Using Optical Methods in High-Speed Aerodynamic Research

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Seeing is believing.

This paper deals with optical methods and results in aerodynamic research. Blade cascades were tested in a high-speed wind tunnel. Interferograms of flow fields were evaluated and analyzed. The distribution of flow parameters, including the exit flow deflection, is shown and described. The conditions of transonic inlet flow are studied experimentally by means of optical methods. Special methodological problems and problems of aerodynamic choking, inlet flow incidence effects, sonic line, flow conditions near the trailing edge, and shock wave structure development are discussed.

Nomenclature

C	[kg/ m^3]	constant of the interferometer
i	[°]	incidence angle
K	[m^3 /kg]	Gladstone-Dale constant
L	[m]	wind tunnel width
M_1	[-]	inlet Mach number
M_{2is}	[-]	exit isentropic Mach number
n	[-]	index of refraction
x, y	[m]	coordinates
ε	[rad]	angular deflection
λ	[m]	wave length of monochromatic light
ρ	[kg/ m^3]	density

Subscripts

x,y	coordinates
$( )_k$	k-th fringe

1. Introduction

Optical methods for high-speed aerodynamic investigations are based on principles of luminous effects or on changes in the optical properties of the flowing medium. The principle of the second case has been used in the Aerodynamic Laboratory in the Institute of Thermomechanics, Academy of Sciences of the Czech Republic. Interferometry and the schlieren method are utilized to a great extent. The optical system was described in detail in [1], but there are further ongoing developments namely in the image system and in image processing. Various types of blade cascades were measured, and extensive sets of experimental data were collected. We can state that the results have contributed to discussion of turbomachinery design, namely with reference to steam turbines, compressors, aircraft engines, special technology, etc. The results have also contributed to new knowledge in the framework of basic research. In [1] experimental data of the etalon cascade SE1050 were introduced. The aim of this paper is to recapitulate the fundamentals of optical methods and to show and discuss some findings concerning the tip cascade of rotor blades of the last stage of a steam turbine of large output.

2. Fundamentals

The basis of our optical methods is the change in optical properties of air when it flows through high-speed aerodynamic tunnel in a built-in investigated blade cascade in the test section. This quantity is the index of refraction. The index of refraction in dependence upon density is expressed by the Lorenz-Lorentz law

$$\frac{n^2 - 1}{n^2 + 2} \cdot \frac{1}{\rho} = \text{const.}$$

We can state that density is an explicit function of the index of refraction. Optical methods based on identification of a change or even on the value of the index of refraction enable us to express a change or a value of the density of the flowing medium.

2.1. Shadowgraphy

Shadowgraphy is a very simple optical method. A point bright source is placed far from the wind tunnel test section (about 8m), as shown schematically in Fig.1. Then the light beam in the test section will be refracted wherever there is a density gradient. However, if the density gradient were constant, every light ray would de deflected by the same amount, and there would be no change in illumination on the viewing screen or photographic plate. Only if there is a gradient in density gradient will there be any tendency for the light rays to diverge or converge. Variations in illumination of the screen are proportional to the second derivative of the density gradient, i.e.,

$$\text{illumination} \approx \frac{\partial^2 \rho}{\partial x^2} + \frac{\partial^2 \rho}{\partial y^2}$$

for modelling plane flow in the test section. Shadowgraphy is thus suited to flows with rapidly varying density gradients, but it is insensitive to flows with gently varying gradients. Figure 2 shows an example of the shadowgraph. The flow is accelerated from inlet Mach number M_1 = 0.188 at incidence i = 0° to transonic velocities exit isentropic Mach number M_{2is} = 1,196 in a nozzle turbine blade cascade.The shadowgraphy offers a telling view of the shock wave structure in the high speed flow field. A quantitative evaluation of flow parameters is impossible from shadowgraphs.

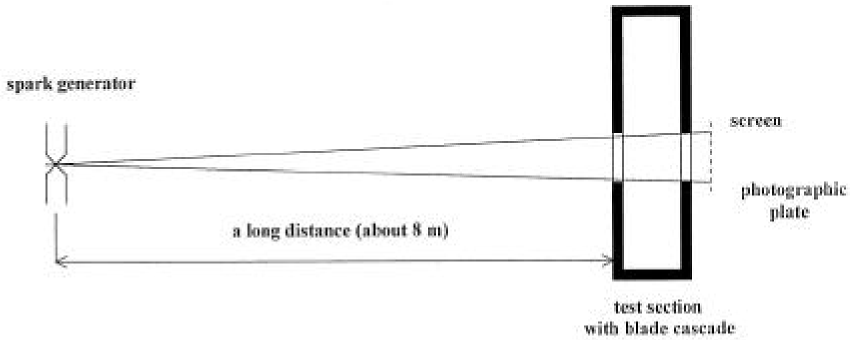

Fig.1

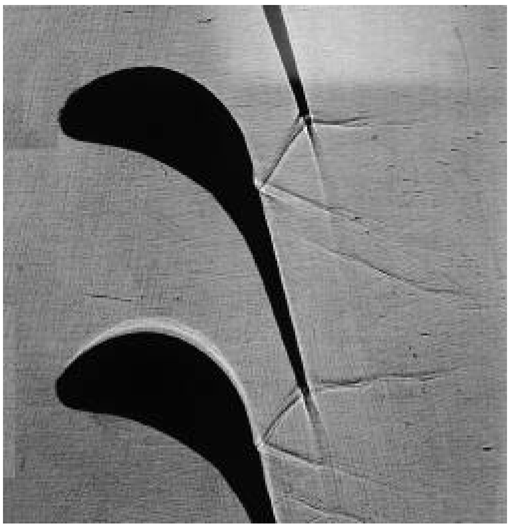

Fig.2

2.2. The Schlieren Method

Numerous types of schlieren arrangements exist. In our arrangement, the linear bright source is made by means of a schlieren slot in the focus of the light system, as shown in the scheme in Fig.3. The light is then collimated by the lens and passes through the test section. It is then brought to a focus by the lens in the image system. At the focal point the Toepler knife is introduced, which cuts off part of the light. Any light ray passing through a test section in which there is a density gradient normal to the light direction will be deflected. Depending on the orientation of the Toepler knife with respect to the density gradient and, of course, depending on the sign of the density gradient, more or less of the light passing through each part of the test section will escape the Toepler knife edge and illuminate the screen of the camera. Thus the schlieren system makes density gradients visible in terms of intensity of illumination. The angular deflections ε of the ray when passing through a test section of width L in the x- and y-directions are

$$\varepsilon_x = L\frac{\partial n}{\partial x} = LK\frac{\partial \rho}{\partial x}$$

$$\varepsilon_y = L\frac{\partial n}{\partial y} = LK\frac{\partial \rho}{\partial y}$$

where K is the Gladstone-Dale constant [2]. If the Toepler knife edge is in the y-direction only deflections ε_x will influence the light passing the Toepler knife edge. Hence density gradients in the x-direction will be made visible, but gradients in the y-direction will not be visible. Similarly, if the Toepler knige edge is parallel to x, only density gradients in the y-direction will become visible. By introducing a special color filter instead of the Toepler knife, color schieren pictures of the flow field can be obtained.

2.3. Interferometry

Several types of interferometers exist. In our arrangement [3], Fig.3, the Mach-Zehnder interferometer proved to be highly useful for high-speed investigations. The coherent power light is divided into two branches on the first semi-permeable mirror. The measuring branch passes through the test section and the comparative branch passes through a compensator. The interferometric image of the flow field in the test section with a blade cascade appears on the second upper semi-permeable mirror. Slight refraction effects in the test section have an influence on the phase differences between the two beams when they form an interference pattern. By this means the interferometric image consists of dark and

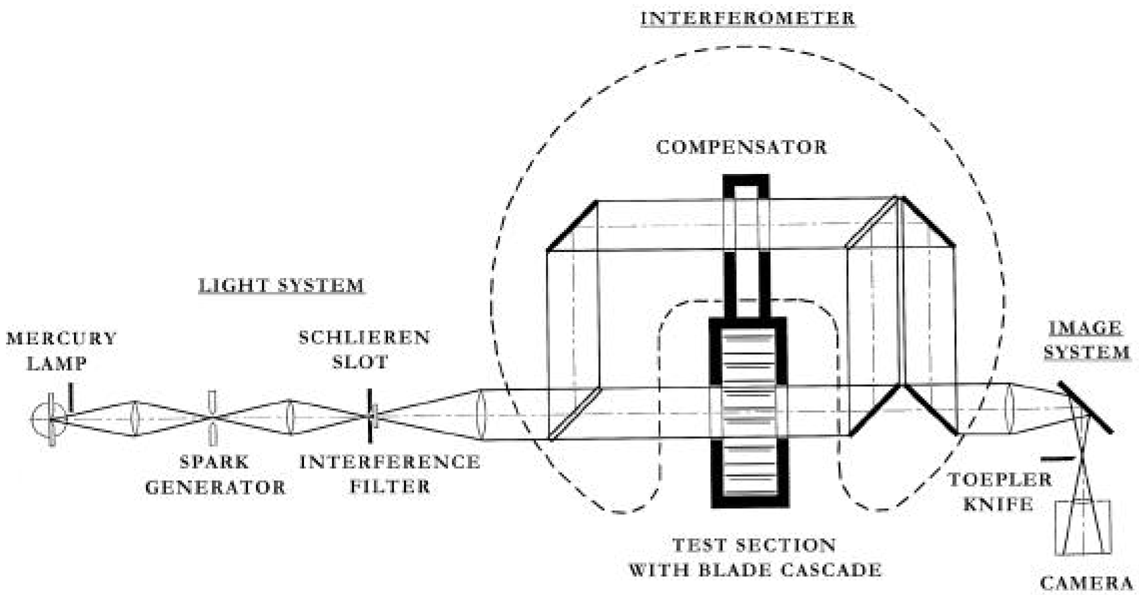

Fig.3

bright bands. They are called interferometric fringes. From the differences in times for a light beam to pass through a fluid in adjacent fringes, and from the wave lenth of monochromatic light we may obtain relation for the difference in the index of refraction between the adjacent fringes

$$(n)_k - (n)_{k-1} = \frac{\lambda}{L}$$

where λ is the wave length of the monochromatic light employed. Through the empirical Gladstone-Dale equation a relation for the difference in density between adjacent fringes is obtained

$$(\rho)_k - (\rho)_{k-1} = \frac{\lambda}{LK} = C$$

where C is a constant of the interferometer. Interferometry is used for measuring the density differences between two points in the flow field. The interferometer can be set for an infinite interference fringe (which is how we mainly use) or for the finite fringe displacement method.

3. Optical Measurement Results and Experimental Data Analysis

Interferometry and the schlieren method were used for investigating a tip blade cascade. The development of transonic flow at increasing exit Mach number and the incidence angle $i = 0°$ is presented in Figs.4 to 14. The interferogram of subsonic blade cascade flow ($M_1 = 0.496$, $M_{2is} = 0.524$) is shown in Fig.4. Boundary layers and the wake can be observed. The interferogram in Fig.5 depicts transonic flow ($M_1 = 0.705$, $M_{2is} = 0.788$). A local supersonic region on the suction side on the leading edge appears and is terminated by an almost normal shock. The transonic flow ($M_1 = 0.760$, $M_{2is} = 0.898$) in Fig.6 has a local supersonic region in the surroundings of the throat of the interblade channel. Aerodynamic choking is attained. Higher back pressure forms a strong shock wave terminating the local supersonic region. A vortex structure appears downstream of the trailing edge. The vortices dissipate and higher losses of kinetic energy will be incident. The interferogram in Fig.7 and the schlieren picture in Fig.8 present transonic flow at $M_1 = 0.807$, $M_{2is} = 1.046$. They show a complex shock wave system in the exit part of the blade cascade. The inner branch of the exit shock waves forms a Mach reflection. A local supersonic region appears on the pressure side in the leading edge. The schlieren method has proved to be more sensitive in identifying a periodic wave vortex structure. The interferogram in Fig.9 shows a transonic flow field at $M_1 = 0.829$, $M_{2is} = 1.108$. A system of strong waves takes place in the exit part of the blade cascade. The interferogram in Fig.10 and the schlieren picture in Fig.11 (both at $M_1 = 0.843$, $M_{2is} = 1.236$) depict the regular reflection of the inner branch of exit shock waves on the suction side of the neighbouring blade. The schlieren picture demonstrates the interaction of the shock wave with a laminar boundary layer with a local separation. The interferogram in Fig.12 and the schlieren picture in Fig.13 show the flow field at $M_1 = 0.886$, $M_{2is} = 1.686$. Supersonic exit flow deflection can be observed. The wake is deflected by about 11°. The outer branch of exit shock waves becomes stronger. The inner branch is weakened by an intensive expansion on the pressure side on the trailing edge, and its reflection in the neighbouring channel can be observed in the window of the profile holder. In the schlieren picture, the tunnel compression system downstream of the blade cascade can be observed. The interferogram in Fig.14 shows the supersonic exit flow at a regime of $M_1 = 0.889$, $M_{2is} = 1.821$. The deflection of the wake is about 15°. The reflection of the weak inner branch of exit shock waves on the suction side is visible in the adjacent channel downstream of the holder. All interferograms presented in this paper were evaluated, and the distributions of the ratio of static and total pressures under assumption of isentropic flow are shown in Fig.15. The effect of shock waves on the suction side and the existence of a local supersonic region on the leading edge on the pressure side are evident. This diagram is very useful for designers and investigators.

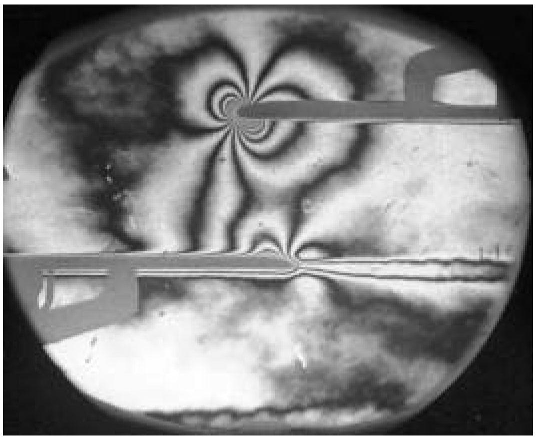

Fig.4

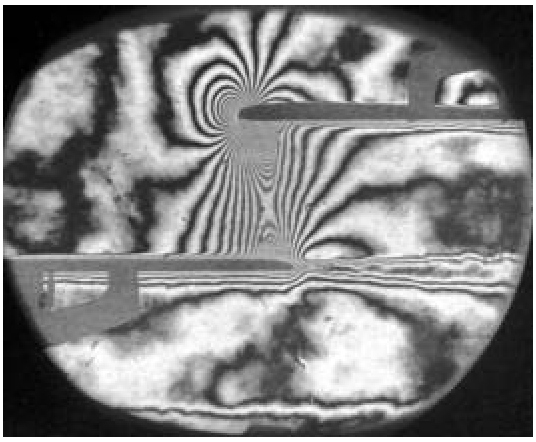

Fig.5

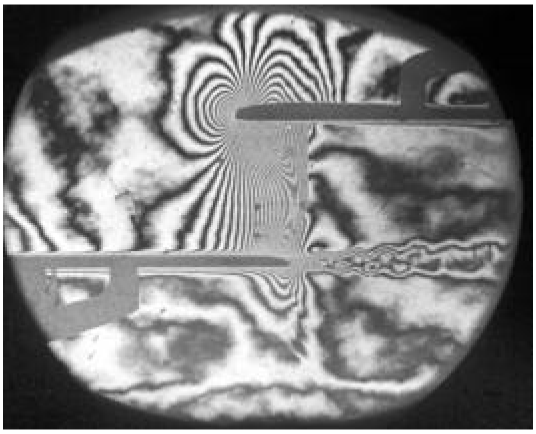

Fig.6

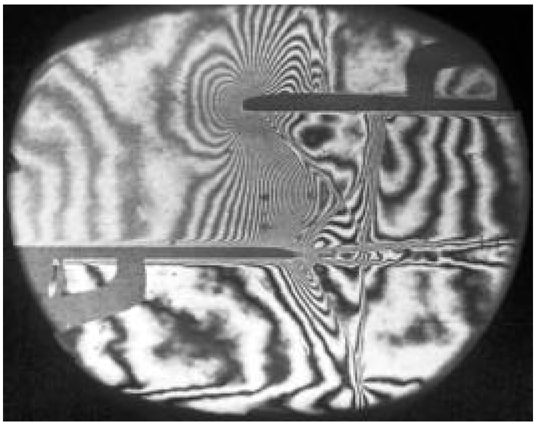

Fig.7

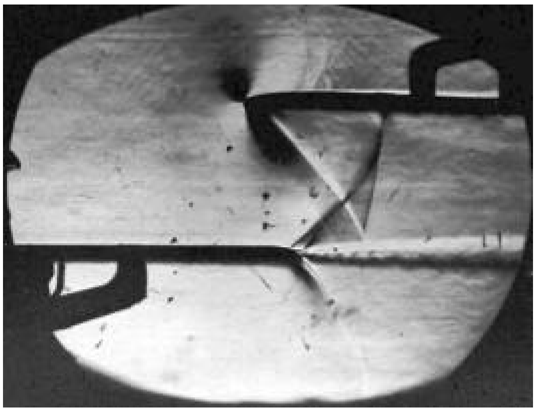

Fig.8

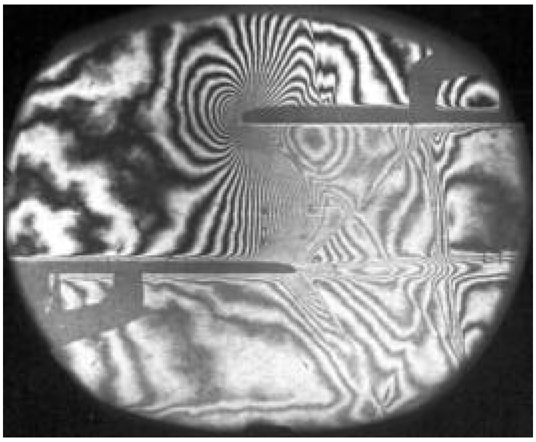

Fig.9

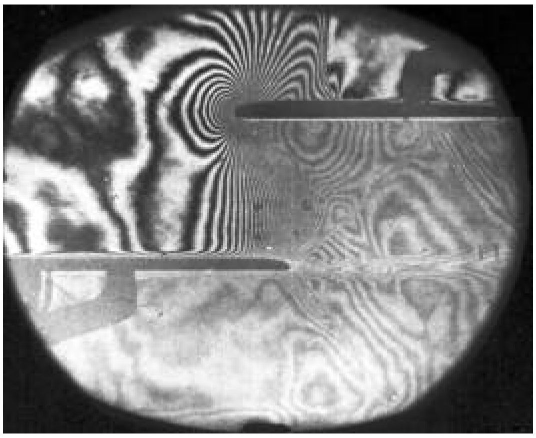

Fig.10

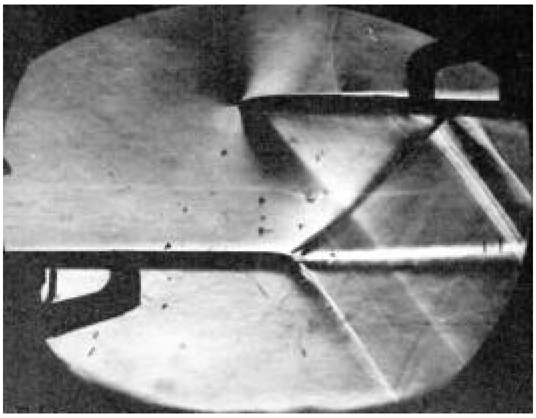

Fig.11

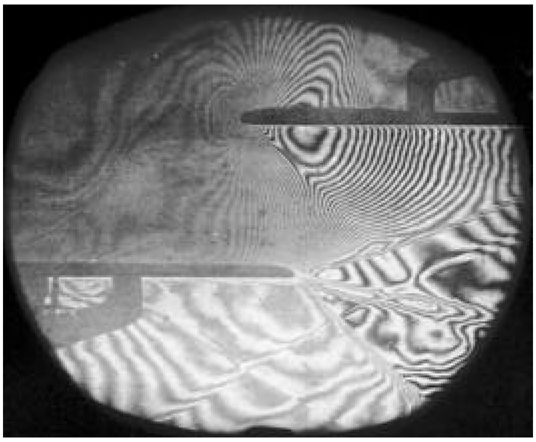

Fig.12

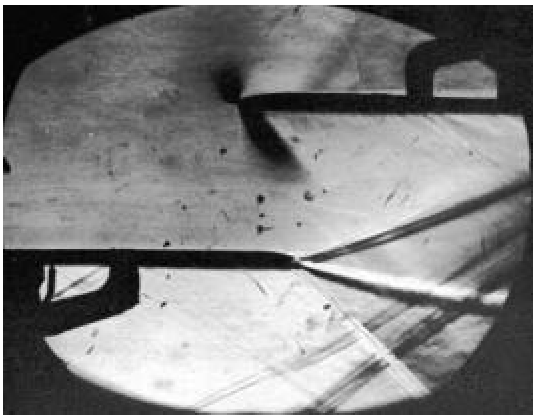

Fig.13

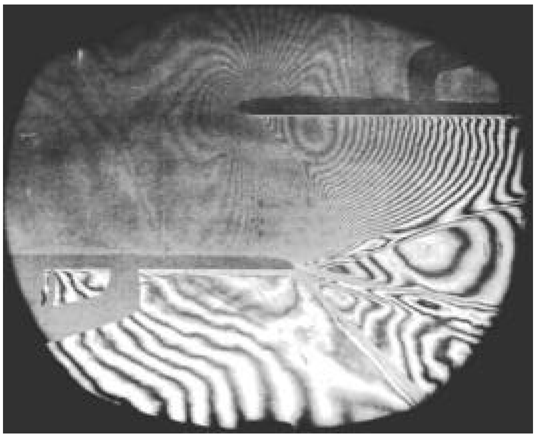

Fig.14

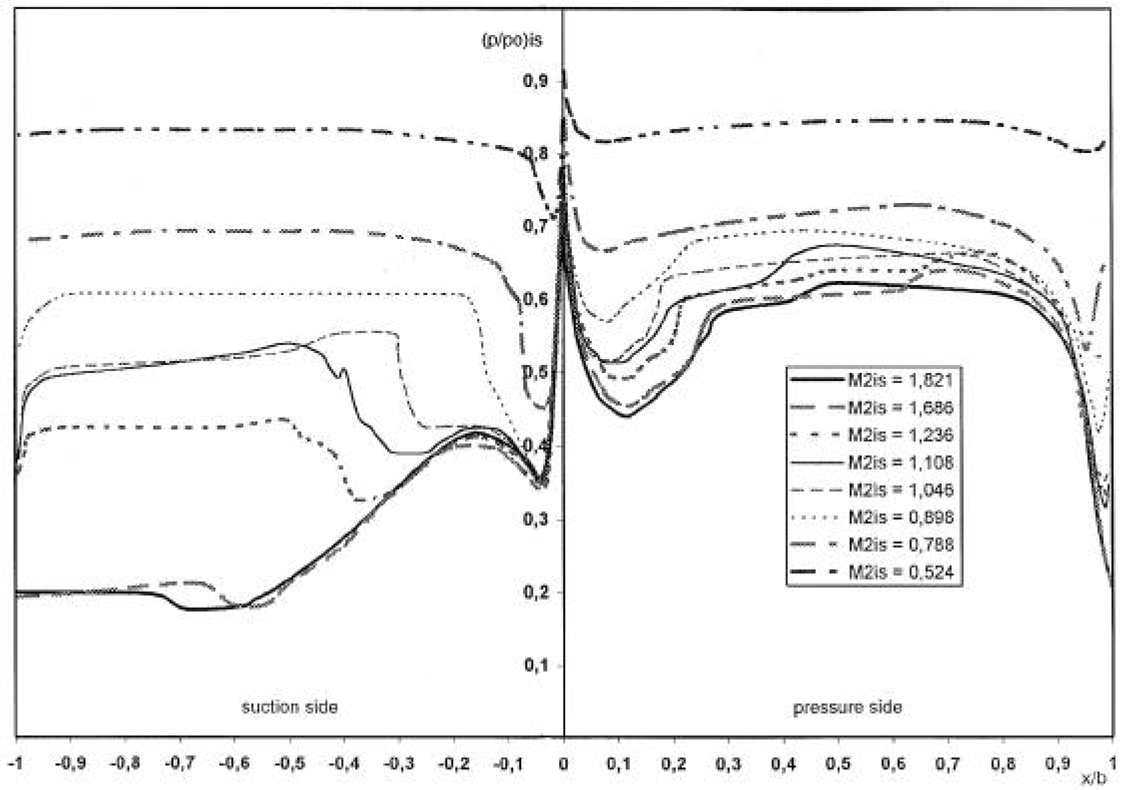

Fig.15

4. Conclusions

Optical methods proved to be a powerful tool for high-speed aerodynamic investigations of blade cascades. Further development of the methods is possible, namely in image processing, in evaluation procedures, in digital photography, in image video recording, etc. The limits of optical methods lie in their restrictions to two-dimensional tasks, and in the additional assumptions made during evaluation (e.g. isentropic flow). Optical methods require heightened perceptivity on the part of the researcher.

Acknowledgements

These experiments were performed at the Institute of Thermomechanics, Academy of Sciences of the Czech Republic under Project No. PP 30/5 U. The authors would like express thanks to Mr.Karel Kleinberg for his long-term, careful and fruitful work with the optical system in the course aerodynamic experiments.

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