iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 5 **Issue:** VIII **Month of publication:** August 2017

DOI: http://doi.org/10.22214/ijraset.2017.8185

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor:6.887
Volume 5 Issue VIII, August 2017- Available at www.ijraset.com

Reliability - Based Robust Design Optimization of Centrifugal Pump Impeller for Performance Improvement considering Uncertainties in Design Variable

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Abstract: Centrifugal pump is commonly used in industries, agriculture and domestic application for transferring liquids. Diffusion of flow process is highly complex in pump operation. Relatively little information is known about the complex flow phenomena inside the pump. It is necessary to design/develop the geometry of impeller and casing to reduce the flow losses in pump and enhancing the performance of centrifugal pump.RBDO is one of the method used to optimize the pump performance considering the inherent uncertainties presents in the design variables such as impeller eye diameter, vane angle and vane width etc. In this work, an impeller model of a centrifugal pump was created using SolidWorks 2013 software from the data provided and then analyzed in ANSYS – CFX. The performance of the impeller was evaluated for modifying certain key parameters like number of blades, outlet blade angle, and blade width. CFD results were tabulated and regression model was developed using response surface method to reproducing the behavior of fluid flow domain in centrifugal pump. Mathematical simulation technique was used to analyze the uncertainties in design variables and response to ensure the operation of the centrifugal pump is stable. Reliable design space was created using the simulated data.
Keywords: RBDO, Uncertainty in design variables, Deterministic design optimization, Monte Carlo simulation , Response surface method

I. INTRODUCTION

As a result of conservative engineering practices, pumps are often substantially larger than they need to be for an industrial plant's process requirements. Centrifugal pumps can often be oversized because of "rounding up," trying to accommodate gradual increases in pipe surface roughness and flow resistance over time, or anticipating future plant capacity expansions. In addition, the plant's pumping requirements might not have been clearly defined during the design phase. Because of this conservative approach, pumps can have operating points completely different from their design points. The pump head is often less than expected, while the flow rate is greater.

The operating regions of mixed-flow and axial flow pumps are limited because of flow rate instabilities. Therefore, we choose radial flow centrifugal pump to optimize the performance through RBDO.

II. RELIABILITY IN CENTRIFUGAL PUMP

Moving element called bladed rotor rotates inside a casing for increasing the moment of momentum of liquid if the flow is continue in the sense. An impeller is a rotating disc called 'hub' to which the blades are attached; the rotary motion of the impeller blades moves the fluid outwards and increasing the velocity of fluids at delivery pipe. The high impeller outlet velocity of fluid is reduced partially by transforming the kinetic energy into pressure energy with the help of diffusers. This conversion loss decides the efficiency of pump. Technology development analysis software's provide opportunities to predict the flow behavior of pump which may not be accurate but the effect of design changes provide some correlation between computer model and practical model. Creating the experimental setup for different impeller assembly for analyzing pump performance is time consuming process and need huge investments. If numerical models are developed for reproducing the behavior of centrifugal pump, then limited number of experiments needs to be conducted to generate the regression model. In this study Response Surface Methodology was used to build the regression model with help of Central Composite Design for deciding optimum number of Experiments locating in the given design space. The application of RBDO enables to restrict number of simulation required for uncertainty propagation during design process; to overcome this limitation several alternative techniques with various degrees of complexity have been proposed.

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In this paper work Monte Carlo Simulation technique was used to evaluate the uncertainty of pump performance. **Sangwon Hong and Sail Lee**, [1] have employed Reliability Based Design Optimization (RBDO) in aircraft axial compressor for stall margin to guarantee stable operation using uncertainty model. An approximation model developed by Artificial Neural Network (ANN) was adopted to reduce the time and cost of RBDO; failure probability for stall margin were calculated accurately by Monte Carlo simulation (MCS) method. This RBDO result was compared with the deterministic optimization result which does not include uncertainty model. When a system contains uncertainty in input parameters, the performance function of the system also shows a probabilistic characteristic. In reliability analysis of any systems, the cumulative distribution of the performance function is one the most important criteria in determining the safety level of the system. While evaluating the reliability of the system, engineers are often interested in the probability of failure of the performance function. Since it provides not only the performance value but also the confidence range till date there was no research study to find the uncertainty in pump performance using RBDO concept. This paper deals with study on uncertainty in pump operations using RBDO technique.

III. METHODOLOGY

A. Problem Formulation

In order to illustrate the general formulation of RBDO problem consists a new form of the objective function F(x, y) was subjected to limit state as well as deterministic and reliability constraints.

Minimize $F(x, y) = f(x)\, d_{\beta}\,(x\ y)$ Equ. 1

Subjected to $G\,(x, y) \le 0$ 2

$g_k\,(x) \le 0$ 3

$d_{\beta}\,(x, y) \ge \beta_t$ 4

The minimization of the function F (x, y) is carried out in the Deterministic Design Variables **'x'** and random variables **y** are subjected to Reliability Constraint G (x, y).

Here the function G (x, y) is failure function which is subjected to the constraint $d_{\beta}\,(x, y) \ge \beta_t$

β_t is reliability index $= \int_{G\,(x,y,\dots)} P_f$ 5

P_f **-** is the failure probability of the system.

In this paper work this failure probability of the system was found using Monte Carlo Simulation Method. Harish Agarwal, [2] developed various frame work to perform reliability based design optimization under sever uncertainties. To understand the concept the following flow chart will brief the reliability based design optimization methods and its inherent use in various discipline briefly explained in his dissertation.

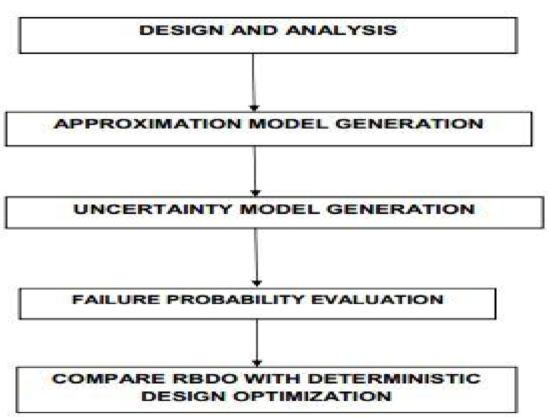

Figure1. RBDO Flow Chart

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B. Solution Phase

The specification of pump selected for analysis is given in Table 1. A centrifugal pump was modeled in SOLIDWORKS software for these specifications.

TABLE1. PUMP DESIGN SPECIFICATIONS

DESIGN PARAMETERS	DIMENSIONS
Impeller Width b	21.5 mm
Impeller Diameter at Suction Side Ds	72.5 mm
Impeller Diameter at Delivery Side Dd	175 mm
Impeller Eye Diameter Di	63.5 mm
Blade Inlet Angle β_1	37.9
Blade Outlet Angle β_2	33.5
Rotation Speed N	2880
Number Of Blades	6
Shaft Diameter	25 mm

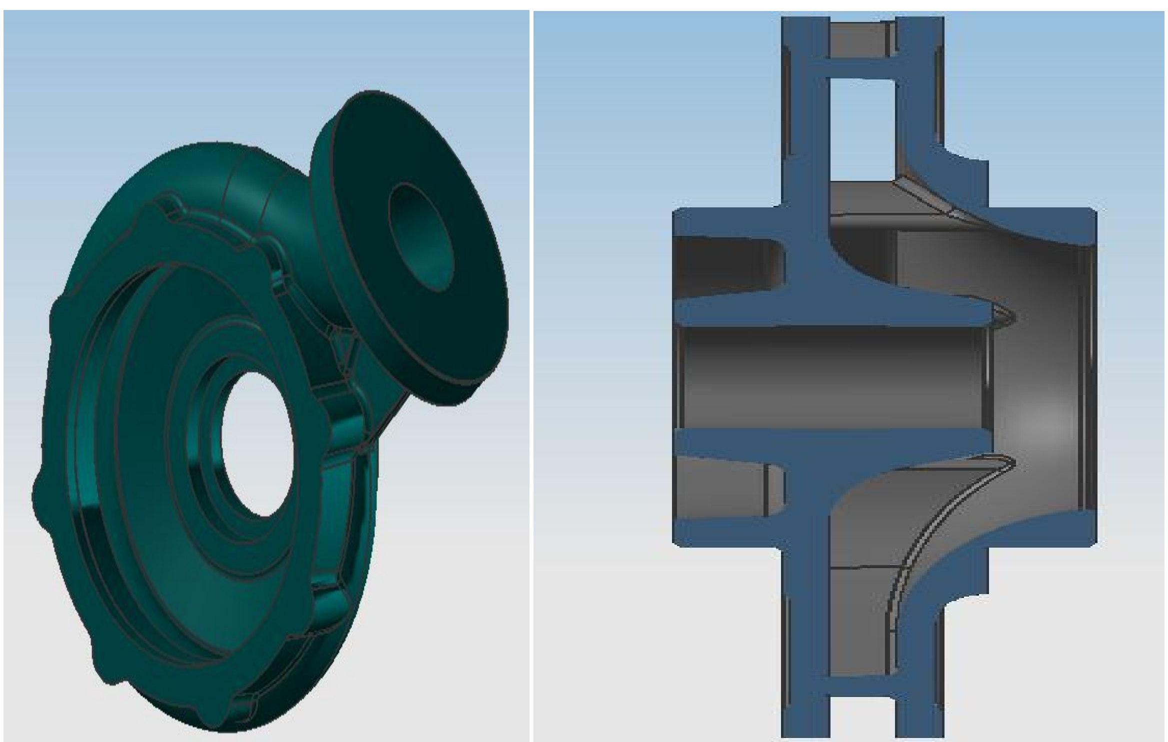

Figure2. Centrifugal pump model

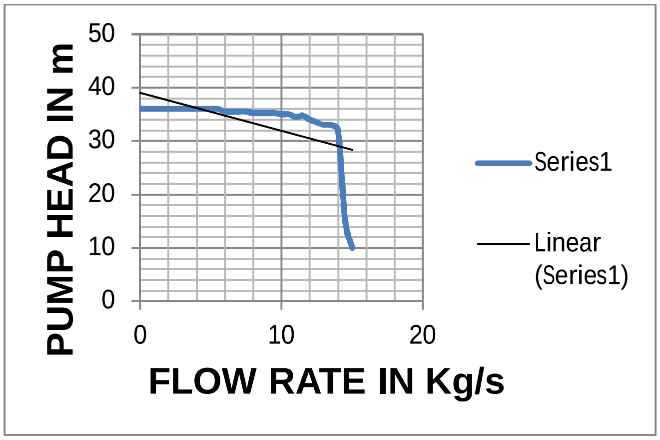

Figure3**.** Performance curve of the given pump model

The performance curve of the given pump model shows maximum flow rate and head achieved by the pump while operate at a speed of 2880 rpm. The experimental data was obtained for different mass flow rate setups. From this response curve, we observed that after reaching 14 LPS flow rate, sudden fall of pump head occurs due to cavitation phenomenon. We already know that at maximum flow rate, cavitation occurs in a pump, because of low pressure developed in suction line. It will damage the pump inner parts and also reduce the pump head. The objective of this work is to optimize the pump design variables to attain the maximum flow rate compared to the actual one and to predict the reliability of pump performance through numerical investigation.

While designing a pump to attain require flow and head we have to choose the design values based on Best Efficiency Point (BEP) from the pump performance curve. But in this project work we already have a model of centrifugal pump. So, here the model was redesigned in NX UNIGRAPHICS. For analyzing the inside fluid flow behavior of pump, we use ANSYS CFX software module. According to CFX software we can analysis the pump flow behavior through two different ways. First one is fluid flow domain method and second one is immersed solid method.

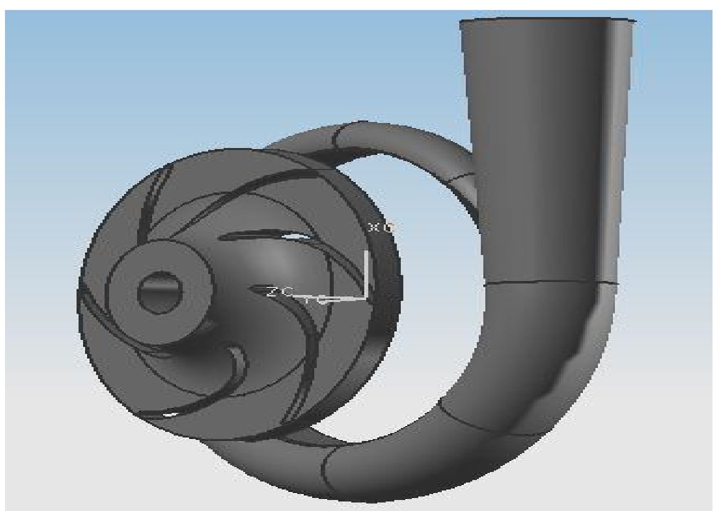

Figure4. Fluid flow Domain

P. Usha sri and C. Syamsundar, [4] have done a work on computational analysis of a centrifugal pump impeller by considering the performance parameters of a turbo machines in ANSYS CFX. They have extracted the fluid flow domain of centrifugal pump from its geometry and analyzed the flow behavior for various boundary conditions. Fluid flow domain in the centrifugal pump was extracted for analyzing the flow behavior. A typical fluid flow domain shown in Figure 2

To analyze the pump, the pump fluid flow domain model is opened with workbench platform in ANSYS - CFX, and following steps are followed, In the Workbench platform, a project schematic appears for the simulation work. The left side of the project

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schematic, a toolbox appears with the list of analysis systems, component systems, custom systems and design exploration. From that, geometry tool is selected in the component system for importing the geometrical model into the Workbench. A Design Modeler window opens after importing the model. By clicking the generate icon for attaching the geometrical model in the workbench. After importing the geometrical model of the impeller, casing and the fluid clearance, the mesh tool is selected for meshing the assembly of pump. The FIGURE 5 shows the meshed model of an impeller and casing assembly.

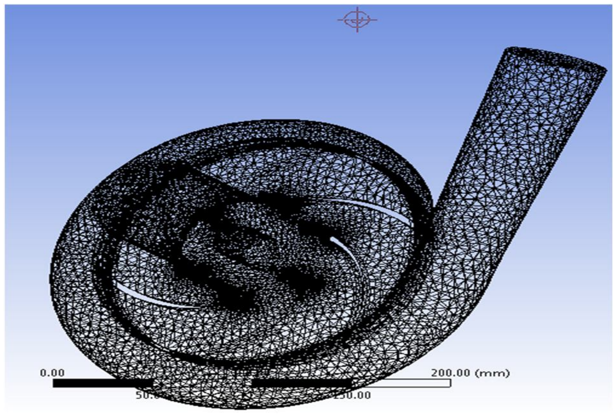

Figure5. Meshed model of an impeller and casing assembly

Then transfer the meshed data to the CFX tool for further CFD analysis. In the CFX, three steps are to be carrying out. First is the CFX Setup (CFX - Pre), here the inlet and outlet parameters have been setup with the turbo mode.

C. Boundary Conditions

1) Centrifugal pump impeller closed type domain is considered as a rotation from of reference with a rotational speed of 2880 rpm anti clockwise direction. The working fluid through the pump is water at 250 C. Casing is considers a stationary domain and the model has low turbulence intensity. Non slip boundary conditions have been imposed over the impeller blades, hub and shroud. Roughness of all walls are considered 20 micron. Convergence precision of residuals was considered as 10-5. The iteration process has been done in the solution (CFX Solver Manager).The final result has been arrived at the end of the simulation and the result is displayed as detailed in the Macro Report. The CFD analysis is carried out to obtain the head, pressure and velocity distributions. Then the pump assembly modified by varying the parameters likes impeller eye diameter and blade width

D. Regression Model Generation

When computationally demanding models are involved, as commonly encountered in engineering practice, the application of RBDO is limited by large number of analyses required for uncertainty propagation during design process. For reproduce the behavior of centrifugal pump, some limited number of experiments conducted to generate the regression model. In this work Response Surface Method used to build the regression model which assist with central composite design for optimum distribution of experiments point in the given design space of impeller eye diameter, vane angle and vane width.

TABLE2. VARIABLES RANGE

IMPELLER DESIGN VARIABLE	VARIABLE RANGE
Impeller eye diameter (mm)	43.5 – 63.5
Vane angle(Degree)	10 – 30
Vane width(mm)	10 – 25

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E. Central Composite Design (CCD)

Central composite designs are often recommended when the design plan calls for sequential experimentation because these designs can incorporate information from a properly planned factorial experiment. The factorial and center points may serve as a preliminary stage where you can fit a first-order (linear) model, but still provide evidence regarding the importance of a second-order contribution or curvature. You can then build the factorial portion of the design up into a central composite design to fit a second-degree model by adding axial and center points. Central composite designs allow for efficient estimation of the quadratic terms in the second-order model, and it is also easy to obtain the desirable design properties of orthogonal blocking and rotatability.

F. Response Surface Method

Response surface methods are used to examine the relationship between a response variable and a set of experimental variables or factors. These methods are often employed after you have identified a "vital few" controllable factors and you want to find the factor settings that optimize the response. Designs of this type are usually chosen when you suspect curvature in the response surface. Many response surface applications are sequential in nature in that they require more than one stage of experimentation and analysis. Based on CCD Table above mentioned geometrical modifications are rebuilt and flow behavior of those models were analyzing. From the ANSYS CFX results, pressure and velocity distribution in suction and delivery side are tabulated. Then using empirical relationship of pump performance characteristics evaluate the Total Head, Static Head, Stagnation Head values are tabulated(without considering the Mechanical and Hydraulic losses). stagnation pressure head is consider as a Response variable in RSM and the regression equation was generate using Analyze Response Design option in Minitab statistics tool bar.

G. Regression Model/Equation

To reproduce the pump behavior regression equation is generated Using Response Surface method; here the coded units are used.

A – IMPELLER EYE DIAMETER

B – VANE ANGLE

C – VANE WIDTH

D – STAGNATION PRESSURE HEAD

D =17.43 - 0.095 A + 0.315 B - 0.284 C + 0.00070 A*A - 0.01970 B*B - 0.00877 C*C - 0.00642 A*B + 0.00708 A*C + 0.01892 B*C

This regression model will used as a transfer function in simulation tool in next chapter to find the failure probability of the system through simulation technique.

IV. RESULT AND ANALYSIS

A. Monte Carlo Simulation

Monte Carlo simulation technique is a simple form of the basic simulation; it provides a useful tool for evaluating the risk of complex engineering systems. It has been widely used in reliability analysis because of its simplicity and robustness, but it requires a large number of analyses for an accurate estimation of the probability of failure, especially when the failure probability is small. In general, accuracy is a concern when the performance function exhibits highly nonlinear behavior. It has also been pointed out that these methods are not well suited to problems with many competing critical failure modes.

In this work, the design variables (impeller eye diameter, vane angle, vane width) were distributed based on their mean value and standard deviation. Around 100000 trails points were generate according to the type of random data distribution function. Here we use Normal distribution for each design variable to generate 100000 trail points using Minitab software. ***Calculator >Random data > Normal Distribution > Mean & standard deviation values > ok***

B. Response Distribution

After distribute each variables according to their mean value and standard deviation, generate Responses for the distributed points using regression model/equation. The response of the system had shown the type of distribution, standard deviation, Maximum and minimum values of Response. This system response is nothing but the Uncertainty Model. ***Statistics > Basic Statistics > Graphical***

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summary in Figure 7 uncertainty model of stagnation pressure head is shown and the standard deviation in response, maximum and minimum response values are tabulated.

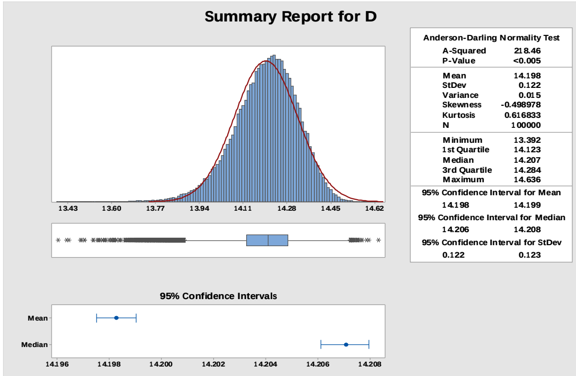

Figure6. Uncertainty model

From this uncertainty model we can evaluate the failure probability of the pump with respect to stagnation pressure head.

Failure probability $P_f = \frac{No\ of\ Failure\ Response}{No\ of\ Simulations\ in\ MCS} = \frac{N_f}{N}$

Already mentioned in the previous chapter the evaluation of this failure probability P_f gives Reliability Index (β). Another method of finding the reliability index is Inverse of Failure probability (1 - P_f).

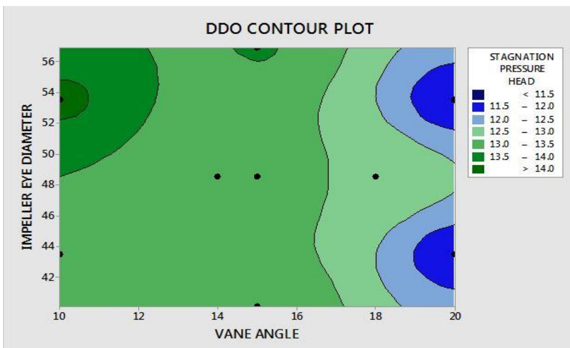

Figure7. Deterministic Design Space

Figure8. shows optimum design space of pump design variables from DDO and Figure9.shows reliable design space for pump design variables which considered uncertainties in design points and response

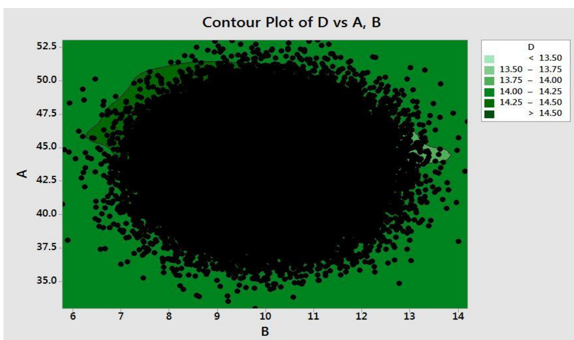

Figure8. Reliability Design Space

From this RBDO, design variables uncertainties are consider while optimize the required objective function provide an optimum design space which is reliable and robust compare to DDO.2

V. CONCLUSION

In this work, an impeller model of a centrifugal pump was created using SolidWorks 2013 software from the data provided and then analyzed in ANSYS – CFX. The performance of the impeller was evaluated for modifying certain key parameters like number of blades, outlet blade angle, and blade width. CFD results were tabulated and regression model was developed using response surface method to reproducing the behavior of fluid flow domain in centrifugal pump. Mathematical simulation technique was used to analyze the uncertainties in design variables and response to ensure the operation of the centrifugal pump is stable. Reliable design space was created using the simulated data.

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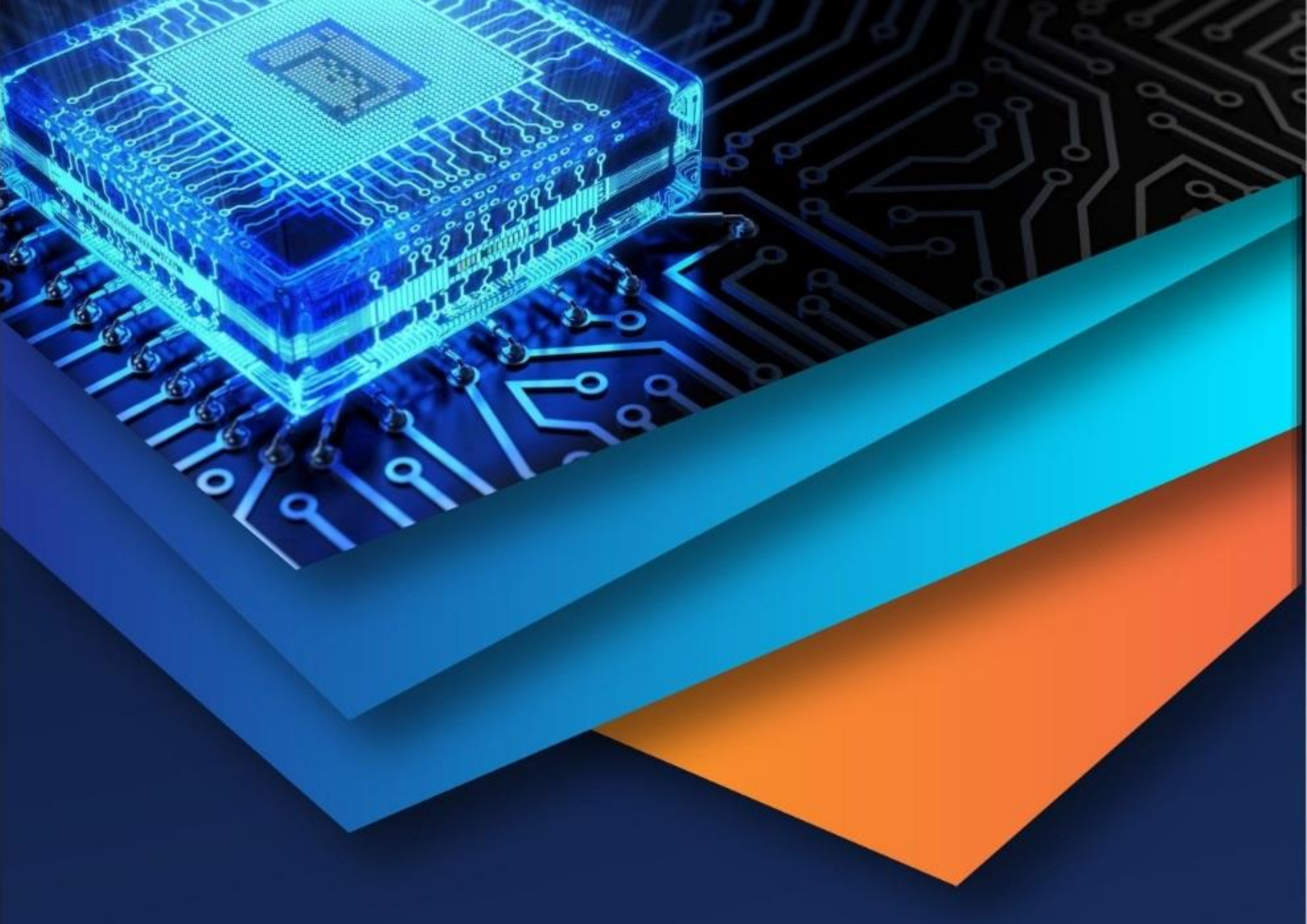

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