ON MEASUREMENT AND EVALUATION OF FLOW CONDITIONS AT LIMIT LOAD OF TURBINE BLADE CASCADES

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ABSTRACT

This paper deals with methods of experimental research on flow past turbine blade cascades under conditions of limit load. Measurements are performed by both optical and pneumatic methods (probe traversing). Obtained experimental data – pictures of flow fields and distributions of total pressure, static pressure, and exit velocity argument – are utilized for evaluation of forces and parameters to show limit load regimes. Subject of the investigation are blade cascades representing tip section and root section of rotor blading with relatively long blades.

INTRODUCTION

There are four significant regimes at operation of high-speed turbine blade cascades. The first regime, called critical Mach number, determines (and is determined by) first occurrence of maximum local flow velocity equal to sound speed of the flowing medium. The second regime concerns transonic flow conditions when aerodynamic choking takes place, i.e. when sonic line first time fully crosses the interblade channel. At aerodynamic choking, maximum nominal flow flux is achieved. The third significant regime can be characterized by flow conditions when regular interaction of internal branch of exit shock waves at the suction side of adjacent blade occurs. This regime determines supersonic flow regimes in exit part of turbine blade cascades. The fourth regime, called limit load, determines conditions at which the back pressure cannot affect flow development in exit part of the blade cascade. In this paper methods enabling to measure flow conditions at limit load of turbine blade cascade are presented and discussed. Remaining three regimes, critical Mach number, aerodynamic choking and regular interaction of internal branch of exit shock waves, are possible to study according to experimental data from optical measurements described in [1].

Parameters of blade cascade limit load are important for designers of those turbomachine blades where working medium exits blading at supersonic velocities. Collocation limit load means no possibility to increase aerodynamic force acting on blade cascade profiles by decreasing exit static pressure under constant inlet flow conditions [2]. Experimental research confirms that with decreasing back pressure flow develops to limit load regime for transonic blade cascades where aerodynamic choking takes place. Pictures of flow fields prove that limit load occurs when the internal branch of exit shock waves touches trailing edge of adjacent blade. Further increase of exit Mach number leads to flow structure at which inner branch of exit shock waves completely misses adjacent blade.

Optical methods provide pictures and data on flow conditions at turbine blade cascade limit load. The authors applied interferometric measurement method and aerodynamic forces are evaluated from interferograms [3]. Obtained data can determine limit load conditions.

Traversing probe method gives also possibility to obtain data on limit load of turbine blade cascade. Parameters from data reduction method – namely exit Mach number M_2 and exit angle α_2 (oriented to machine rotor axial direction) – can determine conditions of limit load according to following condition:

$$\left| M_2 \sin \alpha_2 \right| \geq 1 \ . \tag{1}$$

The authors have at their disposal extensive archive of results from aerodynamic investigations of different blade cascades. Specific regimes can be studied. For purpose of this paper results of investigations of two blade cascades – tip sections and root sections of rotor blading with relatively long blades – are presented and discussed [4].

RESULTS AND DISCUSSION

Application of optical methods for observation of limit load regime of a turbine blade cascade is very convenient. These methods give pictures of flow structures namely configurations of shock waves. Visual information offers evidence of flow development at decreasing back pressure. At supersonic exit velocities exit shock waves arise downstream of trailing edges. Their internal branch determines region which cannot be affected by downstream flow parameters. If the internal branch of exit shock waves interacts with external branch of exit shock waves arising downstream of trailing edge of adjacent blade limit load regime is exceeded.

Figure 1 shows interferogram of flow field at the root section of rotor blading at isentropic exit Mach number M_{2is} = 1.828 and incidence angle i = 0°. Exit shock waves arise behind trailing edges and do not interact with adjacent blades. Namely the internal branch of exit shock waves misses the trailing edge of the adjacent blade i.e. blade loading is at its limit.

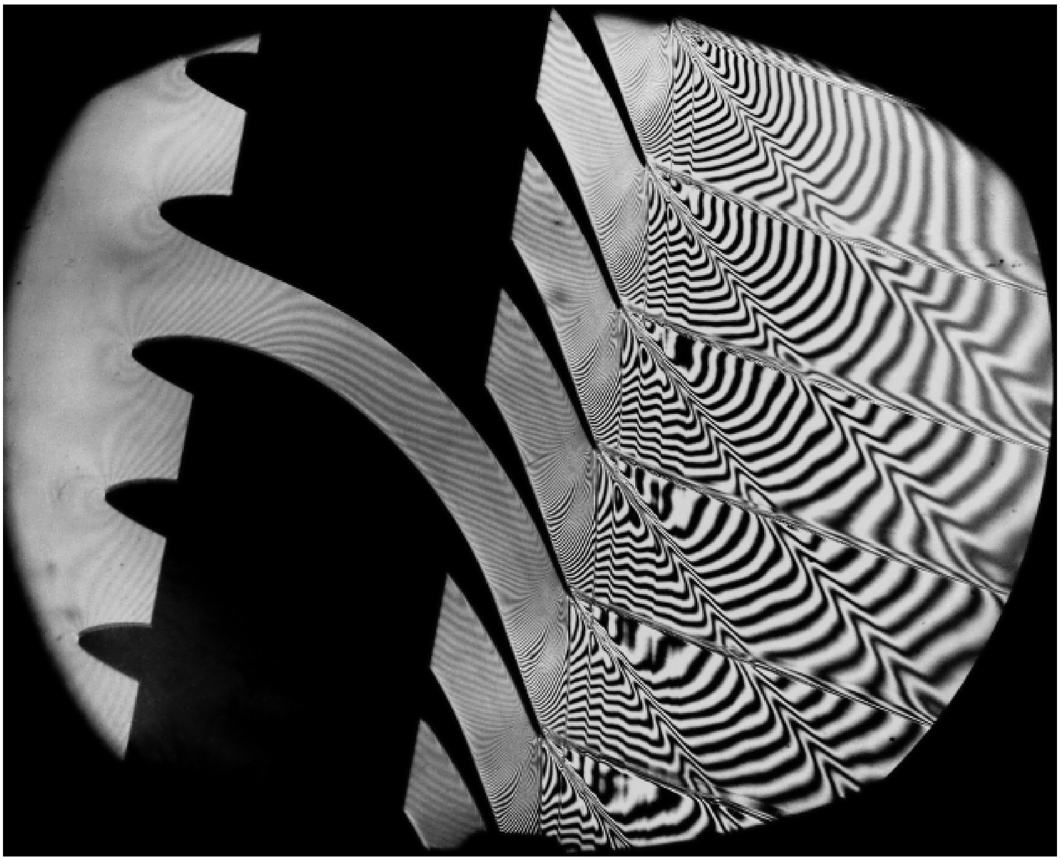

Fig. 1: Interferogram taken at isentropic exit Mach number M_{2is} = 1.828 and angle of incidence i = 0°

Figure 2 shows dependencies of non-dimensional aerodynamic forces $F/(A{\cdot}p_{01})$ on isentropic exit Mach number M_{2is} for constant incidences i [°]. Forces are evaluated from interferograms for the profile of the root section. Aerodynamic force is denoted F [N], A is defined area (pitch x length of the blade) [m^2], and p_{01} [Pa] is the total pressure of the inlet flow. The evaluation is based on the principle of the interferometric method [1] – fringes in the flow field represent lines of constant index of refraction – and on the assumption of isentropic changes in the main flow and constant static pressure across the boundary layer. Aerodynamic force is solved by integration of a distribution of static pressure along pressure and suction sides in peripheral direction. Constant value of aerodynamic force shows limit load regimes of the blade cascade.

Application of traversing probe method for observation of limit load regime of a turbine blade cascade is not so convenient and objective in comparison with optical methods. Measurements of distributions of static pressure, total pressure and argument of velocity vector along pitch in traversing plane give basic data for evaluation of representative data of exit flow. Data reduction method [5] evaluates exit Mach number M_2 and exit angle α_2 (total temperature is assumed to be constant, $T_{01} = T_{02} = T_0$). From the values of M_2 and α_2 it is possible to determine whether limit load regime of the blade cascade is achieved, Eq.(1).

Figure 3 depicts dependencies of kinetic energy loss coefficient ζ on isentropic exit Mach number M_{2is} for constant incidences i. These dependencies were evaluated from traversing probe measurements behind the root section blade cascade. For higher Mach numbers it is possible to observe almost constant values of kinetic energy loss coefficients. It can be significant for achievement of limit load regime. Kinetic energy loss coefficient is defined by relation

$$\zeta = 1 - \frac{M_2^*}{M_{2is}^*} \tag{2}$$

where M^*_2 is non-dimensional exit velocity and M^*_{2is} isentropic non-dimensional exit velocity.

Figure 4 shows dependencies of exit angle oriented to axial direction for the same blade cascade on isentropic exit Mach number M_{2is} for constant incidences i. Experimental data prove obvious changes in the region of high values of isentropic exit Mach numbers. Limit load regimes can be indicated.

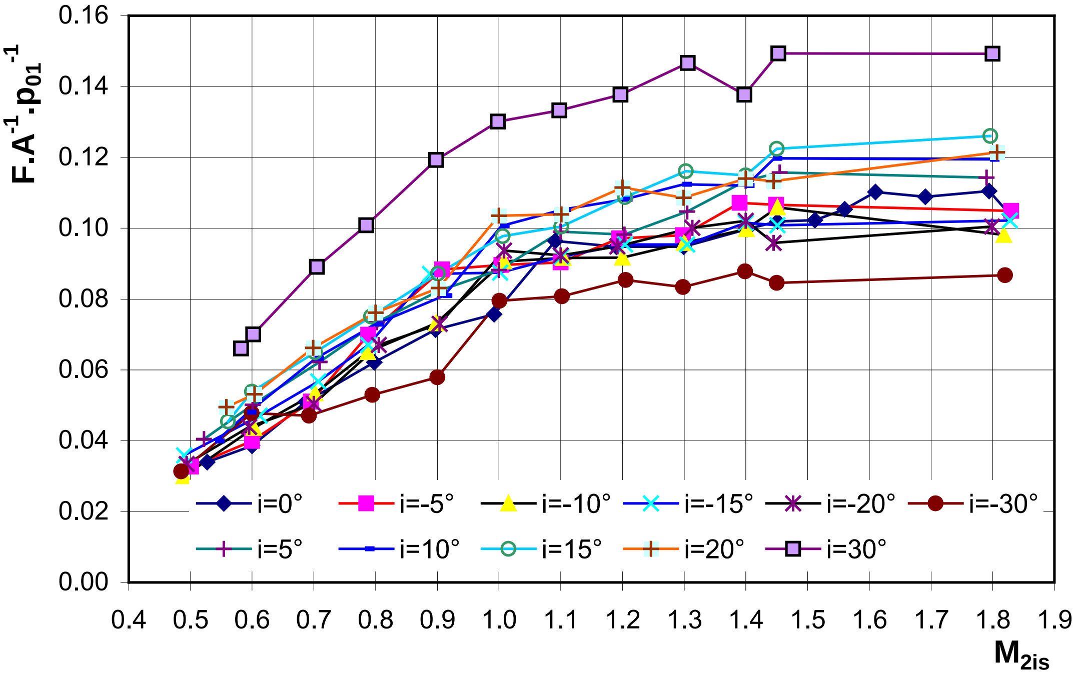

Fig. 2: Dependence of root blade cascade nondimensional peripheral loading on isentropic exit Mach number M_{2is} and angle of incidence i.

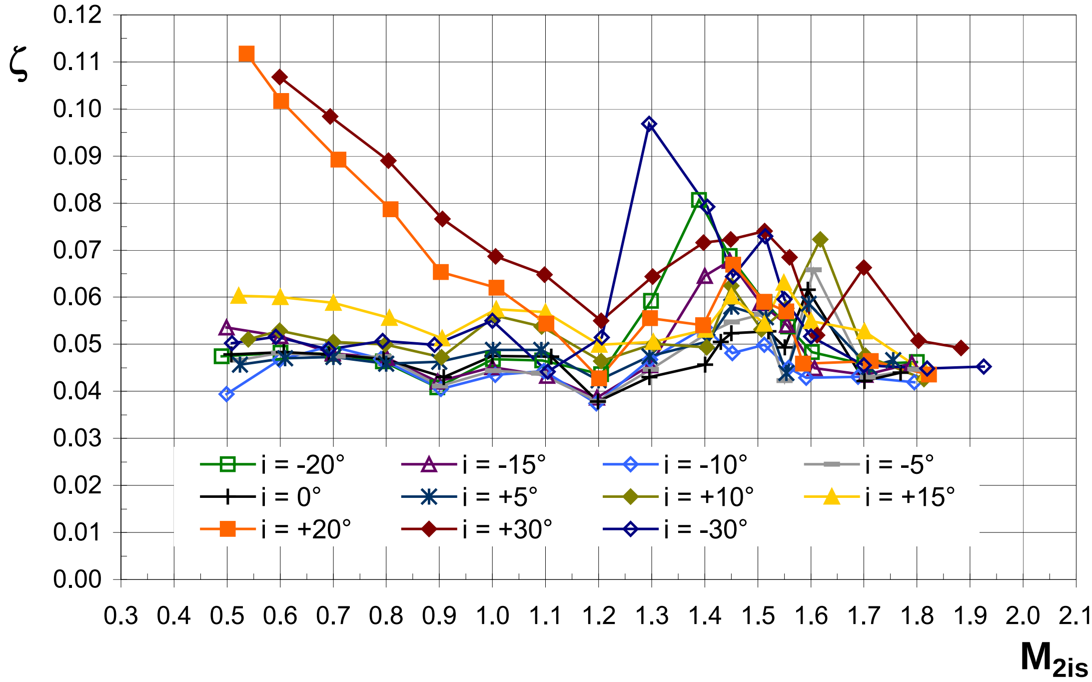

Fig. 3: Dependence of kinetic energy loss coefficient ζ on isentropic exit Mach number M_{2is} and angle of incidence i.

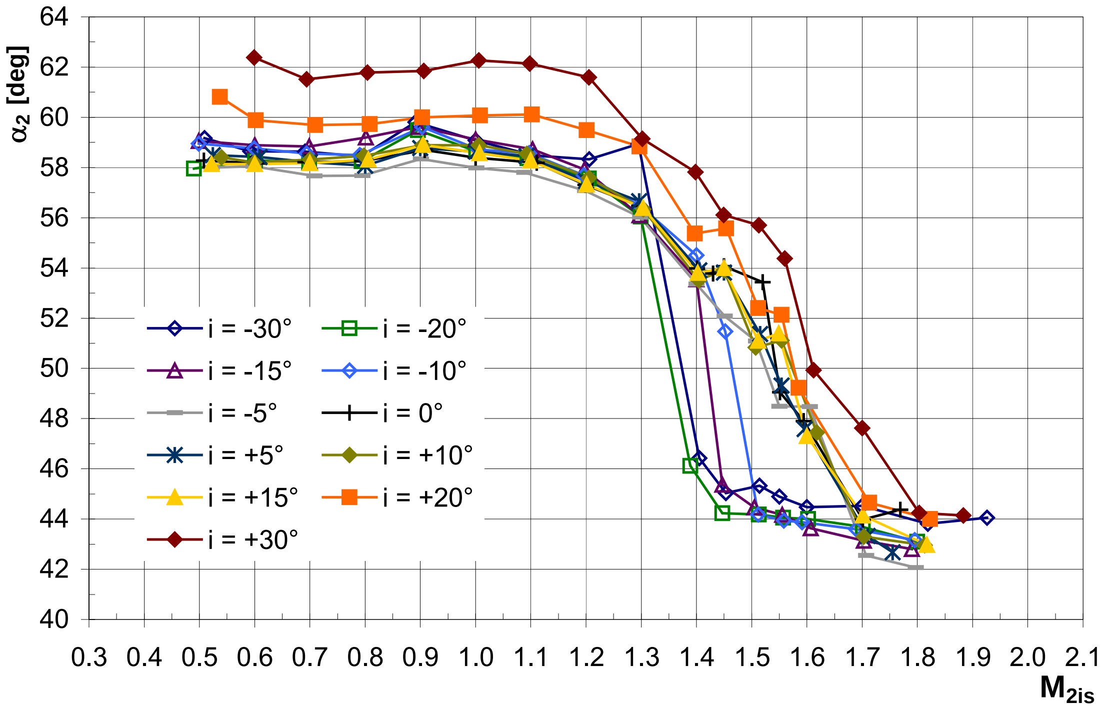

Fig. 4: Dependence of exit flow angle α_2 on isoentropic exit Mach number M_{2is} and angle of incidence *i*.

Detail analysis of traversing probe measurement results can show new approaches to identify limit load regimes. Figure 5 shows results following from analysis by reduction data method [5]. In the diagram, values of modified quadratic expressions $(I_C/I_M)^2$ and $(I_A/I_M)^2$ are plotted. I_M is the integral of mass flux, I_A is the integral of momentum flux normal to the cascade plane and I_C is the integral of momentum flux parallel to the cascade plane. Values of these integrals are solved from traversing probe data. In the detail in Fig. 5, triangles represent measurement points obtained at subsonic flow regimes, transonic regimes, supersonic regimes and limit load regimes defined by $D = 0$. D is a discriminant defined in data reduction method [5]. Maximum non-dimensional velocity M^*_{max} is given by

$$M^*_{\max} = \sqrt{\frac{\kappa + 1}{\kappa - 1}} \tag{3}$$

where κ is the isentropic exponent (ratio of specific heats). Experimental data on aerodynamic parameters of the blade cascade representing the root section is presented in the reports [6], [7].

Investigations of supersonic flows in exit part of turbine blade cascades enables to understand complex flow processes. Conditions for limit load regimes in turbine blade cascades are studied in [6] where distribution of velocity in trailing edge plane is compared for cases of different shapes of suction side in exit part of blade cascade. Parameters and configurations of shock waves should be solved more in detail. A contribution to both regular and Mach interaction of shock waves is presented in [7].

Topical problem of investigations of supersonic flows in blade cascades is still to ensure periodical conditions downstream of the blade cascade. Occurrence of parasite shock waves downstream of the blade cascade is a serious problem namely when the parasite shock wave crosses traversing plane and interacts with suction side of the blade. In Fig. 6 interferogram shows flow field regime close to design parameters of the blade cascade representing middle section of rotor blading of the last stage of large output steam turbine. Parameters upstream of the parasite shock wave are evidently in limit load regime. Parameters downstream of the parasite shock wave show that limit load is not achieved.

CONCLUSIONS

Optical and pneumatic methods enable to determine aerodynamic conditions of blade cascade limit load. Under these conditions working medium flows at supersonic exit velocities. Aerodynamic data on limit load provide important information for designers of turbomachine blades. Supersonic flow in turbine blade cascades is still topical problem for basic research and for its application in turbomachinery.

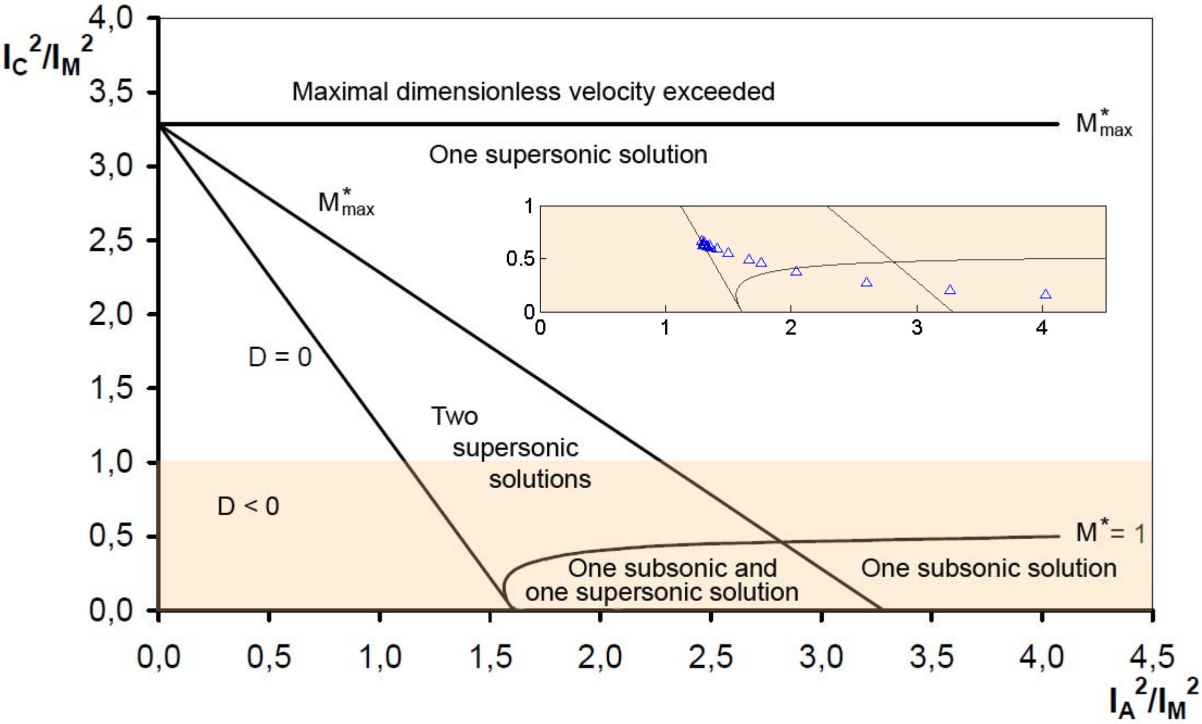

Fig. 5: Diagram of arguments for solution of the conservation equations of data reduction method

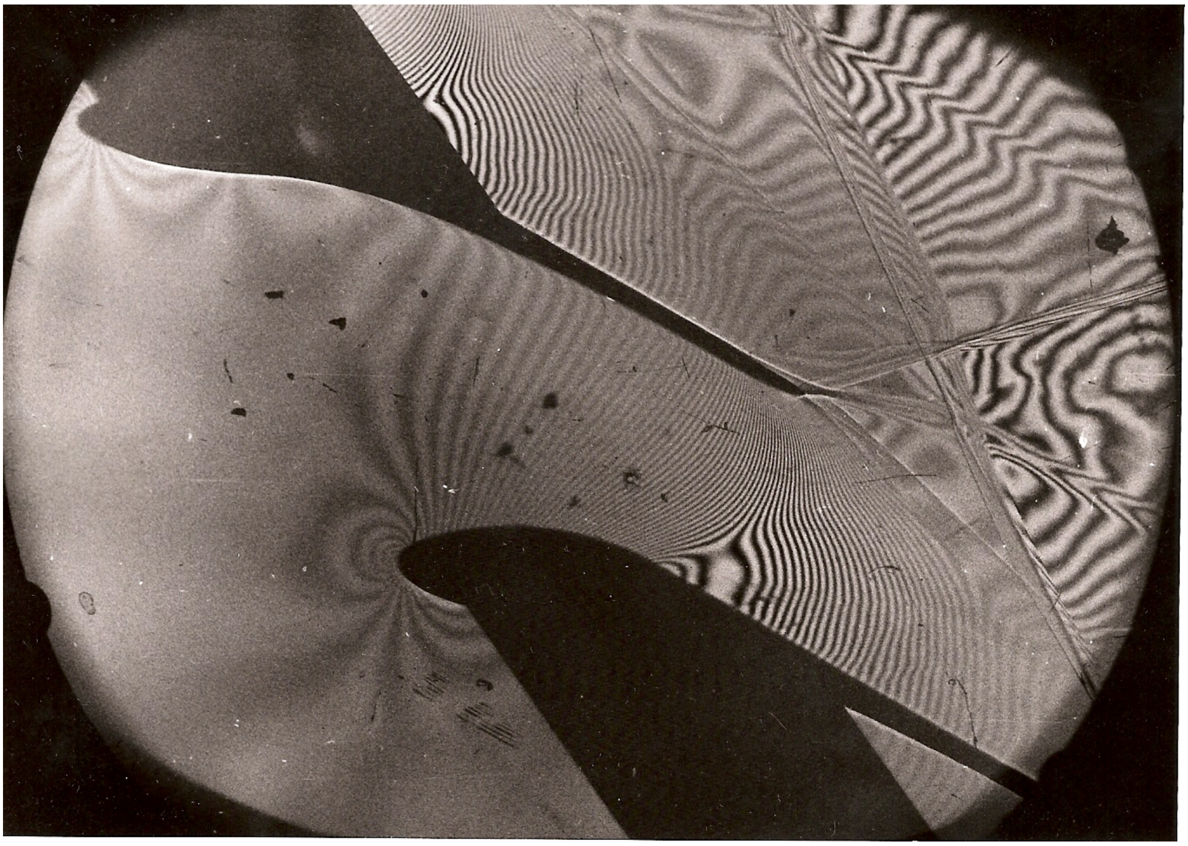

Fig. 6: Interferogram taken at isentropic exit Mach number M_{2is} = 1.353 and angle of incidence i = 0°

REFERENCES

[1] P.Šafařík : Experimental Data from Optical Measurement Tests on a Transonic Turbine Blade Cascade, pp.20(0-14). In : Measureing Techniques for Transonic and Supersonic Flow in Cascades and Turbomachines (editors : C.Gossweiler, G.Gyarmathy), Proceedings of 13th Symposium, ETH Zürich, 1997

[2] S.L.Dixon, C.A.Hall : Fluid Mechanics and Thermodynamics of Turbomachinery, Elsevier, Burlington, 2010

[3] P.Šafařík, V.Vlček : Using Interferometric Measurements in Calculation of Aerodynamic Forces, pp.301-305. In : Optical Methods in Dynamics of Fluid and Solids (editor M.Píchal), Springer Verlag, Berlin, 1985

[4] M.Luxa : On Selected Experimental Methods in High Speed Aerodynamics, Invited lecture VM 2011, Pilsen, 2011

[5] J.Amecke, P.Šafařík : Data Reduction of Wake Flow Measurements with Injection of an Other Gas, Forschungsbericht No.95-32, DLR, Göttingen, 1995

[6] M.Luxa, D.Šimurda : Optical Measurements of the TR-P-2 Cascade, Report Z-1472/11, Institute of Thermomechanics ASCR, Prague, 2011 (in Czech)

[7] D.Šimurda, M.Luxa : Pneumatic Measurements of the TR-P-2 Cascade, Report Z-1473/11, Institute of Thermomechanics ASCR, Prague, 2011 (in Czech)

[8] C.H.Sieverding : Aerodynamic Characteristics of Last Stage Blade Profiles, pp.144-165. In : Aerothermodynamics of Low Pressure Steam Turbines and Condensers (editors : M.J.Moore, .H.Sieverding), Hemisphere Publishing Corporation, Washington, 1986

[9] D.Šimurda : Transonic and Supersonic Flof past Turbine Profila Cascades, PhD. Thesis, Czech Technical University in Prague, Prague, 2011 (in Czech)

ACKNOWLEDGEMENT

The support of GA ASCR (IAA 200760801) is gratefully acknowledged.