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Gliwice, 7.07.2026

Review

of the doctoral dissertation of Ahmed H. Hanfy, MSc. Eng., entitled 'Surface roughness effect on shockwave boundary layer interaction on transonic compressor profile'

The opinion was prepared at the request of the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences in Gdansk, as set out in the letter RN.520.1.2026 of 12 May 2026, on the basis of the contract for the specific work No. 13.05/D/2 of 13 May 2026.

Overview and Structure of the Dissertation

The reviewed dissertation comprises 131 pages of text divided into seven chapters and five appendices. It includes a list of publications, acknowledgements, a nomenclature list, a list of figures, a list of tables, and a list of algorithms. The bibliography contains 183 references.

The doctoral dissertation of Ahmed H. Hanfy, entitled 'Surface roughness effect on shockwave boundary layer interaction on transonic compressor profile', presents the results and conclusions of experimental investigations of the flow through the inter-blade passage of an axial compressor conducted on a test rig at the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences in Gdansk.

Chapter One, Introduction, contains basic information on the operating conditions of transonic compressors and fans. It presents definitions of blade-cascade parameters, compressor operating parameters, and criterion relationships useful in design. Attention is drawn to flow phenomena occurring at the extreme ranges of the compressor operating envelope, such as the choke line and the surge line. After this general introduction to turbomachinery, the issue of shock-wave/boundary-layer interaction is discussed in greater detail. The basic definitions of boundary-layer parameters are cited, and the process of boundary-layer formation during the flow around a blade profile is explained. Particular attention is paid to the formation of separation as a result of the shock-wave interaction with both laminar and turbulent boundary layers. The need to investigate this phenomenon is explained in view of the occurrence of unsteadiness over a wide frequency range and the appearance of boundary-layer separation in both laminar and turbulent regimes. The importance of solutions that allow the shock wave to be maintained in as stable a position as possible is emphasised, in order to eliminate shock-wave motion (transonic buffet), which could lead to aeroelastic blade vibrations and high-cycle fatigue. The next section of the chapter presents the state of the art concerning research on the influence of roughness on flow conditions, in particular in transonic flow. The basic parameters of surface roughness are given, together with the method of accounting for the complex geometric structure of a rough surface in flow analyses based on the equivalent sand-grain roughness. Finally, the objectives of the dissertation are defined and the scientific hypothesis is formulated as follows: The surface roughness of a transonic compressor blade, determined by the final surface finishing process, affects shock wave oscillations and reduces shock-induced flow separation.

Chapter Two contains a description of the test rig together with the measurement system and control system. The rig on which the measurement chamber with the blade-to-blade passage was installed has been operated for many years at the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences. The measurement chamber is presented in detail, together with a description of the experimental conditions. The basic measurement techniques used in the investigations are described: pressure measurements on the blade, Schlieren imaging using a high-speed camera, and the LDA technique with an advanced traversing system. The chapter concludes with a description of the method used to assess measurement accuracy.

Chapter Three presents the profile geometry. The procedure for assessing deviations in the geometry of the manufactured profiles and the quality of their surfaces is discussed in detail. The results of roughness measurements performed using 2D and 3D techniques are presented. Five profiles are analysed in detail, two of which were selected as baseline profiles, while the remaining three were subjected to additional mechanical surface treatment.

Chapter Four describes improvements to image-analysis methods for two non-invasive flow visualisation techniques: Schlieren imaging and oil-flow visualisation. Modern image-analysis and signal-processing algorithms were used to determine flow parameters, including boundary-layer parameters, more accurately.

To investigate the dynamics of changes in the shock-wave structure and to detect the sources of its instability, POD (Proper Orthogonal Decomposition) analysis of high-speed Schlieren images was applied. An improved line-scanning algorithm was proposed for low-quality and noisy images. This increased the accuracy of shock-wave localisation, while wavelet analysis made it possible to determine the frequency of its oscillations. An important part of this chapter is the description of a new method for perspective correction and transformation of an image from the curved suction surface of the profile onto a plane. This enables accurate spatial mapping of oil-flow visualisation using only one camera. The chapter ends with a review of methods for estimating boundary-layer characteristics on the basis of processed measurement data.

Chapter Five focuses on the description of activities aimed at assessing the sensitivity of the test rig to changes in geometric and flow parameters. Such investigations are crucial for determining the correct operating parameters of the rig, for the quality and reliability of the results obtained, and for the conclusions formulated. At individual stages, the influence of the profile stagger angle on flow symmetry, the influence of the upper-channel size on the shock-wave structure, and profile positioning were assessed. Considerable attention was devoted to the effectiveness of boundary-layer suction and to determining the operating parameters for tests investigating the effect of roughness.

Chapter Six discusses the influence of surface roughness on shock-wave/boundary-layer interaction (SBLI) on the suction surface of the fan profile, focusing on the wave structure, flow separation, and boundary-layer development. The study began with analyses intended to confirm that, when the profiles were changed, roughness was the only parameter influencing the flow pattern. In each case, the wave structure and its dynamics were determined. The boundary-layer parameters downstream of the shock wave were also observed and assessed. The chapter ends with conclusions.

The final descriptive part of the dissertation is Chapter Seven, in which all conclusions are collected and systematised, and recommendations are presented.

General comments

The research conducted and described by Ahmed H. Hanfy constitutes advanced experimental investigations of phenomena occurring during flow through the blade row of a transonic compressor typical of aircraft engines. Issues related to compressible-fluid flow in the transonic velocity range must account for the complex structure of shock waves and expansion waves, which makes both numerical analyses and experimental investigations more difficult. The analysed flow cases correspond to current needs in the design of high-efficiency and reliable transonic compressors. The research problem addressed, namely determining the effect of surface roughness on the conditions of shock-wave/boundary-layer interaction in the blade passage of a compressor, is a problem in gas dynamics and turbomachinery and falls within the scope of the discipline of mechanical engineering.

The scientific problem considered in the doctoral dissertation was pursued within the European TEAMAero project, funded by the Marie Sklodowska-Curie programme. As part of the collaboration, Rolls-Royce provided the fan-profile geometry and the surface-roughness specifications. Within the scientific collaboration, Gdansk University of Technology prepared the preliminary geometry and the two-dimensional surface-roughness characterisation, while TU Dresden performed three-dimensional optical surface measurements using non-contact system. The doctoral candidate carried out the experimental investigations and data analyses at the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences in Gdansk. Collaboration in preparing the rig components and in assessing the quality of the tested specimens made it possible to investigate real engine geometries and ensured high-quality geometric and surface-measurement data. In this case, high measurement precision is a necessary condition for drawing reliable conclusions, especially when the characteristic blade dimension is compared with the dimensions of the roughness under investigation.

The introduction in Chapter One is very well conceived and described. General issues are presented with an appropriate level of detail. The information and definitions provided make it easier to follow the content of the subsequent chapters.

Since the introduction of roughness directly leads to an increase in profile losses, determining what roughness value represents the proper compromise - on the one hand ensuring a reduction in the flow-separation zone and on the other hand not deteriorating the efficiency of the compressor stage - is very important information for compressor design and life prediction. This justifies the fact that the investigated roughness configurations were limited to values occurring in standard manufacturing processes. From a scientific point of view, however, the formulation of general conclusions lacks consideration of a wider range of surface-roughness parameters. This problem is quite clearly visible in Fig. 6.14. The value for individual cases is very small, and the differences obtained, although visible, may be affected by significant uncertainty; for example, the orange line theoretically falls in the middle, whereas the measurement points lie lowest. The value is calculated on the basis of k_s^+. The required value k_s (sand-grain roughness) may be determined from roughness parameters using various formulae. The selected formula (1.17) is one of them. The use of other formulae may yield significant differences in the values. The author is aware of this when formulating the conclusions, indicating that the formulation of general conclusions requires the scope of the investigations to be broadened.

The conducted investigations made it possible to state that surface roughness affects shock-wave/boundary-layer interaction (SBLI) on the aerodynamic profile of a transonic compressor. In the dissertation, this qualitative statement was successfully substantiated quantitatively. The demonstrated intensified mixing in the boundary-layer region comes at the expense of increased dynamic parameters of the shock wave. Investigating and demonstrating the relationship between these effects in a quantitative manner is a new and valuable scientific outcome of the doctoral dissertation.

In the investigations, similarity conditions were adopted on the basis of a key parameter, namely the Mach number, or more precisely the isentropic Mach number. Under the experimental conditions, the boundary layer is analysed for a specific Reynolds number. Was similarity based on the Reynolds number considered? What impact on the formulated conclusions would result from accounting for a change of conditions to actual conditions prevailing, for example, at aircraft cruising altitude?

In the description of the flow conditions, a contour plot of the Mach-number distribution in the experimental channel obtained from CFD calculations is used. This wave configuration is defined as the reference configuration. It is regrettable that the dissertation does not explain how this configuration was selected and does not present calculations of the full blade cascade, which could indicate the level of differences in the results between the full-cascade model and the single compressor-passage model.

Ahmed H. Hanfy used modern tools for experimental research in his work and developed computational algorithms for analysing the results of these investigations. He planned and carried out comprehensive experimental studies. The concept of the research and the research plan were correctly matched to the stated objective. The doctoral candidate demonstrated that the proposed hypothesis is true.

I assess the obtained results, together with their analysis and interpretation, as interesting and valuable, and the substantive level of the dissertation as high. The main objective of the work, which was to investigate the relationship between roughness and the conditions of shock-wave/boundary-layer interaction, has been achieved.

The following achievements of the doctoral candidate deserve particular emphasis:

- performing detailed sensitivity tests of the test rig to changes in geometric parameters and operating parameters;
- developing an image-analysis method for Schlieren imaging that increases the accuracy of shock-wave detection and tracking;
- developing tools and applying the Continuous Wavelet Transform (CWT) technique to investigate shock-wave dynamics;
- developing an algorithm for reconstructing the image from the blade surface using a photograph taken with a single camera;
- coordinating investigations of blade surface roughness and developing the experimental plan.

The doctoral dissertation has a very good and clear structure. The division into chapters is appropriate to the subject matter addressed and allows the reader to follow, step by step, the successive stages of the work carried out. The language of the dissertation is correct, and the Author uses terminology from fluid mechanics and turbomachinery proficiently. The figures, tables, and diagrams presented are carefully prepared and appropriately selected for the descriptions. The literature used in the dissertation is extensive and includes both fundamental and current references.

I consider that the presented doctoral dissertation more than meets the requirements imposed on doctoral dissertations.

Detailed comments

While reading the dissertation, doubts arose in several places that would require additional explanation, as well as editorial errors and inaccuracies:

- The list of publications at the beginning of the dissertation contains five items, in two of which the author is not listed among the authors. For what purpose was such a list presented?
- Page 2, line below Equation 1.1 - the definition of M_t is incorrect.
- Page 9 - the symbols of the boundary-layer parameters in the description are not consistent.
- Eq. 2.5 - missed square root symbol.
- The investigated configuration corresponds to the actual relative Mach number at the compressor inlet. What was the assumed absolute Mach number in this case?
- Table 5.8 - Suction on the side walls affects the dynamics of the shock wave ahead of the leading edge and of the reflected wave. Can suction affect the parameters of the shock wave that is the subject of the study?
- Fig. 5.1 - Does the structure shown in the figure present the results of steady-state or unsteady calculations? In this type of flow, where interactions between strong wave phenomena occur, oscillations of the results may be expected, as was observed in the experimental studies.
- Fig. 5.2 - why was pressure not measured closer to the trailing edge?
- Fig. 6.6 - Comparing the flow structures on the basis of oil-flow visualisation, it can be seen that the flow that may be described as undisturbed by the side walls in Figs. a and b occurs in a band 5-8 mm wide. In Fig. c, this may be questioned. The separation zone itself and the flow within it may not cause radical differences in the pressure distribution at the blade midspan; however, the dynamics of changes along the centreline may to some extent depend on the side walls and on the interaction of symmetric vortices along the blade span.
- Figs. 6.12 and 6.13 should be shown with the same scale on the abscissa.
- Fig. 6.14 - no legend is provided for the dashed lines.
- Was no attempt made to eliminate the Mach reflection, in which the reflected wave interacts with the upper part of the bow shock of the upper blade, which may affect the investigated section of the shock wave?
- What is the reason for the asymmetric placement of the profiles in the channel? The investigated channel is shifted downward relative to the centre. Was any analysis carried out in this respect?

Summary

In summary, I state that the topic undertaken by Ahmed H. Hanfy in the doctoral dissertation entitled 'Surface roughness effect on shockwave boundary layer interaction on transonic compressor profile' is timely and important. This research contributes valuable insights into the complex flow phenomena that occur in the design of transonic compressors. The doctoral candidate presented the results of experimental investigations together with their detailed analysis, which required the development of analytical algorithms and programs. The doctoral candidate confirmed the scientific hypothesis put forward in the dissertation regarding the influence of surface quality on shock-wave dynamics.

Ahmed H. Hanfy has proven that he possesses theoretical knowledge of phenomena occurring in compressible-fluid flows. He has demonstrated the ability to organise experiments and analyse experimental data relating to complex phenomena in transonic flows. The investigations conducted and described confirm the doctoral candidate's competence to conduct scientific work in the scientific discipline of mechanical engineering.

In view of the above, I state that the doctoral dissertation of Ahmed H. Hanfy, MSc. Eng., submitted for review, meets the requirements of the Act on Higher Education and Science (Journal of Laws 2023, item 742, as amended) and may constitute the basis for conducting proceedings for the award of the degree of Doctor (PhD) of Engineering and Technical Sciences (*stopnia doktora nauk inżynieryjno-technicznych*) in the discipline of mechanical engineering.

In addition, considering the complexity of the problem under review, the thoroughness of the experimental research, deep knowledge in measurement data analysis, meticulous care for data quality and reliability, international collaboration, and the outstanding editorial quality of the work, I propose that the dissertation be awarded a distinction.