by a 3 MW compressor station, enters the open loop test facility through a spiral casing. There, the tangential inlet flow is turned into axial direction. The remaining swirl is further reduced by a de-swirler that is also located in the inlet casing. In order to ensure a uniform and homogeneous inflow of the turbine stage a perforated plate is located downstream of the de-swirler. Upstream of the turbine stage an additional inlet guide vane (IGV) can be found. With that IGV different inlet flow angles for the turbine stage can be realised in order to be able to test different stages and/or different operating conditions. The IGVs are followed by the low pressure turbine stator and rotor. Downstream of the rotor the turbine exit casing (TEC) with the turbine exit guide vanes (TEGV) is located.
Additional design details of the test rig are summarised in (Moser, et al., 2007). Due to the design of the test rig it is possible to easily adopt all parts. Inlet guide vanes, stator, rotor, and turbine exit casing can be changed fast and different designs can be integrated in the test rig.
Within this paper the influence of a five-hole-probe during a measurement campaign in plane C between rotor and turbine exit casing will be determined and its effect on the rotor blade vibrations are reported.

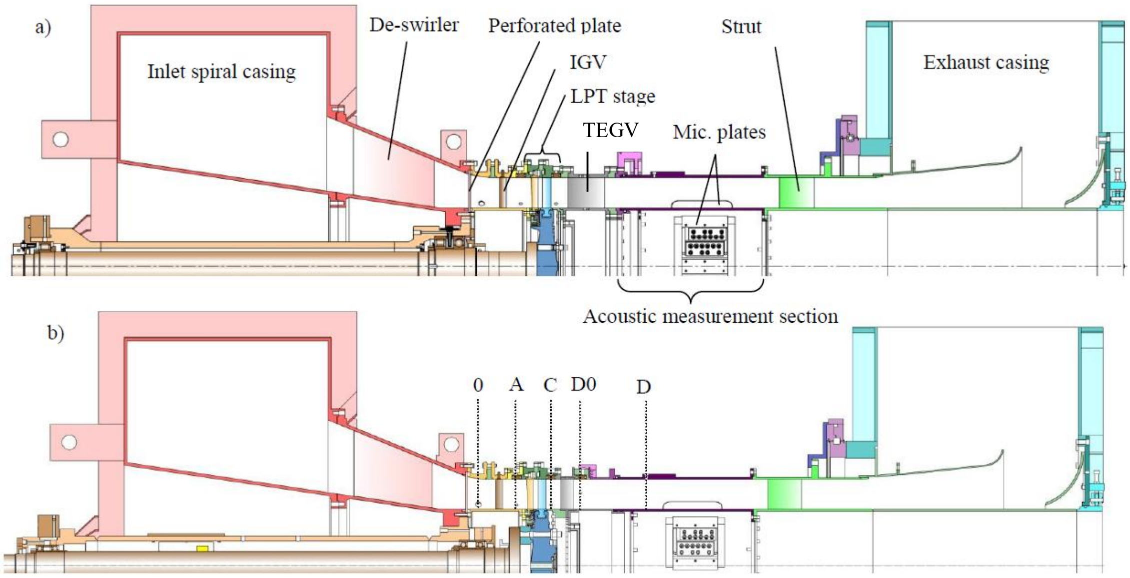

Figure 1. Meridional section of the STTF-AAAI; a) leaned TEC, b) measurement locations

3.2 Turbine Exit Casing

For this investigation the leaned TEC is used. It is an acoustically modified state-of-the-art TEC. The optimisation of the TEC was done by MTU Aero Engines and is reported in (Broszat, et al., 2010). In a parameter study the number of TEGV as well as the angle of the stagger line in circumferential direction (=lean angle) was optimised in order to obtain lowest sound power levels. A strong dependency of the sound power level on the rotor wakes have been observed. Figure 2 left shows a picture of the entire TEC and on the right side a close up view of the TEGV leading edge can be seen as well as a lean angle of 20 deg.

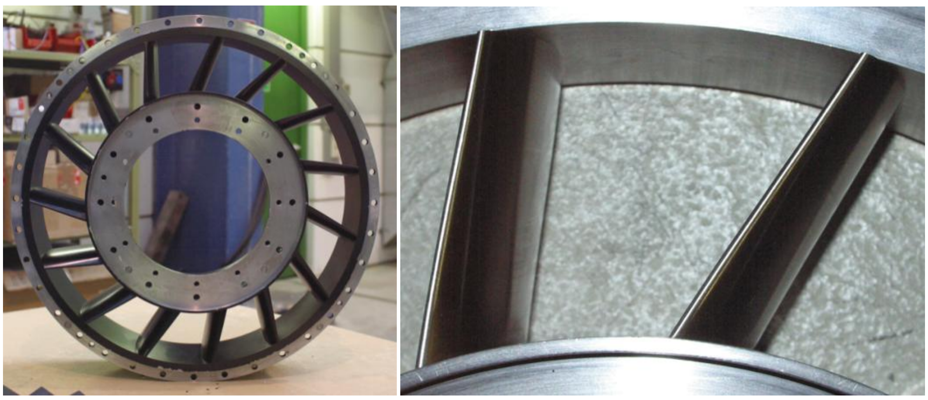
Figure 2. Lean TEC

Table 1 lists the most important technical details. Reynolds number is calculated using inlet flow velocity and chord length of the turbine exit guide vanes.

Table 1. Technical details of the leaned TEC and the turbine stage

No. of TEGV/stator/IGV	-	15/96/83
No. of rotor blades	-	72
Axial Chord Length TEGV	mm	100
Aspect ratio TEGV	-	0.8
Diffusion No. TEGV @ADP	-	0.5
Reynolds No. TEGV@ADP	-	375000

3.3 Five-Hole-Probe

Steady flow field measurements are usually performed by means of five-hole-probes in the measurement locations given in Figure 1 b). Measurements have been performed over one TEGV pitch. The five-hole-probe used for this investigation was manufactured and calibrated at the Institute of Jet Propulsion and Turbomachinery, RWTH Aachen University and is a state-of-the-art probe commonly in use for turbomachinery experiments. In general, five-hole-probes are pneumatic probes to measure the time averaged (steady) flow quantities, total pressure, static pressure, Mach number, and flow angles. Geometrical dimensions of this probe can be seen in Figure 3.

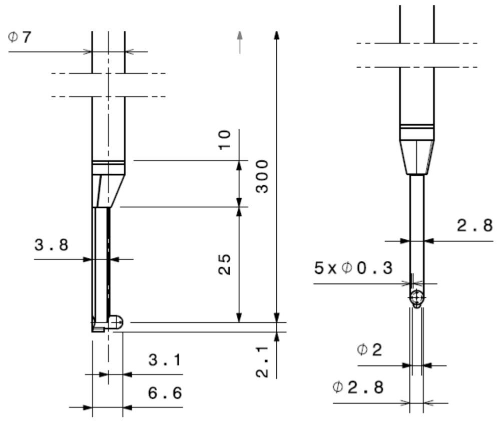

Figure 3.Geometrical details of the five-hole-probe

3.4 Sensor Telemetry System

Blade vibration measurements have been performed by means of strain gauges on different blades at different positions on the blade surfaces and a sensor telemetry system. Details of the strain gauge applications can be found in (Schönleitner, et al., 2015). The sensor telemetry system has a modular design, therefore not only strain gauge signals can be read but also temperature and unsteady pressure signals. For this work at hand 12 channels for strain gauge measurements have been used and 8 for temperature measurements. Technical data can be found below.

- Sensor telemetry system with radial antenna (air gap 2 mm)
- Optimised for turbine rig applications
- Simultaneous data acquisition with 12 bit resolution
- Max. sampling frequency 400 kSamples/s
- Strain gauge resistant 300 Ω
- Quarter-bridge circuit
- Vibration analysis up to 100kHz
- Max. rotational speed 11.000 rpm
- Temperature range -10 °C to +125 °C

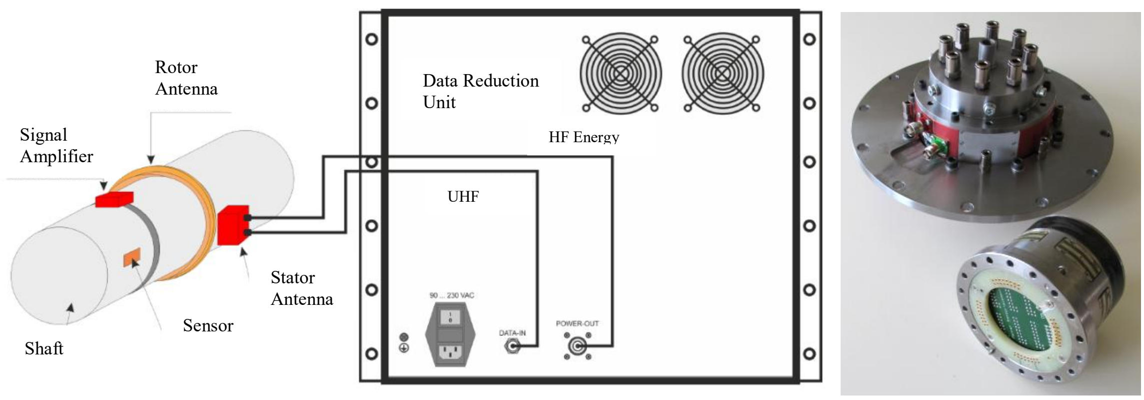

Figure 4. Sensor telemetry system

3.5 Operating Point

The operating point parameters for operating point ADP (aerodynamic design point) are given in Table 2. Due to the fact that the STTF-AAAI is an open loop test facility it is important to adjust the reduced operating parameters in order to have the same comparable operating conditions.

For this investigation the operating point ADP which is the aero design point was chosen.

Table 2 Operating point parameters

			ADP
Total Temperature Inlet	$T_{t,IN}$	°C	100
Stage Pressure Ratio	$p_{t,IN}/p_{t,OUT}$	-	1.131
Mass Flow Rate	$\dot{m}$	kg/s	7.07
Reduced Mass Flow	m_{red}	kg/s	6.86
Speed	n	min^{-1}	3400
Reduced Speed	n_{red}	min^{-1}	2997
Rotor Reynolds No.	-	-	165000

3.6 Measurement Uncertainties

Within this work vibration frequency up to 10 kHz are analysed. With a chosen sampling frequency of 204.8 kSample/s the Shannon-Nyquist criteria is maintained. Simultaneously with the strain gauge signals, temperatures of the applied thermo couples and rig operating parameters are recorded. A trigger signal is provided by the Bentley Nevada shaft monitoring system of the test rig und is also simultaneously recorded. Additionally, the signal of a reference microphone is recorded in order to be able (at a later stage) to perform additional data reduction and evaluation for e.g. trigger on non-synchronous vibrations. The reference microphone (1/4" G.R.A.S. 40BD as in (Selic, 2016)) is located in the TEC close to the trailing edge of the TEGV. For the investigation channels 0 to 11 are used for strain gauge data, channel 14 for trigger data and channel 15 for reference microphone data, respectively.
Strain gauges have a resistant of 350 Ω (+/-0.30%). The k-factor is 2.05 (+/-1.0%) and a temperature coefficient of the k-factor of 101 [10^{-6}/K] (+/-10).
The signal amplifier of type MSV_M_1#2_PCM12 of the telemetry system has a zero drift and amplification drift of 0.02 %/°C. The amplification was set to 0.4 mV/V according to the expected vibration amplitude. The bandwidth of the signal is 0 to 100 kHz (-3dB).
The signal amplifier of type MSV_M_8_PCM12 for the temperature data acquisition has a zero drift and amplification drift of 0.02 %/°C (linearity <0.1%) and a bandwidth of 0 to 5 Hz.
The reference microphone can be used for measurements of sound pressure levels up to 174 dB and frequencies of up to 70 kHz. In a range between 10 Hz and 25 kHz the frequency response is linear (+/- 1 dB). The preamplifier (type 26AC) has a dynamic frequency range between 2 Hz and 200 kHz (+/- 0.2 dB). For the acoustic measurement chain a measurement uncertainty of 1 dB can be assumed.

4 Rotor Characteristics

The low pressure turbine rotor used for this investigation is optimised for highest stage loading. The reference configuration was acoustically investigated within the EU project VITAL. Knowledge of the system properties is essential for the assessment of the operational behaviour. Different numerical and experimental methods are available for system identification. The modal parameter of the rotor have been reported in (Schönleitner, 2016), and (Schönleitner, et al., 2015). Figure 5 shows the rotor with all applied strain gauges 1-12 and thermo couples T_1 and T_2 (left) and one blade with strain gauge no. 3 (right).

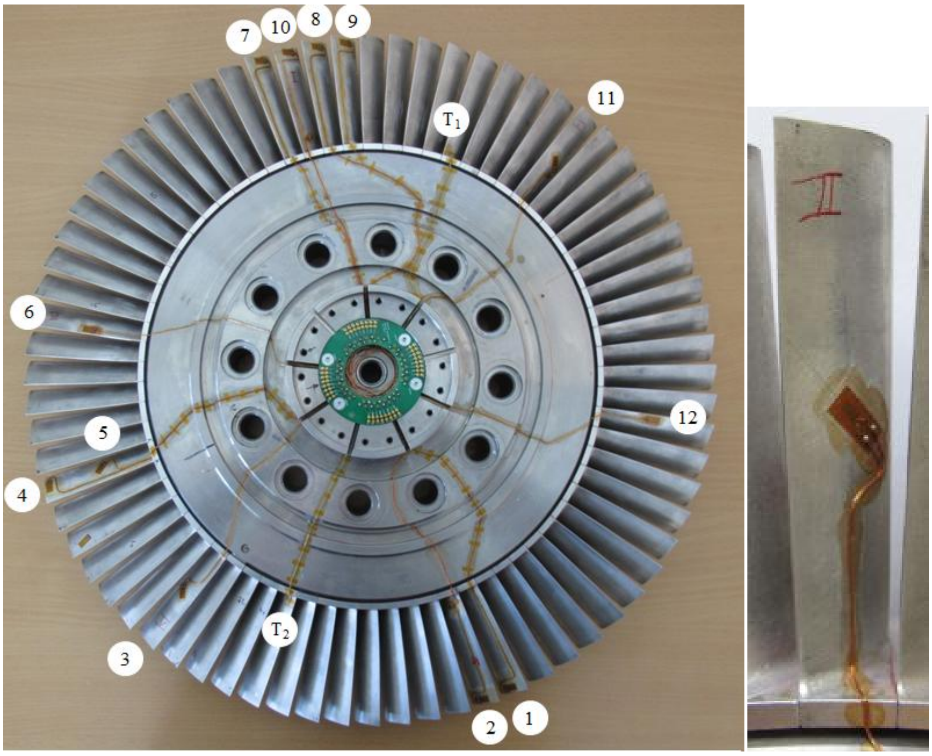

Figure 5. Instrumented rotor (left) and blade with strain gauge #3 (right)

Data of strain gauge no. 3 was used for this paper and is representative for all measurement positions (Schönleitner, 2016).
Campbell diagrams are shown in Figure 6 for the blades (left) and for the rotor disc (right). For the sake of clarity it was decided to draw separate diagrams for the rotor disc and blades. Also, the dashed line indicates the operating rotational speed for this investigation at 3400 rpm. Engine order (EO) lines according to blade-vane-row interactions are also indicated in the diagrams. These lines are dependent of the number of blades and vanes. The origin of the excitation is additionally marked, either with D or U. D represents all effects from upstream vane rows such as stator and inlet guide vane wakes and denotes downstream effects. U represents effects from downstream components such as the turbine exit guide vanes and denotes upstream effects. Modes can also have an upstream and a downstream effect and will be then marked with D/U.

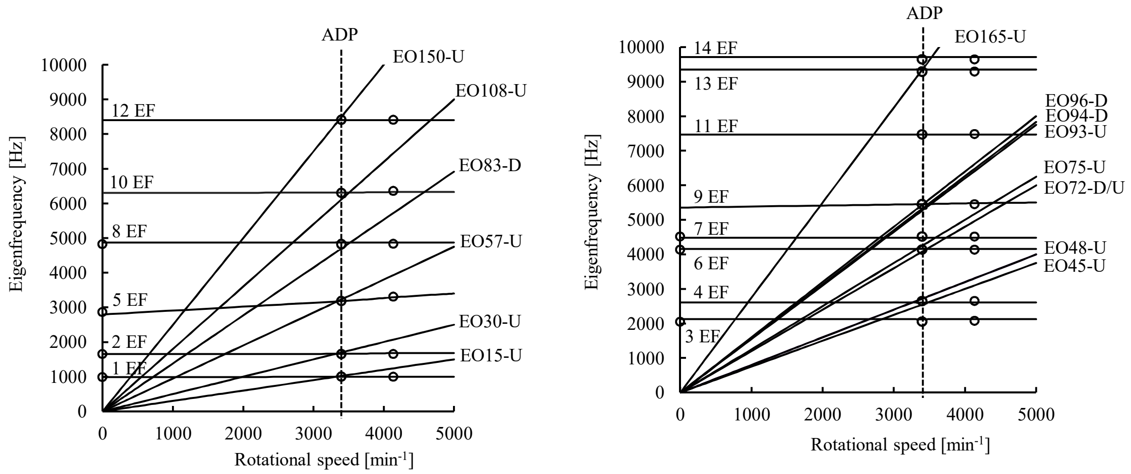

Figure 6. Campbell diagrams; blade (left) and rotor disc (right)

There are 15 turbine exit guide vanes and therefore an EO15 excitation of the first eigenfrequency can be seen. The second harmonic of EO15 excites the second blade eigenfrequency (left diagram). Further, EO45 and EO75 excite rotor disc eigenfrequencies (right diagram). Also EO83 (IGV excitation) and EO96 (stator excitation) are depicted in the diagrams. The operating point was chosen that an excitation of mode 9 due to the stator wakes can be measured. This is one of the most important excitation mechanism in a turbomachine. Also (Tyler, et al.,

1962) reported the importance of vane-blade interaction modes originally for acoustics but these modes are also relevant for forced response.

5 Five-Hole-Probe Measurement Positions

The influence of a five-hole-probe downstream of a low pressure turbine rotor (plane C in Figure 1 b)) onto the rotor and disc vibration was measured. Plane C is important to evaluate the flow field downstream of the rotor and is crucial for aerodynamic investigations of the turbine stage and the turbine exit casing. Usually a turbine exit guide vane pitch is measured in that plane.
For this investigation three typical circumferential and three typical radial positions of the probe are chosen for vibration measurements, see Figure 7. The worst position is expected to be in the middle of the pitch between to turbine exit guide vanes and radial at the most inner position (see Figure 7, bottom right).

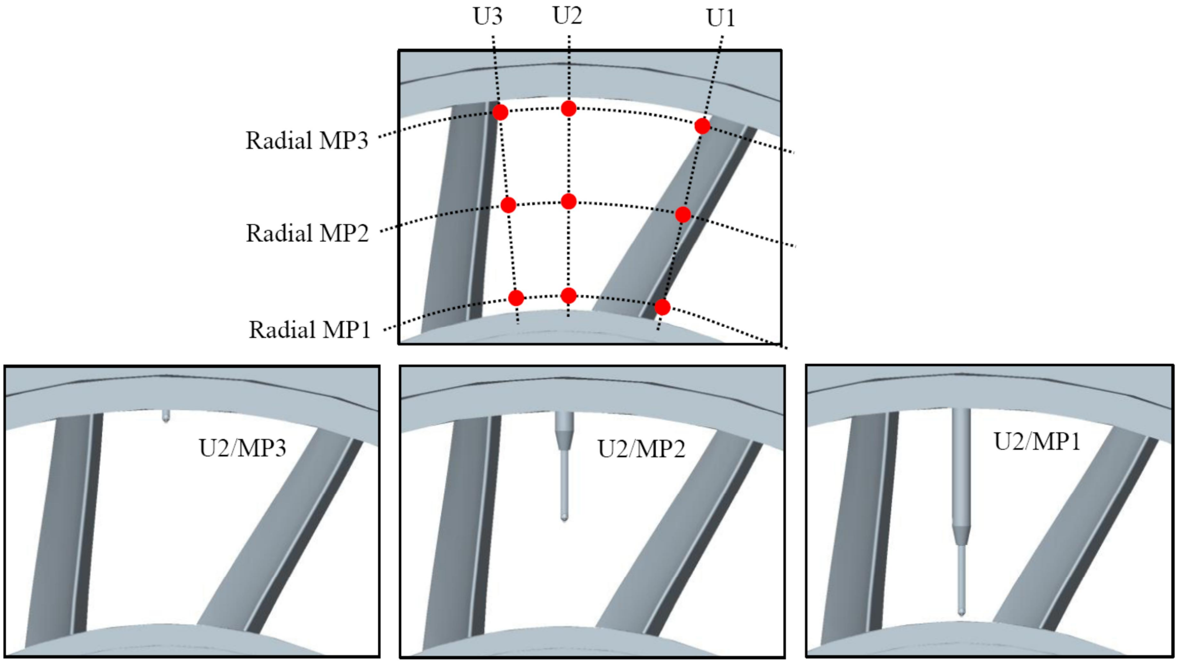

Figure 7. Probe positions for blade vibration measurements

The probe positions where vibration measurements have been performed are shown in Figure 7 at the top and are marked with dots.

6 Blade Vibration Measurements

For the evaluation of the blade vibrations all amplitudes of the respective mode of the different configurations are used. By means of numerical simulations the peaks in the spectra can be clearly identified and assigned to a specific blade or disc mode. These modes can be evaluated separately or together and compared to other configurations. By means of an amplitude weighting a quantitative comparison is possible. For a better representation of the results a net diagram is used.
Figure 8 shows the results of the experimental investigation of the lean TEC compared with the reference configuration (state-of-the-art TEC) presented in (Schönleitner, 2016). The weighted amplitudes for each mode is depicted in the net diagram (Figure 8 left). Amplitudes for the lean TEC as solid line and in amplitudes of the reference configuration as dotted line is shown. A lower vibration level can be seen for the leaned TEC configuration. In Figure 8 on the right side it is distinguished between disc modes and blade modes. Depicted is the sum of all excited modes. It can be seen that 66% of the modes belong to disc modes and 34% to blade modes. The dominant disc modes are a result of the excitation of EO96, EO94, and EO93, where mode 9 show a crossing in the Campbell diagram. For the following discussion mode 1 (blade vibration) and mode 9 (disc vibration) will be analysed in more detail.

Figure 9 shows the spectra without five-hole-probe on the left side and for the worst probe position (circumferential position U2, radial position MP1) on the right side. The influence can be clearly seen when comparing both spectra. Mode 1 (ca. 1000 Hz) and mode 9 (ca. 5400 Hz) show clearly higher amplitudes.

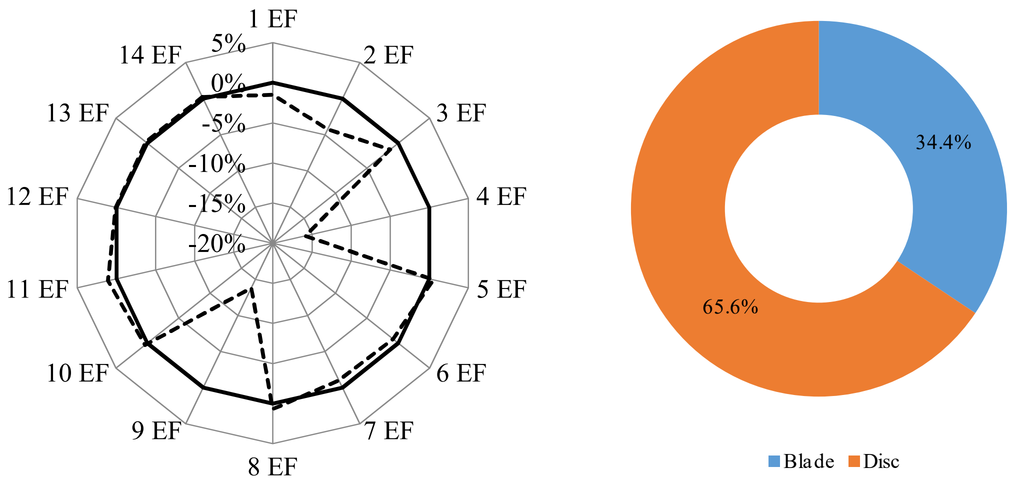

Figure 8. Amplitude levels; net diagram (left) and amplitude distribution of the lean TEC (right)

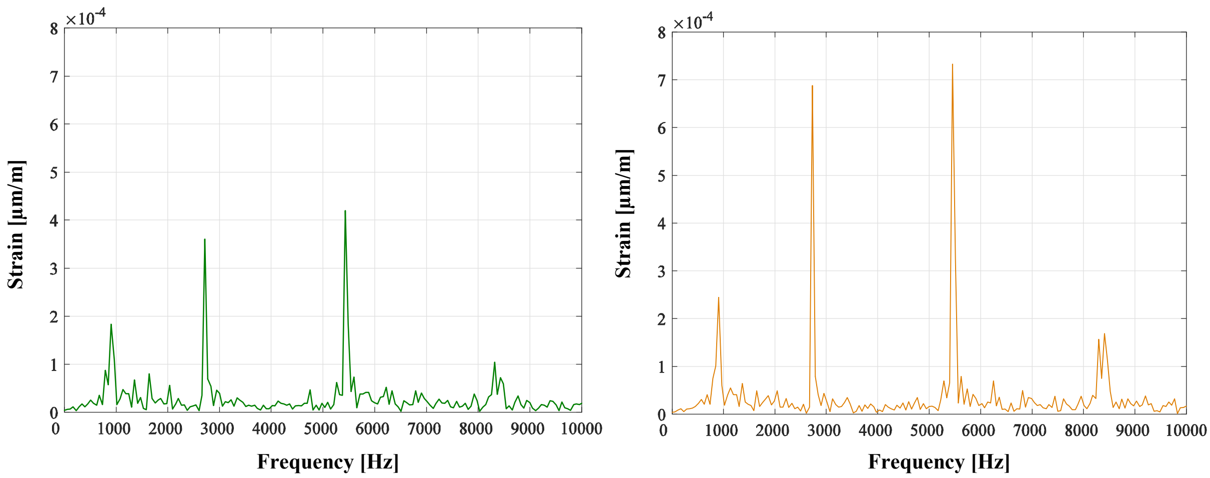

Figure 9. Spectra of strain gauge #3, ADP, without probe (left) and probe position U2/MP1 (right)

7 Results and Discussion

7.1 Amplitude Weighting

For a better comparison of the spectra the amplitudes are weighted based on the amplitudes of the blade vibrations without a probe. The procedure is as follows. All max. amplitudes of the single modes a_i are summed up and give an equivalent amplitude $A_{equivalent}$ independent from the frequency. Related to the equivalent amplitude of a state-of-the-art TEC (standard TEC) a weighting factor is calculated. For other TEC configurations a weighted amplitude $A_{\phi i}$ can be determined. With that amplitude a quantitative comparison is possible.

$$A_{equivalent,standard\ TEC} = \sum a_{i,standard\ TEC} \tag{1}$$

$$\phi_{i,standard\ TEC} = \frac{a_{i,standard\ TEC}}{A_{equivalent,standard\ TEC}} \tag{2}$$

$$A_{\phi i,TEGV} = \left[\frac{a_{i,TEGV}}{a_{i,standard\ TEC}} - 1\right] \phi_{i,standard\ TEC} \tag{3}$$

The procedure was already introduced and applied to compare different TEC configurations in (Schönleitner, 2016) and in (Schönleitner, et al., 2016). This weighting does not take into account if amplitudes of higher frequency are more harmful than amplitudes of lower frequency. For a further lifetime prediction modern methods of durability analysis under consideration of the number of load cycles have to be used.

7.2 Influence of Circumferential Position

The influence of the five-hole-probe onto the blade vibrations changes with the circumferential position of the probe relative to the TEGV downstream of the rotor. Figure 10 shows the weighted amplitudes for blade mode 1 (left) and disc mode 9 (right). The dashed line indicates the blade vibrations without a probe. This vibration level is set as reference value. It can be clearly seen that the vibration level is dependent on the circumferential position as well as on the radial position. In Figure 10 the radial positions are also drawn. The amplitudes are increasing dependent on the radial position. That means that the more the probe is inserted into the channel the higher is the vibration amplitude of the rotor. This is a clear evidence of the negative influence of the probe onto the vibrations of the rotor blades and the rotor disc.
The dependency of the amplitudes on the circumferential positions shows different characteristics for blades and disc. Blade mode 1 is more affected if the probe is in line with the trailing edge of the TEGV (circumferential position U1).

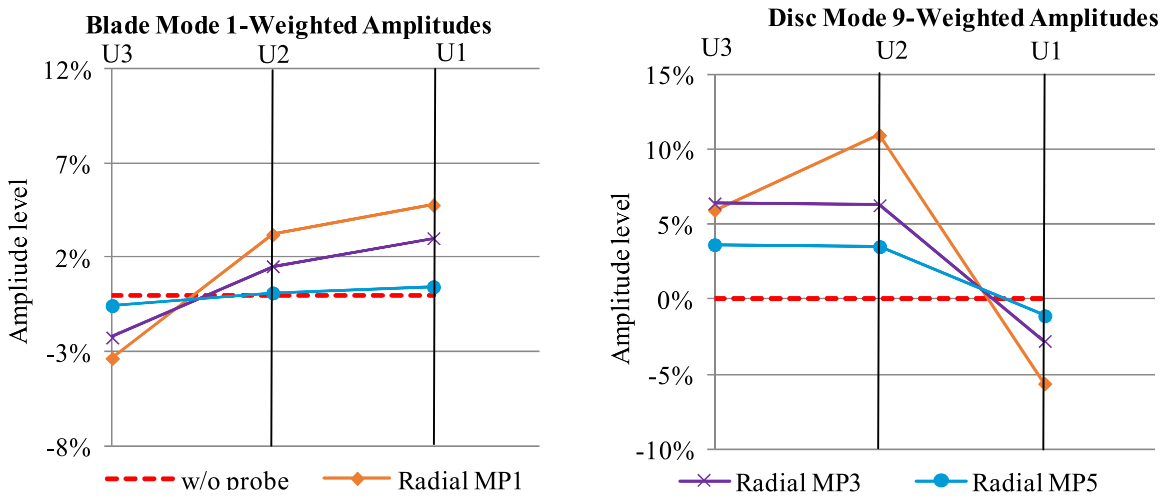

Figure 10. Influence of the circumferential position of the five-hole-probe

The amplitudes decrease if the probe is moved towards the middle of the flow channel between suction and pressure side of TEGVs. These higher amplitudes for circumferential position U1 may be caused by an amplification of the potential effect of the turbine exit guide vanes or it is the sum of the effect of the probe. Looking at the disc mode it is seen that the strongest influence and highest amplitudes occur at circumferential position U2 in the middle of the flow channel. The stronger excitation could be caused by additional blockage effects of the probe and hence a changed flow field through the machine. Contrary to that, the additional blockage effect is less pronounced in circumferential position U1, because the TEGV still produces some blockage.

7.3 Influence of Radial Position

For circumferential position U2 the increase of blade vibrations (left) and the increase of disc vibrations (right) (compared to the vibrations without a probe) for three radial probe positions are plotted in Figure 11. The rotor vibration amplitudes increase the more the probe is inserted into the flow channel. The change is almost linear for the blade vibrations as well as for the disc vibrations. The influence of the probe leads to an increase of blade vibration amplitudes up to 45%. Further, it can be seen, that also in MP3 where only the small probe head of 2.5 mm is in the flow channel, the vibration amplitudes are increased.

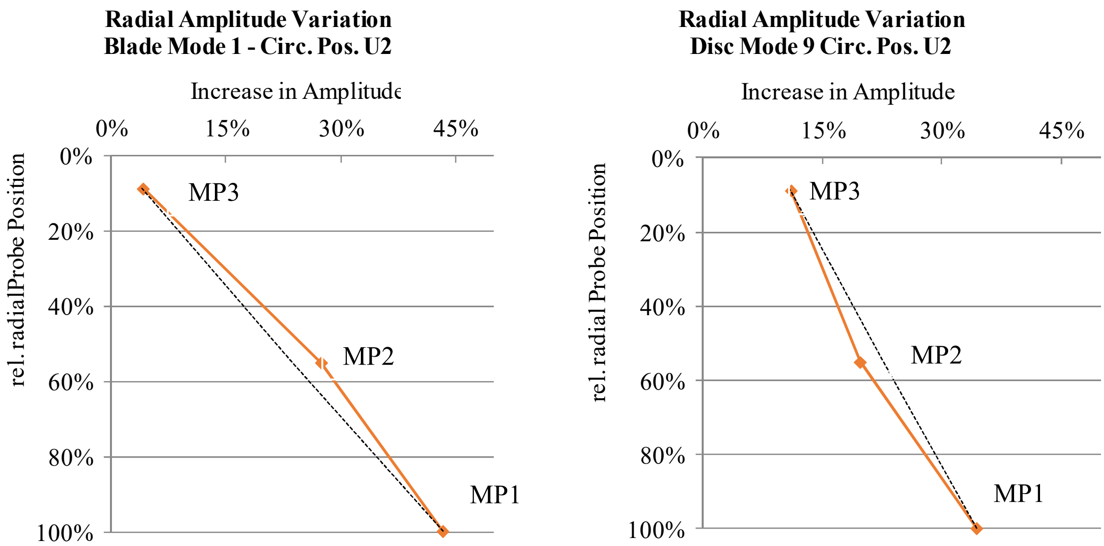

Figure 11. Radial distribution of amplitude variation; blade mode (left), disc mode (right)

7.4 Overall Vibration Levels

To get a better overall view on the vibration amplitudes the data is depicted in net diagrams. Figure 12 shows the amplitudes of all blade modes (left) and disc modes (right) in a frequency range up to 10 kHz.

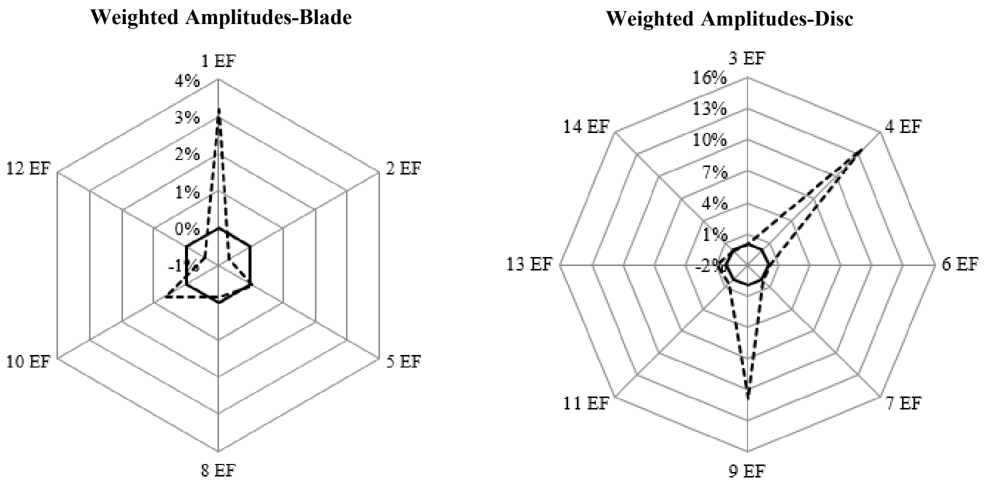

Figure 12. Weighted amplitudes for circumferential position U2 and radial position MP1; blade modes (left) and disc modes (right)

The solid line indicates the case without a probe as a reference with 0% amplitude. Compared to the solid line the amplitudes can be higher, lower or equal. It was shown in previous chapters that the probe position U2/MP1 was the worst one regarding vibration excitation. Therefore Figure 12 shows the amplitudes for that specific probe position. From that figure it can be seen that the influence of the probe is up to 15%. For almost every blade and disc mode an increase of the vibration amplitudes can be seen.

Figure 13 shows the non-weighted amplitudes for all blade and disc modes. Again a large influence of the five-hole-probe is seen clearly. Further, it can be seen that an amplitude increases of up to 80% is measured.

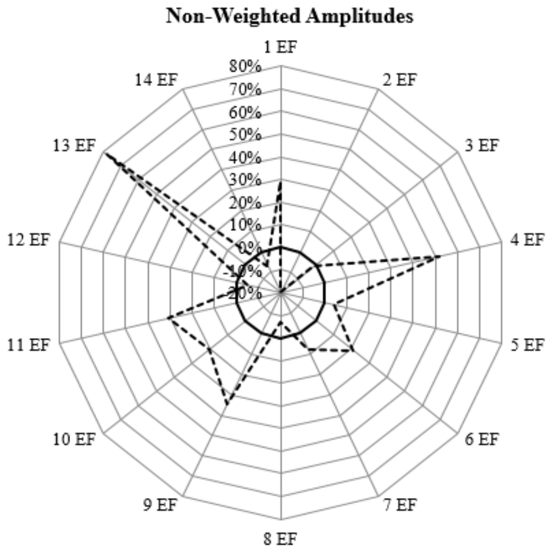

Figure 13. Non-weighted amplitudes of blades and disc at circumferential position U2 and radial position MP1

8 Conclusion

In this paper the influence of a five-hole-probe onto the blade vibrations of a low pressure turbine rotor under engine relevant operating conditions was shown. Further, the dependency on radial and circumferential probe position was reported. For blade and disc modes large vibration amplitude amplifications dependent on the probe position was measured. As expected, the worst probe position was identified if the probe is fully in the flow channel and therefore the largest potential effect and influence of the flow field is assumed, thus increasing the vibration amplitudes of the rotor. In circumferential direction the largest influence has been found if the probe is directly upstream of the TEGV leading edge. Here, the upstream potential effect of the probe and the TEGV are assumed to sum up. Considering the disc modes, the largest influence was found if the probe is in the middle of the flow channel. Here the blockage effect of the vane passage is assumed to play a major role. Amplitude amplification of single modes up to 80% have been measured and shows the importance of considering probes and instrumentation and their position in the design process of rotors intended to be used in test rigs for flow measurements.

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References

Bell, D.L. and He, L.: Three-Dimensional Unsteady Flow for an Oscillating Turbine Blade and the Influence of Tip Leakage. *ASME Journal of Turbomachinery.* January 2000, Vol. 122, S. 93-101.

Broszat, D., Kennephol, F., Tapken, U., Moser, M. and Heitmeir, F.: Validation of an Acoustically 3d-designed Turbine Exit Guide Vane. *16th AIAA/CEAS Aeroacoustics Conference.* 2010. AIAA-2010-3806.

Glodic, N., Vogt, D. and Fransson, T.: Experimental and Numerical Investigation of Mistuned Aerodynamic Influence Coefficients in an Oscillating LPT Cascade. *Proceedings of the ASME TurboExpo.* 2011. ASME Paper GT2011-46283.

Huang, X.Q., He, L. and Bell, D.L.: An Experimental Investigation Into Turbine Flutter Charakteristics at Different Tip-Clearances. *Proceedings of the ASME TurboExpo.* June 2006. ASME Paper GT2006-90541.

Kielb, J. and Abhari, R.: Experimental Study of Aerodynamic and Strutural Damping in a Full-Scale Rotating Turbine. *Proceedings of the ASME TurboExpo.* 2001. 2001-GT-0262.

Moser, M., Kahl, G., Kulhanek, G. and Heitmeir, F.: *Construction of a Subsonic Test Turbine Facility for Experimental Investigations of Sound Generation and Propagation for Low Pressure Turbines.* Beijing, China : s.n., 2007. ISABE Conference. ISABE-2007-1366.

Nowinski, M. and Panovsky, J.: Flutter Mechanism in Low Pressure Turbine Blades. *Journal of Engineering for Gas Turbine and Power.* January 2000, Vol.122, S. 82-88.

Schönleitner, F.: Schwingungsanregung unterschiedlicher Turbinenasutrittsgehäuse zukünftiger Flugtriebwerkskonzepte. *Dissertation, Technische Universität Graz.* 2016.

Schönleitner, F., Traussnig, L., Marn, A. and Heitmeir, F.: Detection of blade mistuning in a low pressure turbine rotor resulting from manufacturing tolerances and differences in blade mounting. *11th International Conference Vibrations in Rotating Machines.* 2015

Schönleitner, F., Selic, T., Schitter, C., Heitmeir, F. and Marn, A.: Experimental Investigation of the Upstream Effect of Different Low Pressure Turbine Exit Guide Vane Designs on Rotor Blade Vibration. *Proceedings of the ASME TurboExpo.* 2016. ASME Paper GT2016-56067.

Schönleitner, F., Traussnig, L., Heitmeir, F. and Marn, A.: Modal Characteristics, Strain Gage Setup and 1-way FSI of a Low Pressure Turbine Rotor as Preparation for Upcoming Experimental Aeroelastic Investigations. *Proceedings of the ASME TurboExpo.* 2015. ASME Paper GT2015-42717

Selic, T.: Experimental Investigation of the Aerodynamics and Acoustics of Exit Guide Vanes for Future Aircraft Engines. *Dissertation, Technische Universität Graz.* 2016.

Tyler, J.M. and Sofrin, T.G.: Axial Flow Compressor Noise Studies. *SAE Transactions.* 1962, Bd. 70, S. 309-332.

Urban, B., Stetter, H. and Vortmeyer, N.: Experimental Investigation of Shock-Induced Blade Oscillation at an Elastically Suspended Turbine Cascade in Transonic Flow. *Proceedings of the ASME TurboExpo.* 2000. ASME Paper 2000-GT-378.

Vogt, Damian M., Fransson, T. and Torsten H.: Experimental Investigation of Mode Shape Sensitivity of an Oscillating Low Pressure Turbine Cascade at Design and Off-Design Conditions. *Journal of Engineering for Gas Turbines and Power.* April 2007, Vol.129, S. 530-541.

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