A NEW LINEAR CASCADE TEST FACILITY FOR USE IN ENGINEERING EDUCATION

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ABSTRACT

A new low-speed air-operated linear cascade test facility has been developed at the Heat and Power Technology Division at KTH, Sweden. The rig has fully remote operability and is used as an educational tool for the students in engineering courses on turbomachinery. Both on campus and distant students are involved in experimental activities with the rig in the form of laboratory exercises. The current setup allows determination of profile losses through a low pressure turbine blade row at low subsonic flow conditions.

The present paper contains a description of test rig design and its commissioning and introduces the concepts for future applications of the facility in investigation of additional flow phenomena in turbomachinery. Findings of the first field experience with the linear cascade are here reported.

INTRODUCTION

Despite the increasing application of computational fluid dynamics (CFD) tools in turbomachinery related research, experimental testing still plays a key role in the investigation of a wide branch of aerodynamic and aeromechanical phenomena. Blade and engine tests are performed before the final design [1] and no power plant or propulsion system can enter the market before having passed very severe testing campaigns.

While the familiarization of engineering students with CFD tools is relatively widespread and easy to include in their educational path, the possibility to give them experience on experimental testing is rather limited, especially in the case of distant students. The department of Energy Technology at KTH has been one of the pioneers in the introduction of remote laboratory activities for distance education. Examples are the work carried out by Navarathna [2] on a linear cascade and the newly deployed remote pump laboratory [3]. The existing linear cascade needed to be strongly refurbished and a complete redesign of the facility for an enhanced laboratory activity has been undertaken.

From an investigation on current research in turbomachinery, it has appeared that linear cascades are still of particular interest for the analysis of two-dimensional flow fields and in the preliminary design phase of axial flow machines. Of technical relevance is the straight cascade tunnel Göttingen (EGG) at DLR [4], and the linear cascade rig at Chalmers University [5]. Applications of linear cascades in research include blade film cooling studies [6], tip clearance effects [7], effect of incoming wakes on blade rows [8], [9] and end wall heat transfer of nozzle guide vanes [10].

While keeping the concept of the linear cascade, the design of the present test facility has been addressed towards a versatile solution easy to adapt to new experiments and remotely controlled for use in on campus as well as distance education.

NOMENCLATURE

c	chord, m
p	pressure, Pa
s	span, m
γ	blade stagger angle, °
	ratio of specific heats, -
ξ	kinematic loss coefficient
2-D	two-dimensional
3-D	three-dimensional
CFD	Computational Fluid Dynamics
DAQ	Data Acquisition System
HPT	Heat and Power Technology
KTH	Royal Institute of Technology, Sweden
PML	Pressure Measurement Lab
RCL	Remote Cascade Lab

Subscripts

ax	axial
0	total
1	inlet
2	outlet

DESCRIPTION OF THE TEST FACILITY

The new aerodynamic test facility at the HPT Division at KTH is shown in Figure 1. The rig is connected to an air supply system delivering up to 2.5 kg/s for an estimated maximum outlet Mach number of about 0.4. At present the rig is equipped with instrumentation for the analysis of the aerodynamic performances of a linear cascade of low pressure turbine blades. The main operating parameters are included in Table 1.

Figure 1: RCL test facility

Parameter	Unit	Range
Inlet flow angle	°	-45 ÷ +45
Inlet Mach number	-	0.05 ÷ 0.3

Table 1: Main operating parameters

The core of the system is shown in Figure 2 and consists of a central disc supporting all the instrumentation for the measurements (1). A second circular disc (2), made of Plexiglas, is maintained at 100 mm distance and constitutes the outer wall. The main disc is mounted on a ring slide (3) and can be rotated to allow variation of the inflow angle between -45° and +45°. Two sidewalls (4) slide vertically following the rotation of the disc by means of a cam follower system. The cross section of the channel measures 300 mm x 100 mm.

During the design of the facility, major effort has been put to extend the flexibility of the system. An opening of 530 mm x 80 mm (5) at the center of the Plexiglas disc allows introduction in the test section of different test objects. For the experimental investigation on linear cascades, the blades are mounted between parallel plates in the form of an interchangeable module.

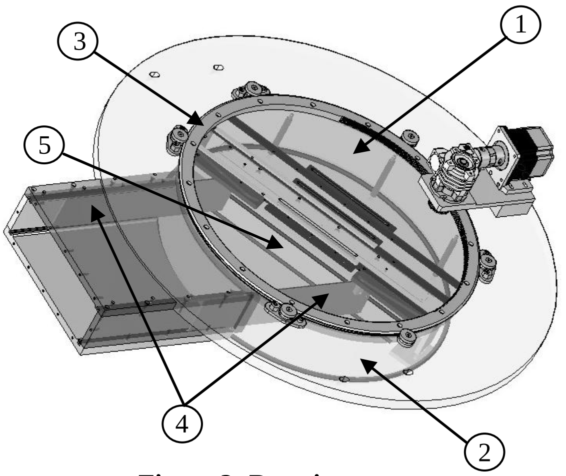


Figure 2: Rotation system

Interchangeable Module

Different blade profiles as well as blades with variable tip leakage can be tested in the RCL. The test rig has been designed such that each set of blades is assembled as a dedicated interchangeable module. The module is pulled out from the test section after having removed two retaining plates fastened to the Plexiglas disk, visible in Figure 1.

Table 2 and Table 3 show the modules currently available and the ones that have already been designed. Results presented in this paper refer to the RCL equipped with the RCL-AETR module with 15 prismatic blades whose specifications are included in Table 4. The blades have been manufactured with SLA (Stereolithography Prototype) process. The same technique will be employed for the realization of blades instrumented with pressure taps on the surface for the determination of the aerodynamic loading at discrete span sections.

An additional module consists of a single plate with several pressure taps – shown in Table 5 - to be used in the PML exercise where the study on the influence of pressure tappings on the measurement values is addressed.

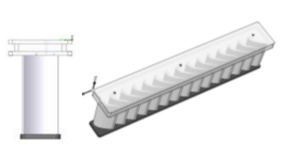
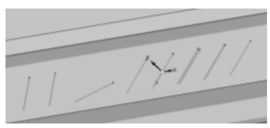
Name	CAD Model	Use / Description
RCL-AETR		RCL Exercise (used e.g. in MJ2244 [11] and MJ 2340 [12]) Prismatic blades
PML	 	PML Exercise 9 different pressure tappings

Table 2: Currently available modules

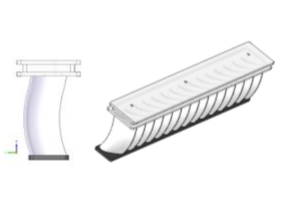
RCL-AETR CS20		RCL Exercise (MJ2244, MJ2430) Compound sweep: maximum 20% of c_{ax}
RCL-AETR TipC		RCL Exercise (MJ2244, MJ2430) Variable tip clearance (motor driven)

Table 3: Modules designed for further investigation of flow phenomena in linear cascades

Parameter	Symbol	Unit	Value
Real chord	c	mm	54
Axial chord	c_{ax}	mm	47
Span	s	mm	100
Aspect ratio	s / c_{ax}	-	2,1
Stagger angle	γ	°	-23
TE metal angle	α_{TE}	°	-60
Blade pitch	ϑ	mm	34,2

Table 4: Blade profile characteristics for RCL-AETR Module

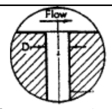
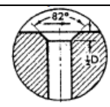
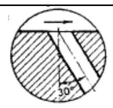
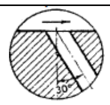
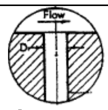
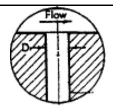
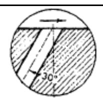
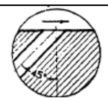
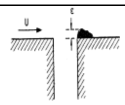
 d=0.6 mm (ref)	 Counter-sink 82°	 30°
 45°	 d=1.0 mm	 d=1,5 mm
 30° backward	 45° backward	 burr

Table 5: Pressure tappings used in the PML

Probe Traversing System

For the experimental investigation of blade profile losses, two aerodynamic 3-hole wedge probes have been used. The probes – detailed view in Figure 3 - are mounted on the bi-directional traversing system shown in Figure 4. Main specifications are included in Table 6. Along with the pitchwise and spanwise positioning, the probes (1) can be automatically rotated around their spin axis for being aligned with the flow at the location of the measurement. The probes pass across the central disc through dedicated slots (5) where sliding plates of low friction plastic material ensure a proper sealing of the test section from the surroundings. A slot for a third pressure probe has been included for future wake evolution studies.

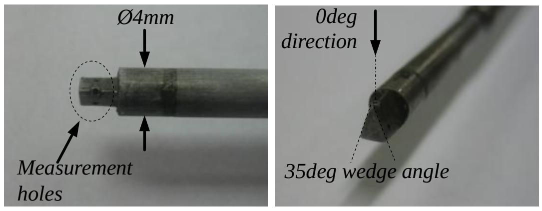


Figure 3: Aerodynamic 3-hole wedge probe

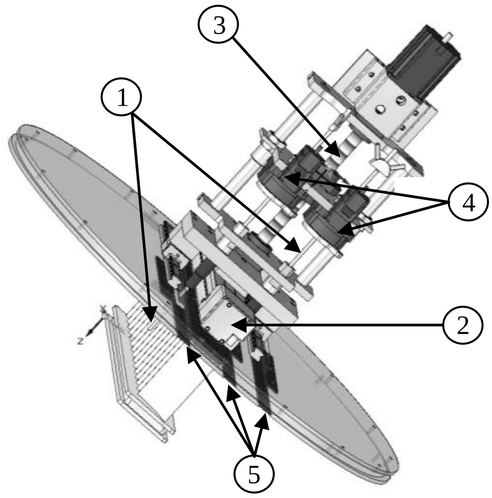


Figure 4: Probes traversing system

Motion	System	Range	Accuracy
Pitchwise	Linear guide (2)	170 mm	±0,05 mm
Spanwise	Spindle and stepper motor (3)	0 ÷ 98 %	±0,02 mm
Probe rotation	Hollow shaft stepper motor (4)	0÷360°	±0,02°

Table 6: Probe traversing system specifications

The choice of 3-hole wedge probes has been driven by the possibility of limiting the complexity of the system while ensuring good readings within a range of ±20° pitch angle. The probes have been extensively used in other arrangements, including an annular-shaped sector cascade. For the future, the adoption of 4-hole or greater multiple hole probes has been considered in order to better capture the 3-D flow phenomena closed to the endwalls.

Data Acquisition System

The laboratory activities to be conducted on the RCL test rig are based on pressure measurements. Two

PSI 9116[1] high accuracy pressure scanners have been included in the facility for a 32-channels capability. Specifications for the PSI9116 are included in Table 7.

Parameter	**Unit**	**Value**
Channels	-	16
Pressure range	psi	0÷5, 0÷15
Accuracy	% FS	÷0,05
Acquisition rate	Hz	up to 500

Table 7: Main specifications of the PSI 9116 pressure scanner

REMOTE OPERABILITY

The new linear cascade at KTH has been designed to be fully operated on distance by non-expert users. This has addressed the choice of the control system and the programming language for the development of the user interface.

The automation system for the rotation of the cascade and for the positioning of the probes is based on stepper motors controlled with two National Instruments NI7334 motion cards for up to 8 axis motion capability. The control interface has been realized in LabView[2] and the Remote Panels Technology[3] has been used to make it accessible on the network.

User Interface

The graphical interface for the operation of the RCL is shown in Figure 6 as it appears when accessed through the web browser at the specified public IP address. What follows in the present description refers to the use of the facility for the RCL exercise where measurements are based on probes traversing.

All controls are arranged on the left side of the page. These include operation of the fan for the air supply to the test rig (frequency control), rotation of the cascade, positioning of the traversing system, data storage and forwarding to the final user.

The central block is dominated by the graphical representation of the cascade including the real-time motion of the probes for a direct association of the pitchwise and spanwise coordinates with the acquired data which are plotted in the graphs underneath. Focus is put on the 0°-direction pressure (refer to Figure 3) upstream and downstream of the cascade – which represent the approximate values of total pressure - and on the side pressures on the downstream probe. The former allows fast identification of the wakes behind the blades while the latter allows rough estimation of the alignment of the probe with the flow at the outlet. By selecting the 'traverse results' tab the view switches to a second window where the current distribution of each of the relevant flow quantities is compared with the distributions from the previous measurements. This allows, for example, a rapid identification of the occurrence of 3D flow phenomena when moving towards the blade tip.

The right-hand part of the interface condensates all the aerodynamic and thermodynamic data acquired. These include the 32 pressures from the two pressure scanners, the total temperature in the inlet pipe and the atmospheric pressure read from the barometer system installed in the department. The graphical representation in the lower corner facilitates the identification and the understanding of the pressures values detected by the two probes.

Network cameras

The room in which the RCL facility is installed is equipped with a set of network cameras[4]. The cameras are fully controllable in pan, tilt and zoom[5], and the user can also choose among a selection of preset views. The cameras are easily accessible also with smartphones and tablets[6]. Free apps such as Netcamviewer can be used which require only typing the IP address [13], the brand of the camera and the credentials. All aforementioned controls and preset views are automatically operable.

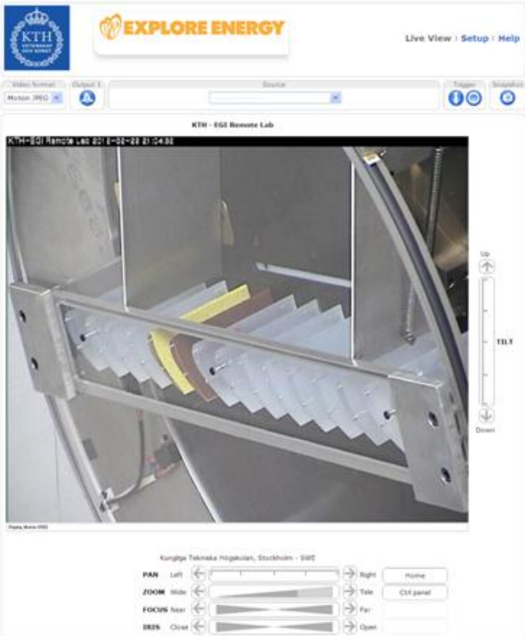


Figure 5: Network cameras in web browser

[1] Pressure Systems Inc., www.pressuresystems.com.

[2] LabView 2010 SP1 Professional Development System.

[3] LabView Remote Panels. Created using the Web Publishing Tool. The host user needs to install the LabView Run-Time Engine - downloadable from www.ni.com - compatible with the operating system of his/her machine.

[4] Contact the authors for access information.

[5] During the first use, it might be necessary for the user to download and install the Axis Media Control Active X, which can also be downloaded for free from www.axis.com.

[6] Tests performed with smartphones and tablets running Apple and Android operating systems.

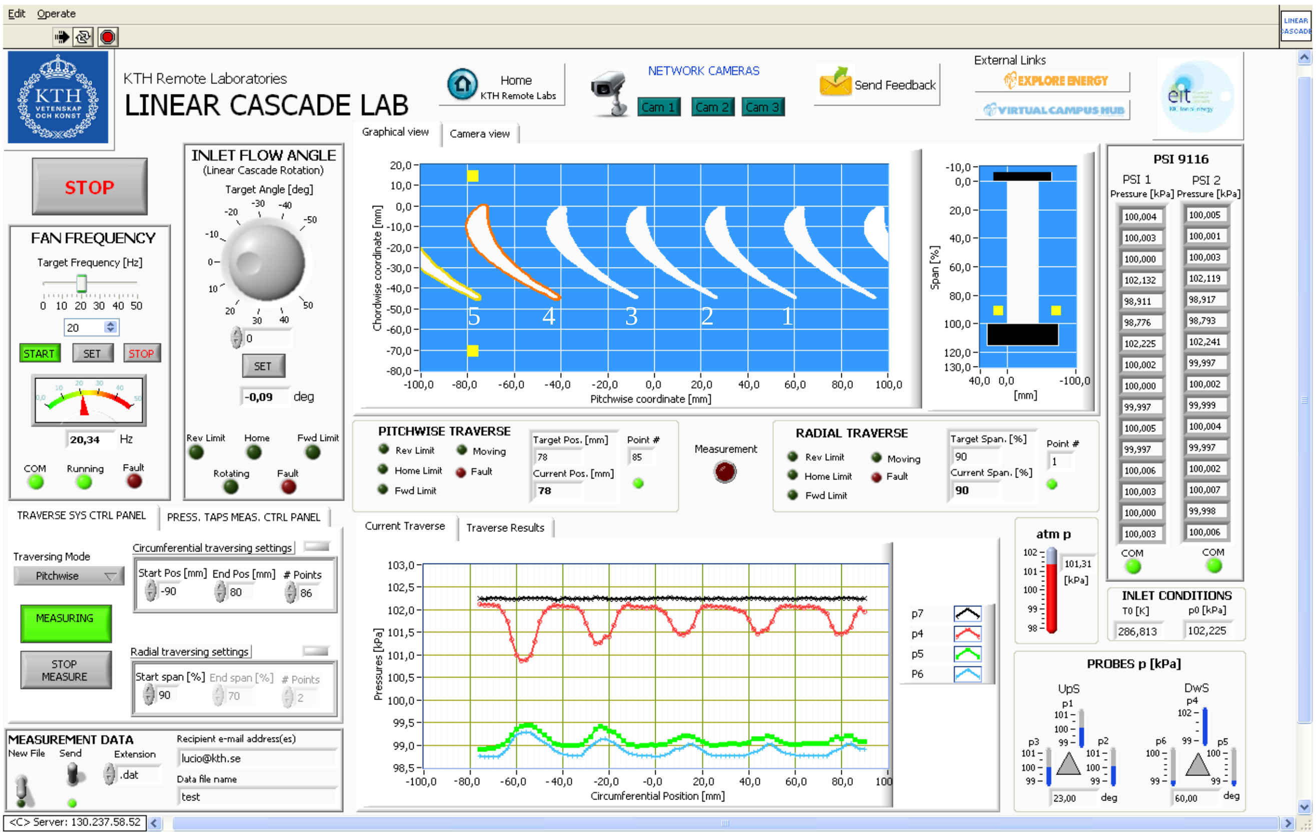


Figure 6: User interface of the RCL accessed through the browser

FIRST FIELD EXPERIENCE

The first application of the linear cascade test facility has regarded the investigation of the downstream flow field distribution and of the profile losses through a low pressure turbine blade row. The cascade performance is determined in terms of the mass averaged value of the kinematic loss coefficient, defined as

$$\xi = \frac{\left(\dfrac{p_2}{p_{02}}\right)^{\frac{\gamma-1}{\gamma}} - \left(\dfrac{p_2}{p_{01}}\right)^{\frac{\gamma-1}{\gamma}}}{1-\left(\dfrac{p_2}{p_{02}}\right)^{\frac{\gamma-1}{\gamma}}} \qquad \textbf{Eq. 1}$$

where the subscripts 0,1 and 2 for the pressure p refer to total, inlet and outlet respectively and γ is the ratio of specific heats.

Data presented here result from the collection of the measurements taken together with the engineering students of the Thermal Turbomachinery and Airbreathing Propulsion II courses in the Academic Year 2012. For the laboratory exercise, the RCL-AETR module has been modified so to include an investigation on the effect of the surface roughness on the steady performances. As visible in the snapshot from the network camera in Figure 5 and underlined in the graphical representation of the module in the user interface in Figure 6, two of the blades within the test section have been covered with sand paper. ISO/FEPA P320 – the brown one – and ISO/FEPA P60 – the yellow one – have been glued on the surface of blade 4 and 5 respectively.

Different inflow angles and different fan frequencies have been tested. Pitchwise and 2D traverses over five passages have been performed at various span locations. Figure 7 shows the downstream distribution of total pressure, static pressure, Mach number and flow angle for a representative case: 20 Hz fan frequency and 0° angle of the cascade. The first set or runs of the linear cascade rig highlights the achievement of a pretty good level of periodicity among the different passages within the positioning range of the pitchwise traversing system. The RCL-AETR module with prismatic blades shows a fairly uniform flow field in the central span sections while rather intense 3D phenomena are detected in the regions closed to the endwalls in complete agreement with the expectations.

Particular interest has aroused from the investigation of the effect of the roughness of the blade surface here reported. This has shown a strong impact on the static pressure, total pressure and flow angle distributions, especially for blade 5. The increased thickness deriving from the application of the sand paper should be accounted for, though very closed to the value of thickness of the P320 the effect of which, instead, is rather moderate.

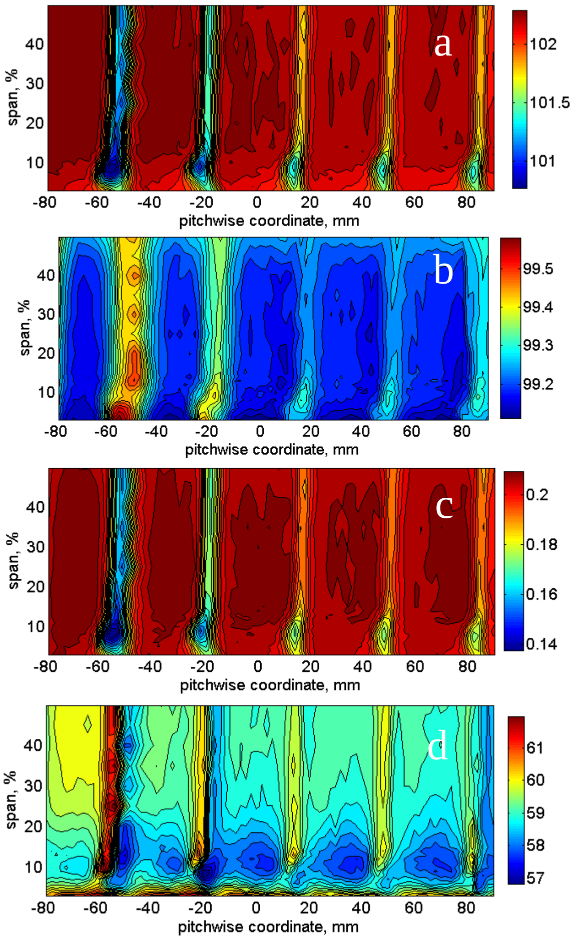


Figure 7: Downstream distributions of (a) total pressure [kPa]; (b) static pressure [kPa]; (c) Mach number; (d) flow angle [deg]

Figure 8 shows the loss coefficient versus the spanwise coordinate for the five blades in the range -80 to 90 mm pitchwise coordinate. These values are obtained from mass average of the flow quantities at a given span location. The periodicity in the results among the first three passages (blades without sand paper) is here confirmed. With increasing roughness of the surface, the loss coefficient increases at all span positions. In the mid passage values move from 5% to up to 9% and closed to the blade tip from 12% to 18%.

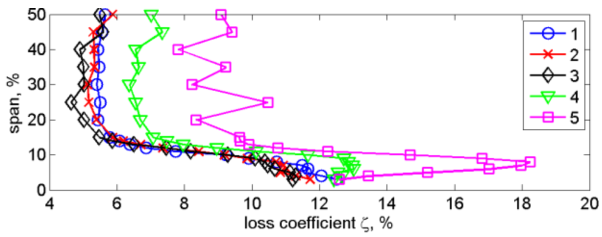


Figure 8: Spanwise loss coefficient. Blade count is the same as in the user interface

CONCLUSIONS

A new aerodynamic test facility for use in engineering education has been realized at the Heat and Power Technology Division at KTH. The test section is equipped with a linear cascade of low pressure turbine blades operated at low subsonic flow conditions. The major element of uniqueness of the facility is represented by its capability of fully remote operation, particularly suitable for use in courses with distant students. Great attention has been spent on the design of a highly flexible system for an easy and fast setup of different laboratory experiments. The most relevant solution regards the arrangement of blades in interchangeable and cost-effective modules. Considerable effort has been reserved for the development of an attractive and user friendly graphical interface including real-time plot of the quantities of major interest for the experiment.

First field experience has shown a good behavior of the test facility. Great periodicity of the flow among the passages has been reached as well as good and reliable operation of the measuring equipment obtained.

On the technical side, further development of the rig includes utilization of instrumented blades, 4-hole aerodynamic probes and the realization of a setup with free vibration of the blades in the travelling wave mode.

On the educational side, laboratory instructions, video tutorials, self- assessments and virtual laboratory exercises are currently being developed in order to offer a complete and comprehensive educational tool. Further experience with the students is required, and teachers and researchers interested in using the remote cascade laboratory are invited to contact the authors for additional information.

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A special thank goes to Alessio Contran who contributed to the design of the laboratory before he decided to meet new challenges in industry.

REFERENCES

[1] Seinturier, E., 2008, "Forced Response Computation for Bladed Disks. Industrial Practices and Advanced Methods", Lecture Series 2008-05: Structural Design of Aircraft Engines: Key Objectives and Techniques. Von Karman Institute for Fluid Dynamics

[2] Navarathna, N., Fedulov, V.Martin, A., Fransson, T.H., 2004, "Web-based, Interactive Laboratory Experiments in Turbomachine Aerodynamics", Proceedings of the ASME Turbo Expo 2004, June 14-17, 2004, Vienna, Austria

[3] Monaco, L., Vogt, D., M., Fransson, T., H., "Implementation of a Remote Pump Laboratory Exercise in the Training of Engineering Students", ASME Paper GT2012-69983 to be presented in ASME Turbo Expo 2012

[4] The Straight Cascade Tunnel 'Göttingen' at the German Aerospace Center, Germany, http://www.dlr.de/at/en/desktopdefault.aspx/tabid-1565/2433_read-3789/, accessed on Feb 29, 2012

[5] Chalmers' Linear Cascade Rig at Chalmers University of Technology, Sweden, http://www.chalmers.se/am/EN/research/research-resources/chalmers-windtunnels/chalmers-8217-linear, accessed on Feb 29, 2012

[6] Gehrer, A., Woisetschläger, J., Jericha, H., "Blade Film Cooling by. Underexpanded Transonic Jet Layers". ASME Paper 97-GT-246

[7] Williams, R., Gregory-Smith, D., He, L., Ingram, G., 2010, "Experiments and Computations on Large Tip Clearance Effects in a Linear Cascade", ASME J. Turbomach, 132, Issue 2, 021018

[8] Coton, T., Arts, T., Lefebvre, M., Liamis, N., 2003, "Unsteady and Calming Effects Investigation on a Very High-Lift LP Turbine Blade—Part I: Experimental Analysis", ASME J. Turbomach. 125, pp. 281

[9] Volino, R. J., 2012, "Effect of Unsteady Wakes on Boundary Layer Separation on a Very High Lift Low Pressure Turbine Airfoil", J. Turbomach. 134, 011011

[10] Rubensdörffer, F., Fransson, T. H., "A new test facility for evaluation of parameters defining nozzle guide vane endwall heat transfer", The 17th Symposium on Measuring Techniques in Transonic and Supersonic Flow in Cascades and Turbomachines, Stockholm, Sweden, September 2004

[11] MJ2244 Airbreathing Propulsion II course, http://www.kth.se/student/kurser/kurs/MJ2244, accessed on Feb 26, 2012

[12] MJ2430 Thermal Turbomachinery course, http://www.kth.se/student/kurser/kurs/MJ2430, accessed on Feb 26, 2012

[13] Network cameras IP addresses are: 130.237.58.71 and 130.237.58.53