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Losses in Turbine and Compressors of Jet Engine - A Review

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Abstract: ***This is a review paper which delivers the review of some papers Published on the topic "Losses in turbines and Compressors due to the boundary layer formed at the blades of turbines and Compressors". This review paper contains information based on research done by the date of May 2020. This review paper helps to understand the efficiency of the Turbine and compressors and the effect of the boundary layer formed on the blades of the turbine and compressors. This paper will also take us to all the factors which can help to increase the efficiency of compressors and turbines. It includes some experiments and their results which will help us to understand the losses in the turbine and compressors.***
Keywords: Axial flow turbine, Turbulence, Computational fluid dynamic, aerodynamics, heat transfer, channel flow, hydraulics, turbulent flows, turbine tip.

I. INTRODUCTION

A boundary layer is a layer of viscous fluid close to the solid surface of a wall in contact with a moving stream (within its thickness δ). The flow velocity varies from 0 at the wall up to U_{s_e} at the boundary. A boundary layer refers to layers of fluid near the bounding surface where the effects of viscosity are very significant. There are two types of laminar and turbulent boundary layers. It determines the aerodynamic drag and lift of flying objects or vehicles. Losses in Turbines and Compressors directly affect the efficiency of Turbine and compressors because of which it becomes an important topic to study. Minor losses include disc friction and wetness losses but losses due to boundary layer are major in Turbine and Compressors.

II. LOSSES DUE TO SECONDARY FLOW IN A TURBINE CASCADE WITH HIGH INLET TURBULENCE

Secondary flows in axial flow turbine blading have attracted a lot of interest because of the losses and changes in the outlet flow angle they produce. In rotor blade passages, the secondary flows are very high due to the high turning, and the resulting losses for low-aspect-ratio blading may account for half the total loss. A comprehensive review of the structure of secondary flows in turbines has been given by Sieverding (1985), but he concluded that not much was known about turbulence in the secondary flow region. Some information was available, e.g., Senoo (1958), Langston et al. (1977), and Bailey (1980), but it was incomplete and no exhaustive measurements had been published. Moore et al. (1987) studied the flow downstream of a largescale, low-speed cascade. They recorded a peak level of turbulence of 25 percent of inlet velocity and showed that the turbulence was of major significance in the loss generation process downstream of the cascade. A detailed study of the turbulence within a rotor blade passage was presented by Zunino et al. (1987). They found high turbulence levels of up to 12 percent associated with the loss core near the throat, with peak values of 15 percent of inlet velocity downstream of the cascade. In another detailed investigation, Gregory-Smith et al. (1988b) found rather higher values of turbulence, 29 percent of upstream velocity in the vortex core, and regions of high turbulence associated with high loss. However, only 17 percent of the loss could be accounted for as turbulent kinetic energy. Downstream of the cascade, the wake turbulence dissipated rapidly, but the overall turbulent kinetic energy continued to Contributed by the International Gas Turbine Institute they presented at the 35th International Gas Turbine and Aeroengine Congress and Exposition, Brussels, Belgium, June 11-14, 1990. Manuscript received by the International Gas Turbine Institute January 12, 1990. Paper No. 90-GT-20. Rise. Spectral analysis of the turbulence showed a dominant low-frequency peak, indicating the gross unsteadiness of the flow. A recent paper by Hebert and Tiederman (1990) also shows high turbulence associated with the passage vortex. Thus it may be concluded that the action of the secondary flow in rolling up the end wall boundary layer, and its interaction with blade boundary layers, results in significant turbulence generation. Although this process accounts for a large portion of the secondary loss, the loss is not manifested as an equal rise in turbulent kinetic energy, because the rate of dissipation of turbulence almost matches the rate of generation.

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The understanding of the turbulent structure in the secondary flow region is very important in developing models of turbulence for Navier-Stokes solvers. As shown by Cleaketal. (1989), very different predictions for the secondary velocities may be obtained depending on how the turbulence is specified within the flow regime. Most Naiver-Stokes solvers for turbomachinery flows use the Boussinesq eddy viscosity concept, whereby the Reynolds shear stresses are related to local velocity gradients by anisotropic eddy viscosity. It may be expected that for a blade passage, the complex flow results in a non-isotropic eddy viscosity and that the action of normal Reynolds stresses is important (Moore et al., 1987, give some evidence for the latter).

The secondary velocities at any point are obtained from the radial component W of velocity and the component in the cross-stream direction, as defined by the midspan direction for the same tangential position. The total pressure loss coefficient is referenced to freestream conditions upstream of the cascade. The coefficient may be mass meant over the pitch of the blades to give the span wise variation in the loss at a given plane, or over the whole area of the plane. Thus the inlet loss coefficient is for the inlet plane, the cascade loss coefficient is the growth in loss across the cascade, and the net secondary loss coefficient is cascade loss less midspan loss. The coefficients for secondary kinetic energy and turbulent kinetic energy are also referenced to upstream velocity, V0. The below table explains the losses in the turbine because of the secondary flow.

	No grid	Turbulence grid
Total Loss Coefficient	0.239	0.211
– Inlet Loss Coefficient	0.041	0.025
= Cascade Loss Coefficient	0.198	0.186
– Midspan Loss Coefficient	0.095	0.102
= Net Secondary Loss Coefficient	0.103	0.084
Midspan Angle	-67.5^{o}	-66.7^{o}

Table 1: Losses in the turbine due to secondary flow

(Source: J. G. E. Cleak, D. G. Gregory-Smith “Secondary Flow Measurements in a Turbine Cascade with High Inlet Turbulence”, https://doi.org/10.1115/1.2927981)

Turbulent flow details through a high turning cascade of axial flow turbine blades have been obtained. Special features are the high inlet turbulence level from an upstream grid, and measurement very close to the end wall using hot-wire anemometry. Concerning the general features of the flow, the following conclusions may be drawn: (a) the high inlet turbulence has little effect on the secondary loss of kinetic energy of the secondary flow. (b) High values of turbulent Reynolds stresses are seen if the loss core and vortex region, and also where separation lines on the end wall and suction surface feed loss into the main flow. (c) The stream wise/radial shear stress iu'w') shows a significant change across the position of the suction surface separation line.id) within the passage the streamwise/cross passage shear stress (u'v') shows negative values in the loss core, but this changes to positive values downstream of the cascade. This sign change can be accounted for by the magnitude of terms in the stress transport equation. (e) The frequency spectrum of the turbulence shows no dominant frequencies where the turbulence is high. Of particular significance for the modeling of turbulence in Navier-Stokes solvers are the following: (/) Downstream of the cascade, a fairly isotropic eddy viscosity is seen in the loss core. (g) There are significant contributions to the loss process by the Reynolds normal stresses, and these will not be allowed for by a Boussinesq eddy viscosity model.

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III. INTERACTION BETWEEN AN AXIAL-FLOW TURBINE AND A TURBULENT OPEN CHANNEL FLOW

An experiment was performed in a laboratory to study a bed-mounted axial-flow hydrokinetic turbine with the dynamically rich interaction of turbulent open channel flow. An acoustic Doppler velocimeter and torque transducer were used to simultaneously measure at the high temporal resolution the three velocity components of the flow at various locations upstream of the turbine and in the wake region and turbine power, respectively. Results show that for low frequencies the instantaneous power generated by the turbine is modulated by the turbulent structure of the approach flow. The Critical Frequency above which the response of the turbine is decoupled from the turbulent flow structure is shown to vary linearly with the angular frequency of the Rotor. The measurements elucidate the structure of the turbulent turbine wake, which is shown to persist for at least fifteen rotor diameters downstream of the rotor, and a new approach is proposed to quantify the wake recovery, based on the growth of the largest scale motions in the flow. Spectral analysis is employed to demonstrate the dominant effect of the tip vortices in the energy distribution in the near-wake region and uncover meandering motions.

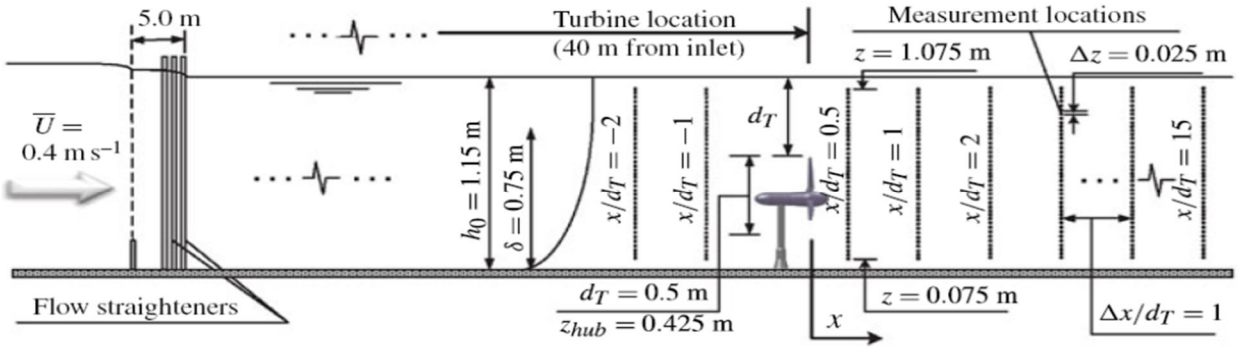

Figure 1: Interaction between turbulent open channel flow and an axial flow turbine

(Source: Chamorro, L., Hill, C., Morton, S., Ellis, C., Arndt, R., &Sotiropoulos, F. On the interaction between a turbulent open channel flow and an axial-flow turbine. Journal of Fluid Mechanicshttps://doi.org/10.1017/jfm.2012.571)

The power generated by a marine turbine which is instantaneous in a turbulent open channel flow was found to be highly modulated by the turbulent features of the flows. Spectral analysis showed that this interaction is confined to the low-frequency range. The frequency (critical) above which the turbine power is decoupled from the turbulent flow structure was shown to vary linearly with the angular frequency of the rotor. A new approach to quantify wake recovery is proposed. It is based on the evolution of the very large-scale motions, defined through the autocorrelation function at hub height. This approach allows a quantification of the rate of recovery of the large scale coherent motions in the wake, which near the turbine are found to be of the order of the rotor.

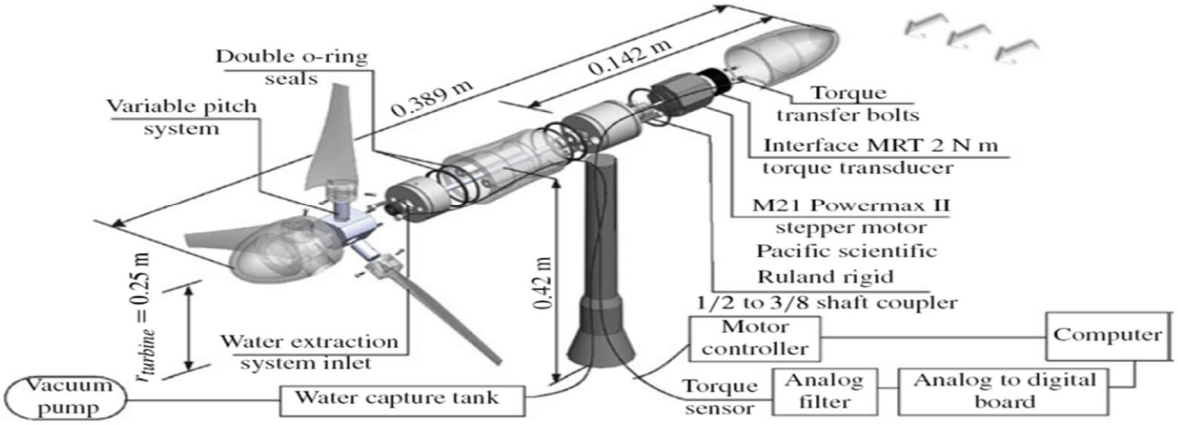

Figure 2: General set up and measurement locations

(Source: C., Morton, S., Ellis, Chamorro, L., Hill, C., Arndt, R., &Sotiropoulos, F. On the interaction between an axial-flow turbine a turbulent open channel flow. Journal of Fluid Mechanics https://doi.org/10.1017/jfm.2012.571)

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The rate of decay of these large-scale motions is found to be independent of the turbine tip-speed ratio. The mean velocity deficit in the downstream wake, measured at the turbine hub height, showed two distinct regions: the first at distances x=dT> 4 where the velocity increased monotonically with tip-speed ratio and the second in the vicinity of the turbine where complex non-monotonic behavior was observed. The upstream wake was negligible at two rotor diameters upstream of the turbine whereas downstream velocity wake deficit was shown to persist beyond fifteen rotor diameters. The dominant effects of the tip vortices within the first three rotor diameters at the turbine top-tip height this was found in the spectral analysis. It was found to be negligible at the bottom tip, even close to the turbine. The evidence provided by the measurement of wake meandering at distances x=dT > 4. This study shows that wake meandering is not only characteristic occurs in marine turbines placed in confined waterways but also wind turbines.

IV. LOSSES DEPEND ON THE GAPES OF BLADES

An experimental and computational fluid dynamic study on a transonic blade tip aerothermal performance at engine representative Mach and Reynolds numbers Mexit 1, Reexit = 1.27*10^6 is presented over here. Oxford University's high-speed linear cascade research facility uses infrared thermography and transient techniques to measure Heat-transfer data. The numerical predictions for the same tip configuration and flow conditions is done by Rolls-Royce PLC HYDRA suite. The result from this experiment shows that the flow over a large portion of the blade tip is supersonic for all regions near the leading edge of the tip gap, surface Nusselt numbers decrease with the tip gap. In the region of trailing edge Opposite trends are observed. In Local Region, Several hot spot features on blade tip surfaces are attributed to enhance turbulence thermal diffusion. Other surface heat-transfer variations are attributed to flow variations induced by shock waves.

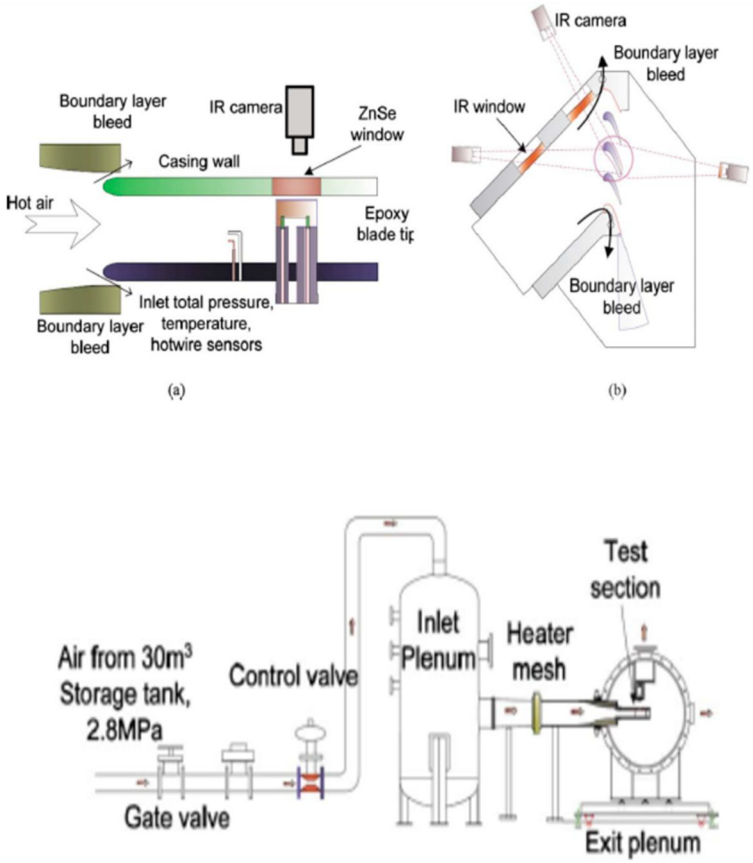

Figure: 3 High-speed linear cascade research facility (Oxford)

(Source: Transonic Turbine Blade Tip Aerothermal Performance With Different Tip Gaps—Part I: Tip Heat Transfer by Q. Zhang, D. O. O'Dowd, L. He, P. M. Ligrani, M. L. G. Oldfield, J. Turbomach.

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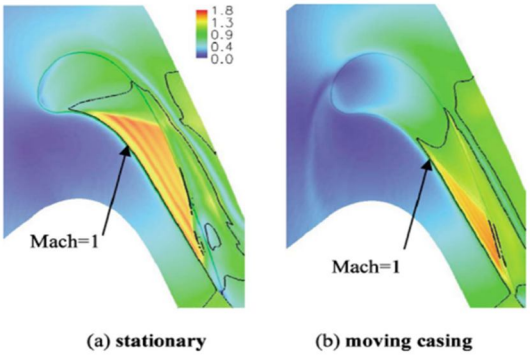

Figure 4: Schematic diagram of the test section (a) front view (b) tip view

(Source: Transonic Turbine Blade Tip Aerothermal Performance With Different Tip Gaps—Part I: Tip Heat Transfer by Q. Zhang, D. O. O'Dowd, L. He, M. L. G. Oldfield, P. M. Ligrani, J. Turbomach.

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A. Effect of Relative Casing Motion (CFD)

In the present study, the experiments with the stationary wall validate the CFD methods used, which can then be used to predict the effects of the relative motion of the blade and the adjacent casing wall, without having to do very difficult transonic, high-pressure, moving-wall experiments. HYDRA prediction using a moving casing is presented in this section and compared with data obtained with a stationary casing. Figure: 5 presents the local Mach number distribution along the plane that is located in the middle of the tip gap for g/S=1.0%. The dark contour lines indicate locations for Mach number=1. With the moving casing, the over-tip leakage flow is reduced along with the size of the supersonic region. Besides, flow speeds are much lower in the upstream subsonic portion of the tip gap. However, in the downstream portion, a significant portion of the tip leakage flow remains supersonic with identifiable choked and shock wave regions when the casing is moving. Figure:6 also presents Nusselt number distributions on the blade tip for a tip gap of g/S=1.0% with and without a moving casing. Here, the local heat-transfer distributions are noticeably affected by relative casing motion. On the upstream part of the tip surface, Nusselt numbers are significantly reduced, and the leading edge "hot stripe" moves toward the middle of the tip surface.

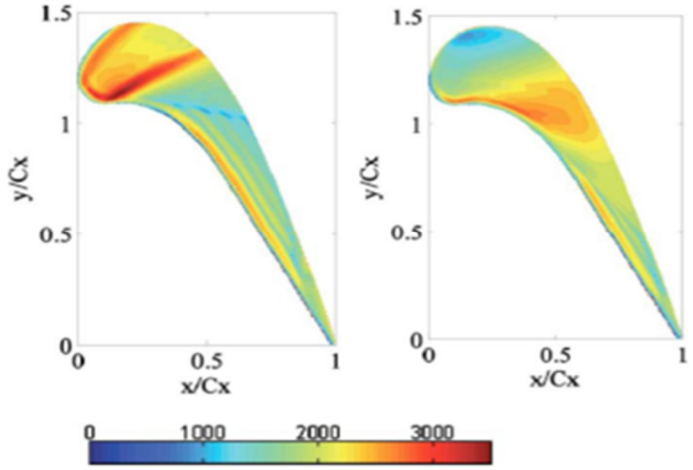

Figure 5: Local tip Mach number distribution for a tip gap of 1.0% with and without moving casting (Hydra prediction) (solid black line corresponds to Mach number of 1)

(Source:: Transonic Turbine Blade Tip Aerothermal Performance With Different Tip Gaps—Part I: Tip Heat Transfer by Q. Zhang, D. O. O'Dowd, L. He, M. L. G. Oldfield, P. M. Ligrani, J. Turbomach)

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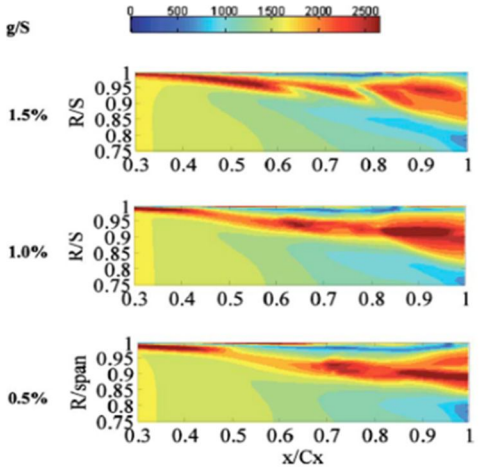

Figure: 6 Nusselt number contours for a tip gap of 1.0% with and without casting (hydra prediction)

(Source: Transonic Turbine Blade Tip Aerothermal Performance With Different Tip Gaps—Part I: Tip Heat Transfer by D. O. O'Dowd, L. He, M. L. G. Oldfield, P. M. Ligrani, Q. Zhang, J. Turbomach.

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B. Near-Tip Blade Surface Heat-Transfer Results

Presented in this section are near-tip blade surface Nusselt number distributions obtained from experiments and HYDRA numerical predictions for the same three ratios of tip gap to blade span: 0.5%, 1.0%, and 1.5. Nusselt number is a dimensionless parameter used in calculations of heat transfer between a moving fluid and a solid body. Aero thermal performance of a transonic blade tip at different tip gaps is experimentally and numerically investigated in the present paper and the companion paper Part II. Part I of this paper focuses on heat transfer on the tip and sidewall near-tip surfaces. Spatially resolved heat-transfer data are obtained by transient thermal measurement using Oxford high-speed linear cascade research facility. The Rolls-Royce HYDRA suite is employed for numerical predictions for the same geometry and flow conditions. Experimental data are used to assess CFD capability. Numerical investigation, on the other hand, provides the necessary interpretation of the observations from the experiment. The main conclusions are as follows. 1Overall experimental heat-transfer data for all three tip gaps are in good agreement with HYDRA predictions. The frontal region of the blade tip Nusselt number decreases as tip gaps get smaller from 1.5% to 0.5%, while the opposite trend is observed for the tip trailing edge region. Although CFD results suggest a lower Mach number for the tip flow as the tip gap decreases, a large portion of the blade tip is still supersonic for all three tip gaps investigated. 2All the present results suggest that, for most of a transonic blade tip, the high heat transfer is dominated by the enhanced turbulence thermal diffusion rather than by a direct increase of wall shear stress. 3Heat-transfer distributions for the near-tip blade surface are also investigated. On the suction side, the Nusselt number decreases, and the peak value position is moved away from the tip edge due to the tip leakage vortex detachment as the tip gap increases. On the pressure side, the peak heat transfer occurs around the near-tip trailing edge corner.4Local heat-transfer distribution on the blade tip is noticeably affected by the relative casing motion. A moving casing results in a smaller supersonic region over the tip and a higher heat transfer near the tip trailing edge. A significant portion of the tip leakage flow remains supersonic with easily identifiable shock wave structures.

V. CONCLUSION

Laboratory experiments were carried out to investigate the wake characteristics of axial flow hydrokinetic turbines under the same inflow condition with different TSRs. The velocities were measured using an ADV up to twenty rotor diameters downstream of the turbine and flow visualization experiments were also conducted to reveal the flow structures in the near wake. The experimental results provided evidence that a change in TSR can significantly affect the mean flow and Reynolds stress fields along with the scale of turbulence, especially in the region within six rotor diameters downstream.

Tip of Compressors and Turbine blades affect the flow which directly affects its efficiency. The design of blades helps to reduce the fuel/power consumption and increase efficiency by managing the flow in the turbine and Compressors.

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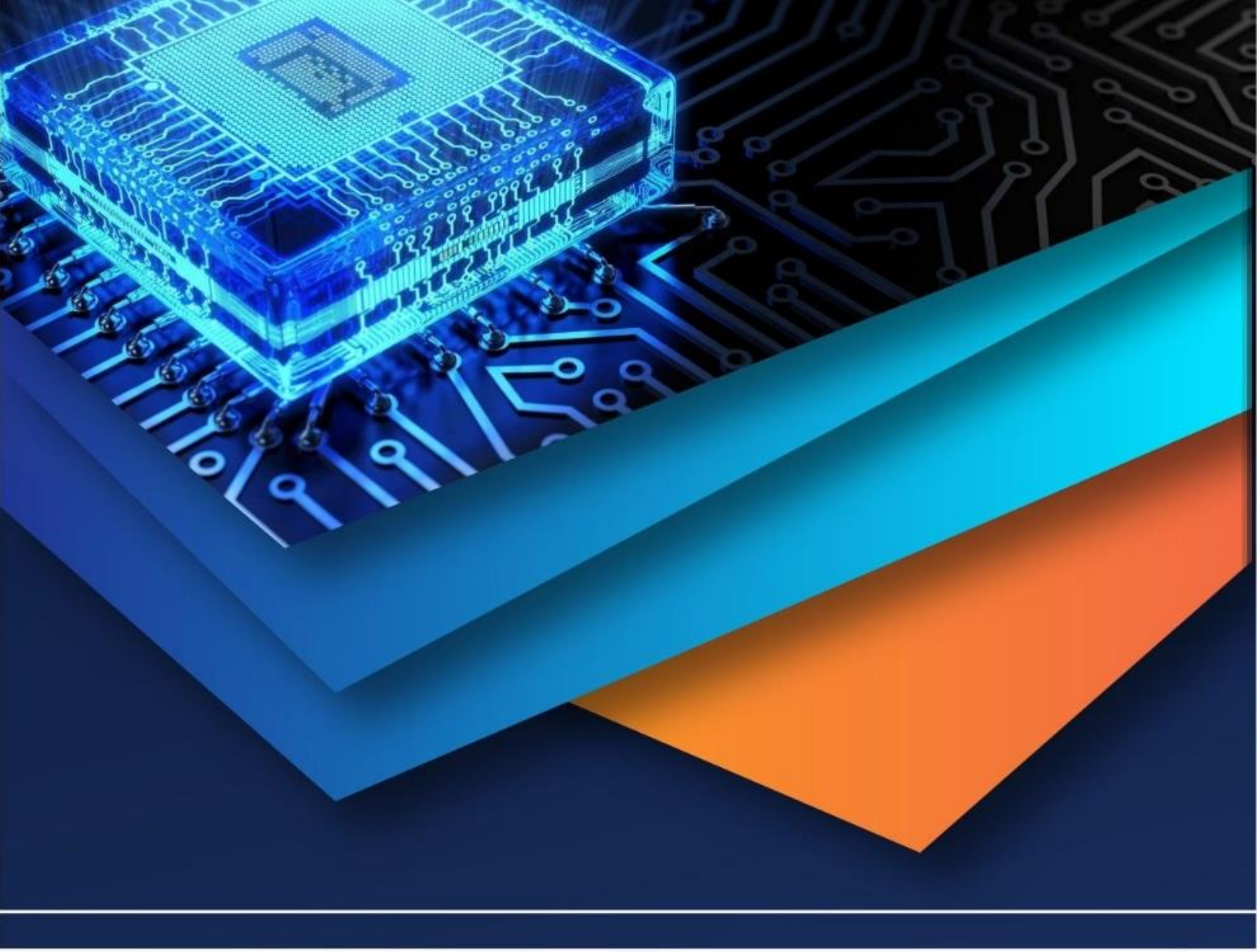

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