A NEW TURBINE CASCADE FOR AEROMECHANICAL TESTING

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ABSTRACT

A new test facility has been built at KTH for the investigation of aeromechanical phenomena in axial flow turbomachines. The addressed objective of the work is to study the aerodynamic coupling in a single blade row environment by means of the aerodynamic influence coefficient technique.

The test facility comprises an annular cascade of low pressure gas turbine profiles operated at high subsonic conditions. Being aware of the technical trouble of performing aero-mechanical experiments in real engine environments a simplified setup has been chosen for the present facility; the cascade is non-rotating and operated at low temperature whilst conserving engine Mach and Reynolds numbers. One blade in the cascade can be made oscillating at different orthogonal three-dimensional modes and realistic reduced frequencies. Possibilities are given for achieving more complex blade oscillation modes by combining two modes at certain phase shifts or by introducing blades made of engineered flexible material.

The design of the test facility and the blade actuation mechanism is discussed and advantages and limitations of the chosen setup are addressed.

INTRODUCTION

Over the last decades the trend in gas turbine design has led to considerable increase in aerodynamic loading of the components at reduced weights driven by the demand for higher power densities. Whilst the jet engine manufacturers historically seen had to deal with such conditions before the energy producing gas turbine society the problems have become more integral due to the recent effort to produce cleaner and more efficient gas turbines. The operation of such engines is often performed at exacerbated sets of boundary conditions leading to aeromechanical problems causing high cycle fatigue (HCF). Denoting reciprocative interaction of an oscillating structure and the surrounding flow these problems are referred to as *forced response* (excitation from an external force) and *flutter* (self-excitation).

The work put forward here addresses flutter in low pressure gas turbines solely. The objective thereby is to determine experimentally the aeromechanical characteristics of a blade row by delineating potential regions for flutter with reference to operating conditions. Given the blade row environment the aerodynamic coupling is of additional interest to the mere aptitude of single blades to flutter.

Several investigations have been carried through previously assessing the physical understanding of the phenomenon. Typically cascades of one or more elastically supported blades have been used. The aeroelastic stability could then be described by monitoring the motion of the blades. Although distinct states of flutter could be achieved the possibilities for controlling the parameters were rather limited and the setup did not represent the situation in real engines. More realistic conditions can be achieved by directly controlling the oscillation of one or more blades. Buffum and Fleeter (1998) investigated aeroelastic phenomena in a linear cascade with all and individual blades only oscillating. Körbächer and Bölcs (1994) conducted experiments in an annular cascade with all blades oscillated in controlled modes. From the latter it has been shown by means of the aerodynamic influence coefficient technique that the influences of one oscillating blade and its neighbors can be linearly superpositioned. The aeroelastic stability of a cascade can thus be determined by having only one blade oscillating and measuring the response on all neighbor blades. The parameters reduced frequency, interblade phase angle and incidence angle have shown most significant for describing flutter stability.

As a matter of fact almost all previous flutter investigations were of two-dimensional nature in terms of achieved blade oscillation modes. Real engine flutter however is to a large degree dominated by three-dimensional modes as the blades are fixed at the root in the rotor disk and the blade tips are either free-ending or shrouded. Bell and He (1997) have for the first time shown the importance of three-dimensional blade motion. They investigated the aerodynamic response on a single blade in a linear cascade oscillating in a generic three-dimensional flex mode and showed that the local pressure response was heavily non-linear.

The present facility ties up with the previous results and has been designed to investigate the aeroelastic behavior of a low pressure turbine cascade in a realistic environment. The cascade is of annular shape and comprises a number of blades one of which can be oscillated in controlled orthogonal three-dimensional modes. The aerodynamic response is measured on the oscillating blade as well as the non-oscillating neighbor blades and recombined to aerodynamic influence coefficients. The aerodynamic boundary conditions can be set in a certain range in order to determine the respective influence on the aeroelastic stability.

Below the facility is described elucidating the features for achieving controlled flutter. Furthermore the planned measurement techniques are discussed.

NOMENCLATURE

c	chord, m
f	frequency, Hz
k	reduced frequency, -
p	pressure, Pa
r	radius, m; radial direction
s	span, m
u	flow velocity, m/s
Re	Reynolds number
Ma	Mach number
Y	radius ratio r_{shr}/r_{hub}, -
α	blade metal angle, °
γ	blade stagger angle, °
ϑ	blade pitch angle, °
ρ	density, kg/m^3
Θ	circumferential direction
2D	two-dimensional
3D	three-dimensional
CFD	computational fluid dynamics
HCF	High cycle fatigue
KTH	Royal Institute of Technology, Sweden
TE	trailing edge

Subscripts

ax	axial
hub	hub
shr	shroud

DESCRIPTION OF THE TEST FACILITY

Based on the analysis of previously performed aeromechanical experiments the importance of the following parameters have been identified for investigations dealing with flutter:

- Shape of the test section (annular, linear)
- Oscillation shape (2D, 3D)
- Achievement of flutter condition (self-excited, controlled actuated)

The effects of these parameters are shortly discussed in the sections below followed by the description of the new test facility.

Shape of Test Section

Although real engines are of annular shape experiments are often carried out in linear facilities in order to keep complexity and experimental effort low. A linear facility consists of prismatic blades stacked in a parallel manner and represents the flow field on a respective span section. Depending on the shape of the test section being linear or annular an additional pressure gradient is imposed to the flow in the latter case. This gradient arises from the additional deviation of the fluid in the r-θ plane and is acting in radial direction. Its magnitude depends on the circumferential velocity component of the fluid, the local fluid density and the radius of the streamline curvature in the r-θ plane and can be determined from the following equation:

$$\frac{dp}{dr} = -\rho \frac{u^2_\Theta}{r} \qquad \text{(Eq. 1)}$$

Consequently the pressure increases in radial direction from hub to shroud in annular ducts and thus has an influence on the spanwise velocity distribution along the blade. The influence is especially of big importance in regions of low momentum fluid.

Other than in annular facilities the extension of the duct in direction normal to the main flow (i.e. circumferential) is limited for linear setups. Flow periodicity is thus not inherently present in such facilities and has to be achieved artificially. This is often achieved by means of tailboards that are hinged at the outlet of the cascade. Depending on the setting angle tailboards can induce local flow diffusion and thus affect the backpressure locally downstream of the cascade, which per se can be used for controlling the velocity distribution in the flow passages.

Annular cascades are apart from their inherent flow periodicity and close modeling of real engine flow mainly disadvantaged by high preparative and operational costs. Large-scale facilities often require oversize peripherals (compressor for turbine cascade, motor for compressor cascade) when operated in continuous mode. As a compromise short-duration facilities have appeared over the last decades. Such facilities operate with discharging pressurized fluid from a plenum and thus have as main drawback the heavily limited measurement duration, which typically is of the magnitude of parts of a second.

A rather new and unknown type of facility is the annular sector cascade. Combining the strength of the annular cascade (real modeling of flow features, radial pressure gradient) it avoids excess preparation and operation costs thanks to reducing the flow channel to a sector rather than a full annulus. Flow periodicity is thus no longer inherently present but can be achieved artificially comparable to the task in linear facilities. A simple representative of this type of facility has been described in El-Shamaa (1978) however without the possibility for actively achieving flow periodicity.

Shape of test section / Oscillation shape ↓	2D	3D
2D	1, (2), (3)	(4)[1]
3D	(5)	(6)

1 self-excited oscillation
(1) controlled oscillation

1 Siemens KWU, linear cascade, Urban et al. (2000)
(2) EPFL, linear cascade, Bölcs and Fransson (1986)
(3) Kyushu University, linear cascade, Kimura and Nomiyama (1977)
(4) EPFL, annular cascade, Körbächer and Bölcs (1994)
(5) Durham, linear cascade, Bell and He (1997)
(6) KTH, new facility

Table 1. Locating the new KTH test facility in relation to previous studies

Oscillation Shape

The oscillation shapes of blades in real engines are often very complex and depend heavily on the direct environment of the blade. To name a few, the mounting of the blade to the disk, the structural interconnection of blades by part span shrouds or shrouds and the presence of under platform dampers are parameters of major importance. To discuss the oscillation shapes of blades it has to be separated between pure blade modes and blisk modes, i.e. modes in which the individual blades play a subordinate role and are to be seen as part of the disk. In the present test facility blade modes only shall be investigated.

In a simplified manner the blade is thereby seen as a long and slim and thus flexible object fixed to a considerable more rigid structure. The blade is fixed at its root and deforming elastically in a certain mode shape. Typical blade modes include torsion, chordwise bending (flex modes) and edgewise bending. These shapes can occur in different harmonics as pure shapes or as combined shapes. Regardless the prevailing mode shape it can be stated that blades are deforming 3D in real engines.

For the sake of simplicity the oscillation shape in experimental investigations however is often reduced to a simple 2D motion. Prevailing modes in the open literature include torsion and plunging movements often investigated in linear facilities, see for example Buffum and Fleeter (1998) and Urban et al. (2000). As these investigations focus on the phenomena on a given 2D stream section the degree of modeling is thereby considered high enough.

Achievement of Flutter Conditions

Given the fact that flutter is a self-excited phenomenon it might seem unnatural not to achieve it this way in experiments. Achieving flutter conditions in a controlled actuated way, i.e. one or more blades are actuated in a certain mode shape at a certain frequency, allows however scientific investigation of the phenomenon even in regions of non-flutter and thus to establish aeroelastic stability maps for a given set of boundary conditions. Other than the pure observation of the set of conditions that lead to flutter in the self-excited case conclusions can be draw on the frequency-dependent aptitude of a cascade to flutter.

The New KTH Test Facility

After reviewing previous aeromechanical experimental investigations it has been one of the design goals to recombine the above-discussed parameters in a novel way thus completing existing experimental results. It has thereby been noticed that studies have been carried through, which varied both in the shape of the test section as well as the oscillation shape, see an overview in table 1. None of these however has been performed in annular facilities and with blades oscillated in 3D modes.

The new KTH test facility ties up at this point as indicated in table 1. It comprises an annular test

[1] Although the blade motion is of quasi-3D shape the data is of 2D nature

section and offers the possibility to oscillate one blade in controlled 3D modes. In the base setup a cascade of low pressure gas turbine rotor profiles will be used. The facility is operated in a non-rotating way in order to keep the tasks related to controlled blade oscillation technically feasible in the provided frame.

In order to keep operation and preparation costs to an acceptable level an annular sector shaped test section has been applied rather than a full annulus. To provide comparative possibilities for achieving flow periodicity as in linear cascades a new type of sidewall has been engineered which can be used as tailboard in the annular environment. The potential in periodicity control using this type of sidewalls has been assessed in an early design stage performing full-scale 3D CFD analyses with promising results. By applying the same type of sidewall as inlet duct guidance off-design flow conditions can be achieved.

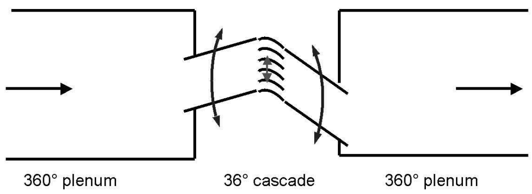

Figure 1. Schematic of the new test facility

Ducting the flow up- and downstream of the cascade has shown necessary in order to provide a boundary condition for maintaining a radial pressure gradient in the outer passages of the cascade. Results from simulations with the cascade discharging into a step diffuser (circumferential direction) indicate that no radial gradient can be maintained in the outer passages and that the gradient in the center passages does not match the real conditions.

The newly developed semi-flexible sidewalls are made of flexible material (polyurethane), which acts similar to a skin on a bearing structure underneath. The structure itself consists of rips that are guided by flexible steel bands thus allowing deformation in one direction as well as twisting whilst resisting to aerodynamic loading.

A schematic of the facility principle is shown in figure 1. The flow is entering a large settling chamber where it is straightened and conditioned by means of a honeycomb and an arrangement of turbulence grids. An annular sector shaped duct is acting as nozzle and guiding the flow to the cascade. The sidewalls of the inlet duct can be operated separately and thus controlled acceleration of the flow can be achieved. Possibility for sucking-off the boundary layer upstream of the cascade is given at the hub.

The cascade itself consists of 9 blade passages but can be reconfigured in blade count to other requirements. Each blade is mounted individually, which allows arbitrary combinations of oscillating and non-oscillating blades. Thanks to a unique fast locking blade fixation mechanism and a service access window the effort for reconfiguring the cascade has been kept to a minimum and can be done without dismantling the facility.

The flow is discharging into a large outlet plenum through the outlet duct that features the above-mentioned flexible sidewalls for periodicity control.

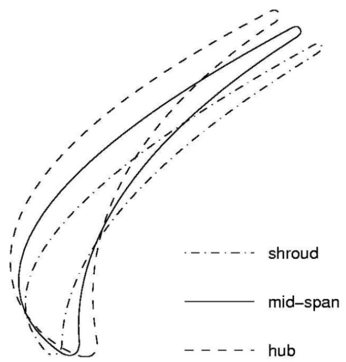

Figure 2. Blade profile sections at different spanwise positions

A possible limitation with the chosen setup is the influence of pressure wave reflections on the downstream walls on the determination of the aeroelastic stability. To date no practical experience has been gained with the facility and thus no statement can be made on this issue. The problem will however be assessed in future experiments. It will be tried to quantify possible influences by performing tests with the oscillating blade being placed at different positions and thus achieving an interference pattern between two configurations.

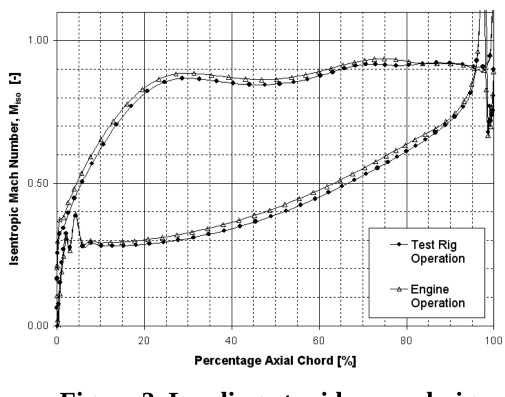

Figure 3. Loading at mid-span, design conditions; results from 3D inviscid CFD analysis

The facility is operated in continuous mode and is for this purpose integrated as exchangeable module into an existing air supply and discharge system at KTH. A screw compressor of 1MW power is supplying air at 4.5bar and a mass flow rate of 4.75kg/s. The temperature of the air can be controlled in a range from 303K to 358K. By means of a set of valves on the supply as well as discharge side of the facility, the Mach and Reynolds number can be controlled independently in a certain range.

Parameter	Symbol	Unit	Value
Real chord	c	mm	54
Axial chord	c_{ax}	mm	47
Span	s	mm	97
Aspect ratio	s/c_{ax}	-	2.1
Stagger angle	γ	°	-32
TE metal angle	α_{TE}	°	-60
Blade pitch	ϑ	°	4.5
Shroud radius	r_{shr}	mm	480
Radius ratio	Y	-	1.25

Table 2. Key parameters of the blade profile

A recently designed experimental low pressure turbine rotor profile is being used for the study, see figure 2. The profile compromises requirements of flow conditions, mechanical integrity and the aptitude for extensive instrumentation whereof the latter directly set a minimum limit for profile thickness. The resulting profile is high-subsonic and uniformly highly loaded. It has been scaled by 150% compared to real engine operation to ease instrumentation. Nevertheless Mach and Reynolds number ranges have been preserved to a large degree at test rig operation and boundary conditions are set such as to achieve engine operation blade loading at a reference section (mid-span). The blade sections near hub and near tip are however operated at positive and negative incidence respectively due to non-sheared inflow as present in real engines.

A set of key parameters of the used blade profile is given in table 2.

Parameter	Unit	Value	Range
Inlet flow angle	°	26	-60/+30
Inlet Mach number	-	0.31	-0.06/+0.13
Outlet Mach number	-	0.82	±0.15
Re_{cax}	-	4.2e5	±1e5
Total temperature	K	300	-0/+30

Table 3. Key operating parameters

One of the major limitations of the new facility is the absence of a centrifugal force as well as non-sheared inflow field due to operating a rotor cascade non-rotating. The absence of the centrifugal force field has a large effect on the natural flutter frequency due to stiffening the blades but can be neglected given the nature of the present experiment with the blade oscillated in a controlled way. Great attention has however been given to the inflow shearing aspect when designing the profile. The transformation of the real engine profile to test facility operation has been performed such as to preserve conditions at mid-span and minimizing incidence effects near hub and shroud. Figure 3 shows the loading at blade mid-span at design conditions.

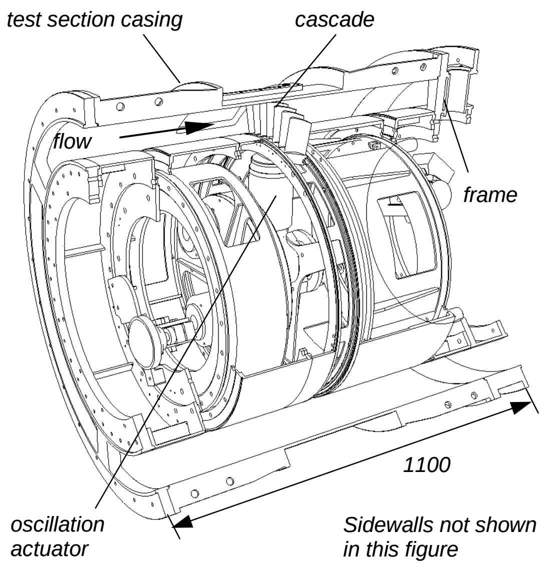

Figure 4. Cutaway view of test section frame

Design-point operation of the cascade is high-subsonic at moderate turning. Off-design operation capabilities include both controlled variation of inlet incidence as well as outlet Mach number. The achievable ranges are listed in table 3.

Despite the annular sector shape of the flow channel in the test section the test facility has been built fully circular in order to allow a rotating traverse movement during measurements, see figure 4. The cascade can be rotated with a high position accuracy (0.030deg), which gives a maximum resolution of 150 points per blade-to-blade passage in circumferential direction. The instrumentation used during traverse operation is fix relative to ground, i.e. the cascade is moving relative to the observer. By adding one additional linear traverse to the measurement device used (machine radial direction) a fully 2D mapping system is achieved. Especially when using optical flow measurement techniques simple traversing techniques are greatly acknowledged.

The traversing motion is PC controlled and features double encoder feedback to compensate for eventual mechanical backlash. It has been designed to operate in either traverse direction meaning that it can be used for traversing against the flow. Diverse precautions have been installed to guarantee safe operation of the facility.

Station	Type	Purpose
1	Fast-locking hinged door	Service access to cascade
2	Extending sector Plexiglas window	Low-tech visual access (flow viz) Blade oscillation analysis (Laser)
3	Exchangeable pad	Probe Laser window (plane)
4	Exchangeable pad	Pressure tapping (steady-state, time-resolved KULITEs)
5	Extending sector Reserve	Integration of future extensions (e.g. varying tip clearance)

Table 4. Measurement stations in test section casing

A number of measurement stations have been distributed around the circumference of the fully circular facility casing. The extent of the stations has been chosen large enough to cover the entire sector cascade whilst avoiding interfering operation at two stations simultaneously. Some of these stations are equipped with exchangeable modules that shall allow a fast and easy change of the instrumentation used. A listing of the stations is given in table 4.

In addition to the casing instrumentation the pressure is measured both steady-state and time-resolved on the hub up- and downstream of the cascade. Recessed mounted KULITE sensors (XCQ-062 on the shroud, LQ-080 on the hub) are used for the time-resolved measurements. Each tap is calibrated dynamically using an in-house developed calibration unit described in Vogt (2002). The unit generates pressure pulses at variable frequencies that are ducted to a calibration head with integrated flush-mounted reference sensors. The transfer characteristic is thereafter determined applying PC-based signal analysis routines.

Analogous to the casing pressure the blade surface pressure is measured steady-state and time-resolved. A number of 100 pressure taps has been distributed evenly on the blade surface. Practically the instrumentation has been distributed on a number of different blades due to geometrical limitations. The results of the different blades can be recombined by means of three reference taps that are located on each blade. The unsteady pressure will be measured at 30 positions using recessed mounted KULITE sensors.

A multi-channel pressure measurement system (PSI8400) is used for the steady state measurements. The system has an accuracy of 0.05% full scale, resulting in ±50Pa for the used 100kPa scanners. The accuracy of the barometer used for measuring the atmospheric pressure is 0.01% full scale or ±11.5Pa. This gives a total error of ±111.5Pa for the absolute total pressure leading to ±0.5% for the Mach number.

The time-resolved pressure measurements are performed using KULITE sensors (types: XCQ-062, XCQ-2-062, LQ-5-080) and a high-speed data acquisition system (Kayser-Threde KT8000). The system features 32 channels with individual analog signal treatment and 14bit AD-converters. Data can be sampled at 200kHz on all channels simultaneously. Accuracy of the sensor after calibration for non-linearity is ±0.1% full scale for the XCQ type (range 172kPa: ±172Pa) and ±0.5% full scale for the LQ types (range 172kPa: ±860Pa). The resolution of the AD-converter adds with ±12μV (±100mV range), which corresponds to ±20Pa taking into account the transfer characteristic of the sensor.

DESCRIPTION OF THE OSCILLATION ACTUATOR

The task of the oscillation actuator is to achieve controlled oscillation of one blade at orthogonal 3D modes. The blade is thereby hinged at the hub and oscillated as a rigid body. This leads to a 3D motion for bending types of oscillation motions with higher amplitudes at the tip and lower at the hub. However oscillation in torsion mode is of 2D shape, as operation under elastic deformation of the test object will be avoided. The real resulting oscillation shapes will be assessed using strain gauges as well as stroboscopic techniques.

As mentioned previously the reduced frequency is one of the most important parameters when analyzing flutter characteristics in turbo-machines. It is defined by the following equation:

$$k = \frac{2\pi f c}{u} \qquad \text{(Eq. 2)}$$

For different types of flutter (supersonic stall flutter, choke bending, supersonic bending) critical values for reduced frequencies are varying between k=0.1 and 0.8. The interest in the present test facility has been put on a range in reduced frequencies of k=0.05 to 0.6, which corresponds to a range in blade oscillation frequency of 42 to 500Hz.

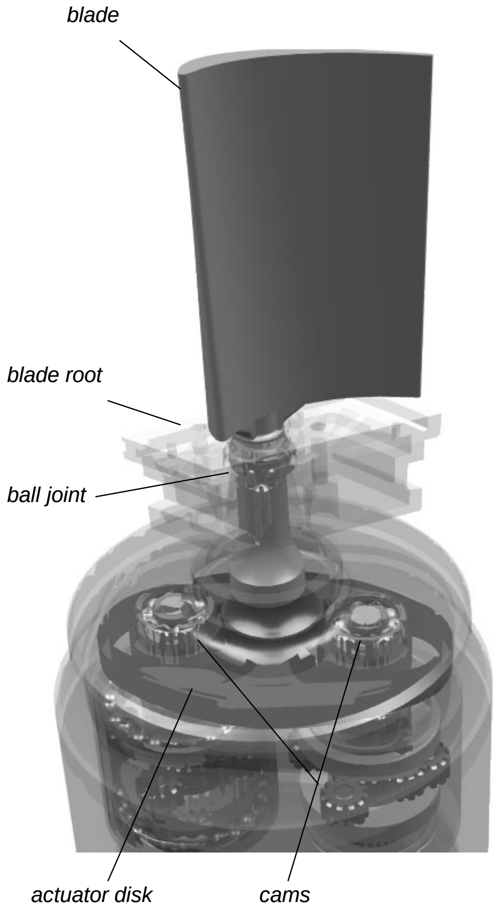

Figure 5. Oscillation actuator

The oscillation actuator is of mechanical type and is located below the hub. It is integrated into the facility such as to serve any blade with arbitrary blade index in the cascade. The oscillating blade is thereby hinged at the root by a ball joint and actuated by means of a rod extending below the hub. Thanks to this setup no intruding parts are affecting the flow field in the test section. The transition between the oscillating blade and the root is made of flexible polyurethane (60ShA) that is vulcanized on both the blade and the root. Thus a smooth and fully sealed transition is guaranteed during oscillation.

The actuator consists of a disk that is guided by two cam-like rotating actuators inside a duct as shown in figure 5. Both camshafts are actuated synchronously and co-rotating and are powered by a frequency controlled AC servomotor. Load variations during the oscillation cycle are damped by means of integrated flywheels.

Parameter	**Control**	**Range**
Reduced frequency	Rotational speed of cam actuators	0…0.6
Mode shape	Phase lag of cam actuators	Bending Torsion Combined (B[2]&T[2], fix phase lag)
Amplitude	Eccentricity of cam actuators	B[2]: 0…6.5deg T[2]: 0…9.5deg

Table 5. Parameter range of oscillation actuator

The eccentricity of the cams can be set to control the oscillation amplitude. The oscillation frequency is directly proportional to the rotational speed of the actuator cams.

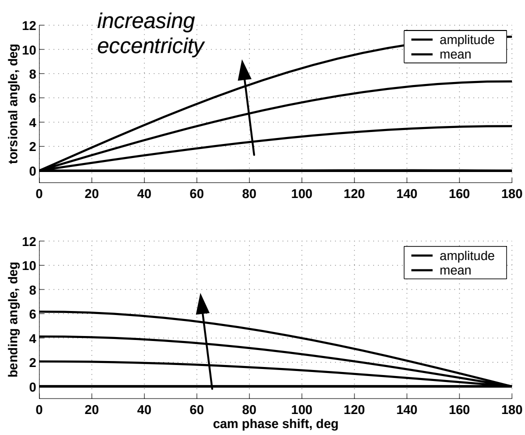

Figure 6. Kinematics of oscillation actuator

By controlling the steady-state phase lag between the two actuator cams different oscillation shapes (pure torsion, pure bending, combined torsion and bending) can be achieved as the results from a kinematics analysis shown in figure 6 indicate. The combination of the two modes however is with this type of actuator limited to a fixed phase angle. Future versions of the actuator will try to overcome this limitation and offer any arbitrary combination of frequency and phase shift.

Table 5 gives a summary of the parameter range of the present actuator. Due to structural limitations the range of achievable amplitude is frequency dependent, i.e. the maximum achievable amplitude decreases with increasing frequency.

[2] B: bending, T: torsion

SUMMARY

A new test facility for the experimental investigation of flutter in low pressure turbines has been built at KTH. It features an annular cascade test section for achieving realistic 3D flow conditions and allows oscillating one blade in controlled 3D modes. The experiments are thus carried through in a forced-oscillation manner; the blade is oscillated at various frequencies and amplitudes and the aerodynamic response is measured on the oscillating blade as well as on its neighbors. By recombining the results to aerodynamic influence coefficients results of interest concerning the aeroelastic stability will be gained.

The new facility is unique from the point of view of achievable flow and oscillation conditions. For the first time ever as the authors are aware it allows the controlled investigation of 3D oscillating blades in a 3D flow environment. Thanks to reducing the annular cascade to a sector rather than a full annulus the required mass flow rate could be reduced considerably whilst maximizing the size of the test object and still achieving transonic operating conditions.

A novel type of blade oscillation actuator has been designed that allows the controlled oscillation of one single blade in 2D torsion and arbitrary 3D bending modes (chordwise, edgewise). In addition combination of orthogonal modes can be achieved. The oscillation actuator is thereby located underneath the hub and operating in a non-intrusive way.

Consequently it can be summarized that the new facility will allow the controlled investigation of flutter in a cascade of low pressure turbine rotor blades at relevant conditions. Big attention has been given to achieving realistic though well-controllable oscillation conditions.

As major limitations the non-rotating operation of the cascade has been pointed out. Its effects on the oscillation behavior and the aerodynamic performance have been discussed and justification for the given setup has been given. The main influences arise from the inflow conditions not being sheared in the experiment. The associated influence has been taken into consideration already during the design of the new experimental turbine blade and thus low impact on the physical relevance of the experiments is expected.

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