EXPERIMENTAL RESEARCH OF SURFACE ROUGHNESS IMPACT ON TRANSONIC FLOW IN BLADE CASCADES

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ABSTRACT

The impact of surface roughness was investigated using linear blade cascades. Two basic types of roughness (sand-roughness and grooves) were applied on specific parts of the vanes. The aerodynamic performance of a linear turbine blade cascade was evaluated via energy loss coefficient ζ. The outlet angle α_2 and Mach number M_{2is} as well as pressure distribution (along the vane surface and behind the model) and flow field structure were examined. Experiments were carried out under the conditions of transonic regimes and two levels of Reynolds number (Re = 4×10^5 and 8×10^5 or 8.5×10^5 according to model). Two levels of sand-roughness (Ra = 10, 30) and one level of oriented groove roughness (Ra = 33) were tested against smooth surface (Ra = 0.4). Representative results are presented in the form of ζ (M_{2is}) and α_2 (M_{2is}) diagrams. Flow filed structure is depicted by means of schlieren pictures.

INTRODUCTION

Surface roughness as a significant factor influencing flow through linear blade cascades has been systematically examined at Aeronautical Research and Test Institute in Prague (VZLU) since 2003.

The research was initiated by the Czech major producer of turbomachines SKODA POWER, which is focused among others on steam turbines design and development.

The first experimental results [1], [2] have proved the importance of systematic research in this field of turbomachinery. Therefore, a new methodology has been defined at VZLU in cooperation of SKODA POWER to investigate the phenomenon by means of wind tunnel measurements. The research is based on an analysis of aerodynamic characteristics of the linear blade cascades and on the flow structure study in inter-blade channels as well as downstream the cascade.

Although a long-term aim is to model flow fields influenced by real surface damage (described e.g. by Bons et al. [3]), during the first stages only a simple artificial roughness was applied. There were two specific kinds of roughness examined during the experiments. First of them was roughness created by means of carborundum powder, the latter one was characterized by straight grooves along the vane surface. These two modifications allow an evaluation of the impact on basic aerodynamic characteristics of the cascade.

The sand-roughness, as more or less directionally uniform surface quality degradation, represents initial step to the future modelling of erosion, corrosion and foreign deposits on the vanes. In contrast to this the directionally dependent groove roughness was a rough simulation of tool traces originated in the manufacturing processes.

It is obvious that both the approaches are of significant interest of the turbine manufacturer. While the knowledge of operational wearing influence is vital for optimal timing of overhauling, the required quality of surface finishing is an important factor of possible manufacturing cost reduction. Certainly, all the results help also VZLU to specify the manufacturing demands during preparation of models for standard industrial measurements.

NOMENCLATURE

c	[mm]	chord length
M	[1]	Mach number
Ra	[1]	centreline averaged surface roughness
Re	[1]	Reynolds number
t	[mm]	pitch

Symbols

α	[deg]	angle
γ	[deg]	angle of stagger
ζ	[1]	loss coefficient

Subscripts

1	inlet condition
2	outlet condition
is	isentropic quantity

Abbreviations

LE	leading edge
TL	trailing edge
VZLU	Aeronautical Research and Test Institute

Fig.1: Transonic continuous wind tunnel & ZEISS 80 schlieren device (©VZLU)

EXPERIMENTAL FACILITY & MODEL

All the experimental data were acquired by means of a special transonic continuous wind tunnel designed for the examination of linear blade cascades (Fig. 1). The tunnel has a test section of 0.1 × 0.4 m equipped with optical windows. The operational conditions are defined for the turbine experiments by the range of isentropic outlet Mach number M_{2is} = 0.10 – 1.40 and Reynolds number Re = 0.2 – 10 × 10^5. With respect to the chord length of the model and inlet total pressure the Reynolds number can be set independently on the Mach number.

Pressure measurements are realized by means of static pressure taps on the surface of the model (centreline of the vanes) and on the side tunnel walls. A traversing system equipped by a direction probe as well as a total pressure and static pressure probes is used to map pressure distribution across the flow field downstream the model.

Standard flow visualization is based on the shlieren method and for that purpose the ZEISS 80 schlieren device is utilized (Fig. 1). The apparatus is designed to visualize a circular area of interest with diameter of 80 mm. This technological restriction defines the number of inter-blade channels observed during one stage of the experiment.

For the flow structure investigation the Schardin's band-lattice-cut-off method (colour images) was employed. A halogen lamp was used as a light source. All the images were taken by Canon EOS 350D camera.

The first aerodynamic model was assembled of eleven SE1050 turbine profiles according to Fig. 2 (t/c = 0.554, c = 65 mm). While the optical measurement was focused on the central part of the model, the static pressure taps were placed along the 4^{th} inter-blade channel (12 pressure taps on suction side, 13 on pressure side). The probe traversing one central wake was placed 20 mm behind the trailing edge plane (0.55 c downstream TL plane).

The second model consisted of eight turbine stator vanes (VS33 profile). In case of this cascade only wake pressure measurements were carried out 15 mm behind the TL plane (0.89 c downstream TL plane). Similarly to the SE1050 measurements one central channel was examined.

SURFACE MODIFICATION TECHNOLOGIES

Within the scope of the test campaign described in this article it was decided to investigate two types of roughness applied to the vane surface.

Sand-roughness as an artificial, directionally independent surface degradation was investigated in two levels. Different size of carborundum particles was tested to modify a surface quality defined by centreline average surface roughness values Ra = 10 and 30. To fix the powder on the vane, the particles were scattered on a thin layer of spray paint applied to the surface. Certainly, such an application requires careful handling to assure a uniform surface quality across the whole vane or its selected part.

An example of the modified VS33 blade is depicted in the Fig.3.

Directionally dependant roughness was modelled by means of straight grooves along and crosswise the flow direction. Instead of milling the grooves into the blade surface the use of fine wires was chosen in order to enable subsequent modifications. The wires were placed parallel to each other and fixed again by a thin spray paint film (Fig.4).

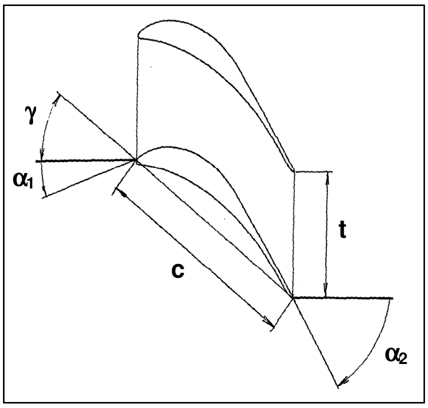


Fig.2: SE1050 linear blade cascade configuration (©VZLU)

Fig.3: Sand-roughness applied to the VS33 vane (Ra = 30) (©VZLU)

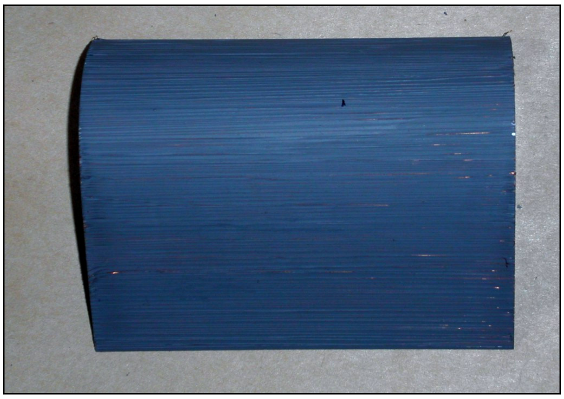


Fig.4: Oriented roughness applied to the VS33 vane (crosswise the flow direction, Ra = 33) (©VZLU)

The level of roughness was defined by wire diameter and displacement as well as by film thickness. The originally intended roughness Ra = 30 measured perpendicularly to the grooves was not achieved exactly, but the actual value of Ra = 33 was close enough and therefore accepted for subsequent wind tunnel measurements.

There are several merits as well as drawbacks related to both types of model modifications, which have to be taken into account.

The way of powder or wires fixation on the blades allows numerous surface variations without the necessity of repetitive manufacturing of the original blade. Thus, significant cost reduction is achieved and many configurations can be investigated.

Once the paint spray film creation and powder scattering techniques are acquired, the model can be relatively easily modified to any required configuration.

On the other hand, creation of sprayed film and fixation of different deposits on the vane surface leads to the actual aerodynamic profile change. From this point of view it is necessary to keep the film layer as uniform as possible. Certainly, the powder scattering or wires placement is ruled by the same demand.

The thickness of the sprayed film is also one of the most important factors. The thinnest the layer the less influenced is the aerodynamic shape. Nevertheless, the film has to be thick enough to keep the wire/powder fixed even when exposed to aerodynamic forces under transonic conditions.

MODEL CONFIGURATIONS AND INVESTIGATED REGIMES

With respect to the measuring techniques – i.e. pressure taps and traversing probe position, schlieren window placement etc. – it was decided to modify seven vanes of the SE1050 model. Thus, only the first two vanes and last two ones were left unmodified. In this particular phase of the campaign the sand-roughness was applied on the whole surfaces of the vanes.

Respecting the SKODA POWER demands the VS33 model was successively improved as follows: the sand roughness was applied to the four central (of eight) vanes. At the beginning only a 20 mm wide strip on suction side along the leading edges was roughened as it is depicted in Fig.5. The next step was to apply sand-roughness on the whole suction side and finally on the whole surface of the vane (suction and pressure sides) [4].

Qualitatively different type of roughness – oriented groove roughness – was examined using the VS33 model according to [5]. Similarly to the modification described above the four central blades were adapted to simulate imperfect surface finishing. During two stages of the test campaign the grooves were oriented in two directions: parallel (Fig.4) and perpendicular to the flow.

Since both the SE1050 and VS33 profiles are designed for transonic speeds of the flow, the ranges of isentropic Mach number were determined as in Tab.1.

Fig.5: Sand-roughness applied to the VS33 vane (LE region, suction side, Ra = 33) (©VZLU)

model \ M2is	min.	max.
SE1050	0.6	1.2
VS33	0.5	1.2

Tab.1: Outlet Mach number ranges.

model \ Re	level 1 $\times 10^5$	level 2 $\times 10^5$
SE1050	4	8
VS33	8.5	10

Tab.2: Reynolds number levels.

model	alfa1 [deg]
SE1050	19.3
VS33	0

Tab.3: Inlet angles.

To examine the Reynolds number effect the two levels were defined for each model (Tab.2).

Both the models were measured under the condition of designed inlet angle (Tab.3).

SAND-ROUGHNESS EFFECT

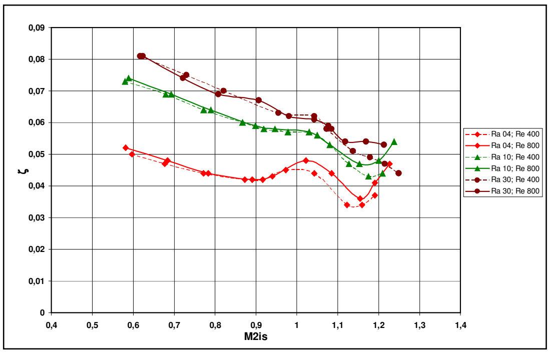
Comparison of the vane with the hydraulically smooth and all-roughened surface was based on the SE1050 model measurements.

Impact of the surface quality is depicted in Fig.6a, b. Figures 7a and 7b introduce flow field structure under transonic conditions defined by α_1 = 19.3 deg, M_{2is} = 1.2 and Re = 8×10^5. The smooth surface (Ra = 0.4) in Fig.7a is compared with roughened surface (Ra = 10) in Fig.7b.

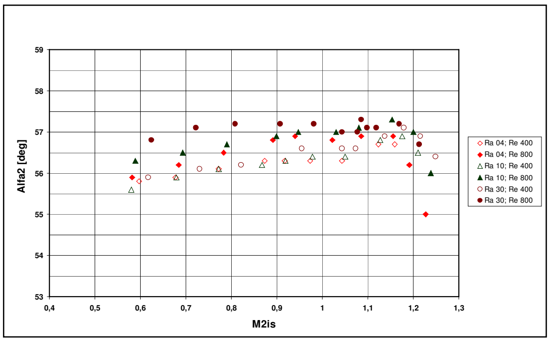
There is no significant impact of Reynolds number (defined by two values Re = 4×10^5, 8×10^5) on loss coefficient noticeable in Fig.6a. The outlet angle α_2 was slightly influenced when the surface was roughened and the outlet velocities remained subsonic (Fig.6b). The maximum difference is approx. 1 deg. Within the transonic region the Re effect seems to be nearly negligible.

Loss coefficient values in Fig.6a prove strong effect of surface quality in the subsonic region, where friction is of major importance. When the outlet Mach number was close or above unity, the total aerodynamic losses were radically influenced by shock waves and the importance of surface quality decreased. Nevertheless, it is evident from all measured regimes that the loss coefficient values are significantly higher when the surface quality is degraded.

The results based on pressure measurements in Fig.6a correspond to the flow observation introduced in Fig.7. Unfortunately, it is not possible to distinguish the character of boundary layer in the schlieren pictures. However, similarities in flow structure suggest that due to higher Re value (8×10^5) the transition point is placed upstream the point of impact of an internal branch of the terminal shock wave from neighbouring blade. The shock wave – boundary layer interaction is then alike in both the cases of smooth and roughened surface. According to Fig.6a the loss coefficient is of approx. 1% higher in case of Ra = 10 under condition of M_{2is} = 1.2 (while there is an increase of approx. 2 – 3% in subsonic region). Nevertheless, the integral character of ζ does not provide any information of the loss nature. It can be observed in Fig.7a and Fig.7b that the shock wave reflected from the smooth surface is weaker than that one from the roughened surface. Therefore, the flow velocity is higher downstream the interaction and the external branch of the terminal shock wave is obviously stronger. Regarding the wake, it is apparently bigger when the surface quality is decreased.

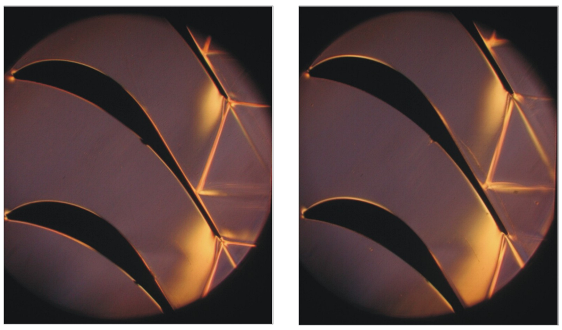


a)



b)

Fig.6: Sand-roughness effect
(SE1050 model, Ra = 0.4, 10, 30, Re = 4×10^5, 8×10^5)
(©VZLU)



a) Ra = 0.4 *b)* Ra = 10

Fig.7: Sand-roughness effect
(SE1050 model, Ra = 0.4, 10, Re = 8×10^5)
(©VZLU)

The influence of partially roughened blade was investigated by means of the VS33 model. The results are summarized in Fig.8a and Fig.8b.

The first modification compared with the smooth surface was that one with roughened strip along the LE on suction side. While the inlet angle and Reynolds number were kept constant (α_1 = 0 deg, Re = 8.5×10^5), the outlet Mach number was gradually increased from the value of 0.5 to 1.2. According to Fig.8a there is no measurable difference between the original (Ra = 0.4) and modified (20 mm strip, Ra = 30) model up to M_{2is} = 1.0. Quantitatively remarkable increase of ζ occurs in subsonic region (predominant friction losses) when the whole suction side is characterized by Ra = 30. Subsequent decrease of pressure side quality led to relatively small increase of ζ (Fig.8a). This effect can be explained by considerably lower velocity of the flow along the pressure side.

Shock waves and their interaction with boundary layer are the main sources of aerodynamic losses within the transonic region. Degradation of the surface quality causes shift of a transition point upstream. Therefore, an internal branch of terminal shock wave may interact with turbulent instead of laminar boundary layer. From the energetic point of view such an interaction is much favourable as the region of separated flow is smaller. Although no flow field image of the VS33 model is available, the results related to roughened LE (Fig.8a) imply that there is an intensive laminar boundary separation at the point of interaction with a shock wave.

On the other hand, when there is most likely turbulent boundary layer separation (all-roughened suction side) the increase of ζ is rather gentle.

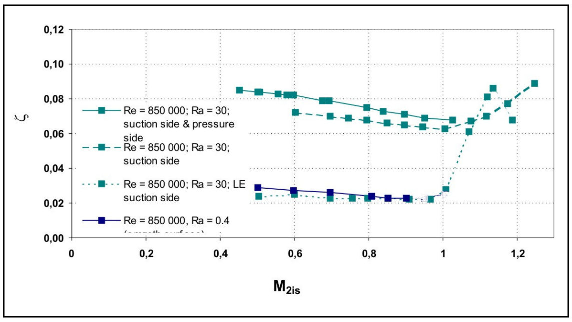
Regarding the Fig.8b it is evident that the biggest flow deflection is under subsonic Mach numbers caused by hydraulically smooth or partly roughened (LE strip) model. Increase of Ra value on the whole suction side/vane reduces the flow deflection by approx. 1 deg. On the contrary, laminar boundary layer separation supposed for smooth vanes at transonic regimes moderates the flow deflection above M_{2is} = 0.9.

Development of the corresponding curves of the smooth and partly roughened (LE strip) model in Fig.8a and 8b is in a good accordance and supports the assumption of laminar boundary layer at the point of interaction with the internal branch of terminal shock wave.

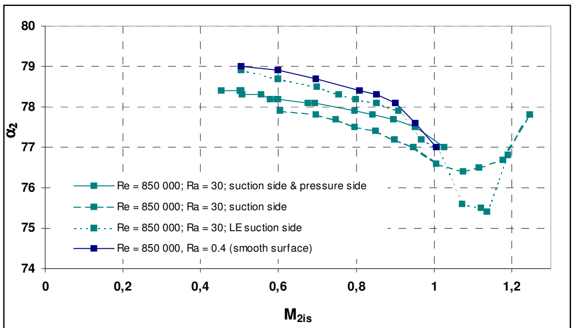
ORIENTED GROOVE ROUGHNESS EFFECT

Investigation of the groove roughness is summarised in Fig.9, in which measurements of the VS33 model with smooth and roughened vanes are put side by side. The grooves on the whole blade surface are oriented along and crosswise the flow direction.

Under the conditions of α_1 = 0 deg, Re = 8.5×10^5 the roughness based on grooves perpendicular to the flow (Ra = 33) induces similar character of ζ-curve as in the case of sand-roughness (Fig.8a).

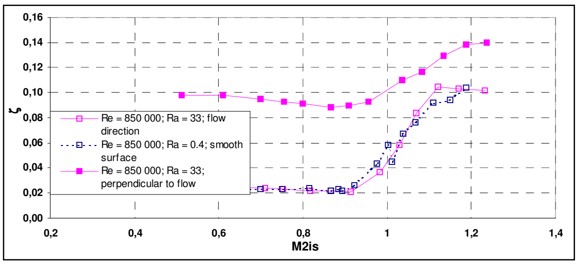


a)

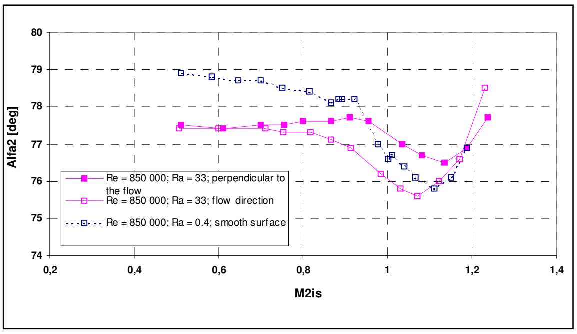


b)

Fig.8: Sand-roughness effect – partially roughened surface
VS33 model, Ra = 0.4, 30, Re = 8.5×10^5)
(©VZLU)



a)



b)

Fig.9: Oriented (groove) roughness
VS33 model, Ra = 33, Re = 8.5×10^5)
(©VZLU)

Nevertheless, increase of the loss coefficient values due to roughness is bigger within the whole range of examined Mach numbers. Comparing the ζ values in subsonic region the groove roughness produces higher losses of about 2% while at transonic regimes the difference is approx. 3% when $M_{2is} = 1.0$ and even 6% when $M_{2is} = 1.2$.

Examination of the groove roughness oriented in flow direction provided rather unexpected results. While in previously described situation the increase of ζ was dramatic, the grooves parallel to the flow induce almost the same losses as the hydraulically smooth surface from $M_{2is} = 0.5$ to 1.2.

Figure 9b depicts the change of flow deflection behind the VS33 model. Character of the curves is comparable to those in Fig.8b and it is supposed that the aerodynamic phenomena are of similar nature as well. When the grooves were oriented perpendicularly to the flow, the change of outlet angle was close to the sand-all-roughened blade (Ra = 30). Grooves parallel to the flow have under corresponding conditions similar impact as sand-roughness applied to the whole suction side of the blade (Fig.8b, Fig.9b).

RELATED RESEARCH ACTIVITIES

The experimental results discussed earlier in this article enforced the motivation of SKODA POWER to employ its experimental steam turbine in roughness impact investigation.

To illustrate this closely related research, there are some experimental data depicted in Fig.10. For the purpose of a turbine stage efficiency assessment the two following modification were tested within a subsonic range of Mach numbers. The data related to smooth stator wheel (Ra = 0.8) are marked “smooth vane”, while the roughened stator data (Ra = 9) are inscribed “roughened vane”. The stage efficiency values are presented with respect to Reynolds number of the stage.

From. Fig.10 it is evident that the roughness impact is of major importance at high Re. On the contrary up to approx. Re = 8×10^5 the effect is minimal.

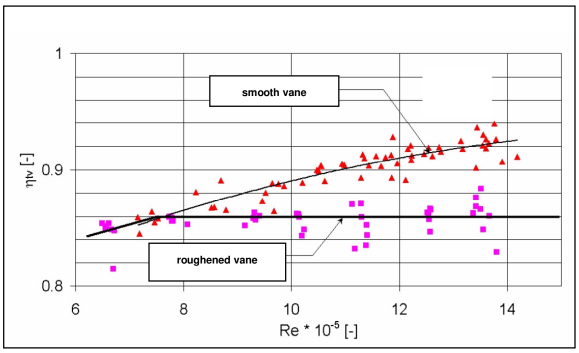


Fig.10: Sand-roughness impact on turbine stage efficiency (stator wheel roughened, Ra = 0.8, 9) (©SKODA POWER)

CONCLUSION

The aim of this article was to discuss an impact of decreased quality of the surface on the flow characteristics within a wide range of outlet velocities. The aerodynamic performance of two linear turbine blade cascades was evaluated via energy loss coefficient ζ. The outlet angle α_2 and Mach number M_{2is} as well as pressure distribution (along the vane surface and behind the model) and flow field structure were examined. In all cases the results related to the hydraulically smooth surface (Ra = 0.4) were taken as reference values.

The SE1050 model was used to examine the effect of increasing sand-roughness. It has been demonstrated that directionally uniform roughness (Ra = 10, 30) causes significant increase of energy loss coefficient. It was observed and recorded during the experiments that the contribution of particular loss sources to the overall ζ value alters as the roughness was changed.

By means of the same model the Reynolds number effect was tested and found almost negligible within the values from Re = 4×10^5 to 8×10^5.

Surface quality importance with respect to specific parts of the vane was investigated using the VS33 model. Three modifications were prepared for wind tunnel measurement. Firstly only a part close to the leading edge on suction side was sand-roughened (Ra = 30). Roughness of the same type and intensity was then applied to the entire suction side and finally to the vane as a whole.

The results summarised in Fig.8a prove the importance of suction side surface roughness. As the character of shock wave – boundary layer interaction is of crucial importance for the total energy loss, the transition point placement is essential. Therefore, the surface quality has to be assessed carefully with respect to the design conditions of every turbine stage.

Simulation of tool traces originated in the manufacturing processes was accomplished by oriented groove roughness applied to the VS33 blades. While there was an extraordinary increase of energy loss coefficient values when the grooves were perpendicular to the flow, the impact of grooves in the flow direction was surprisingly small. In Fig.9a it is evident that the differences between the smooth surface and grooves in the flow direction are minimal.

Regarding the original motivation of SKODA POWER and VZLU the research described in this article provided primary information of the surface roughness effect and helped to identify subjects of future experimental investigation.

From the manufacturer’s point of view the directionally uniform roughness (represented here by sand-roughness) has negative impact in general. Nevertheless, only profound research based on a real damage simulation can bestow reliable data, according to which optimal operational wearing estimation could be practised.

On the other hand, the simulation of tool traces is closer to a real situation and gained experimental data could be therefore directly utilised by the SKODA POWER turbine producer.

The oriented roughness is strongly dependant on the direction of grooves with respect to the actual flow direction. If the grooves are parallel to the flow, the roughness effect could be – under certain conditions – of minor magnitude. Demand for perfect finishing increase the manufacturing costs, especially when there are complex shapes and surfaces in the case. However, any imperfection – even with no impact on the flow characteristics – could be a spot of potential foreign particles deposition. Such a part could probably also be more sensitive to corrosion occurrence and development.

ACKNOWLEDGMENTS

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REFERENCES

1. Ulrych, J., Valenta, R.: *Impact of the surface roughness on the transonic flow through the straight turbine blade cascade*. In: Letecky zpravodaj (Aerospace proceedings), (3), 2003, p. 25-27.
2. Benetka, J., Ulrych, J., Valenta, R.: *Measurements of Surface Roughness Impact I*. VZLU Report No V-1778/03, Praha: VZLU, 2003 (in Czech)
3. Bons, J.P., Taylor, R.P., McClain, S.T., Rivir, R.B.: *The Many Faces of Turbine Surface Roughness*. Journal of Turbomachinery, Vol. 123, 2001.
4. Benetka, J., Valenta, R.: *Measurements of Surface Roughness Impact III*. VZLU Report No V-1816/04, Praha: VZLU, 2004 (in Czech)
5. Benetka, J., Valenta, R.: *Measurements of Surface Roughness Impact II*. VZLU Report No V-1788/04, Praha: VZLU, 2004 (in Czech)