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# Optimizing an Intake System of a Single Cylinder 4-Stroke Engine by Acoustical Supercharging

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***Abstract: This paper focuses on optimizing the intake system of a formula student car engine which focuses on increasing the performance of the engine under certain set of rules. The paper gives a versatile methodology that can be used for any 4-stroke engine to optimize its performance. The paper discusses the research work that is used and also discusses the manufacturing details for the formula student teams. The air coming into the engine is considered as an acoustical wave and hence its resonance in the intake system and also how the resonance is used for forced induction is briefly discussed. Analysis of the same is done to show the actual results and can be used for comparison with that of the normal intake system. CFD analysis has been performed after number of design iterations.***
***Keywords: Restrictor, runner, plenum, intake manifold, acoustical supercharging, resonance, compression pressure, SAE supra, computational fluid dynamics.***

## I. INTRODUCTION

The paper is concerned to the formula student teams where they are required to modify the intake system of the engine according to the rule mentioned by the competition and thus the modification which is performance oriented has been discussed in the paper. Thus, the paper gives the detailed procedure that can be used for designing the intake system.

The intake system can be fundamentally be divided in three components that are the restrictor, the plenum and the runner. The implementation of the restrictor in the intake system is according to the rule stated by the formula student competition. The need for using the restrictor was to restrict the mass flow rate entering the engine which will ultimately limit the engines power output. In these competitions there are no rule for the selection of the engine. The only rule for the selection is that the engine should be below 600cc. This will be a clear advantage for the teams using bigger engines to win. Due to this the component restrictor is used in the intake system. The other two components are used for enhancing the performance.

The air entering in the engine through the intake system is considered as an acoustical wave and hence the calculations are done further. But the paper focuses on various approaches that are used while designing the intake system. Fluid as well as acoustics are the different approaches that we have used while designing the intake system.

## II. RESEARCH METHODOLOGY

The intake system is assumed to be resonance chamber for the incoming air charge. Thus, the designing is proceeded using two approach. The first approach is by assuming the air intake as acoustical waves. And the other approach being the fluid for getting an uninterrupted flow in the chamber.

### *A. Acoustical Approach*

The study of the acoustic vibrations in the manifold system and its effects in operation and output of the internal combustion engine begun as early as 1904 when Koester brought out the characteristics of wave motion in intake pipes. This approach is focused on the effects of the acoustical phenomenon and how it affects the length of the intake pipe and the diameter of the intake pipe and how these parameters allows us to obtain the supercharging effect in our 4-stroke internal combustion engine i.e. the length of the intake pipe at which the maximum compression pressure is obtained.

### *B. Theoretical Analysis*

Theoretically, to obtain maximum supercharge effect, the intake valve should close when the cylinder pressure is at a positive peak, and near the bottom dead centre. The momentum of the gas in the intake chamber will determine the magnitude of pressure. This momentum is the result of an impulse earlier in the intake stroke when the pressure in the cylinder is below atmospheric. Hence maximum momentum and maximum supercharge will result from maximum initial impulse. As the impulse is the product of force and time, thus maximum time is desirable.

Now the induction period in a four-stroke engine occupies approximately one-half a revolution of the crankshaft, thus the ratio of the natural frequency of the cylinder and pipe (which is the resonator) should be approximately twice the piston (or the crankshaft) frequency.

The air in the cylinder will oscillate for the period of the intake valve opening and when the valve closes pressure waves persist in the pipe. The pressure wave does not demolish but resonates in the intake manifold. Thus, the resonance causes the increase in the velocity of the air in the chamber and thus at the time when the valve opens, the air with increased velocity is pushed into the cylinder and thus we obtain a supercharged effect. The results can be cascading if the resonance of the air in the manifold does not ends up when the valve open. When the valve is just closing at pressures greater than atmospheric, then the waves will have a supercharging effect and will produce an increase in power. In order to obtain a good amount of supercharge, the momentum of the air in the intake pipe, and hence the velocity during the surge, must be large. At resonance the air builds up momentum rapidly enough so that it is being decelerated by the excess pressure in the cylinder when the valve is closing.

Maximum supercharging will then occur when the natural resonant frequency is approximately twice the piston frequency and at those engine speed maximum compression pressure is achieved.

Thus, Helmholtz resonator theory is used and the relation between the resonant speed of the engine and the pipe length is expressed as

$$N = 77c\left[\left(\frac{S}{LV}\right)\left(\frac{R-1}{R+1}\right)\right]^{\frac{1}{2}}$$

Where,

N = the engine speed in rpm where maximum effect is desired

C = velocity of the sound in the intake pipe in ft/sec

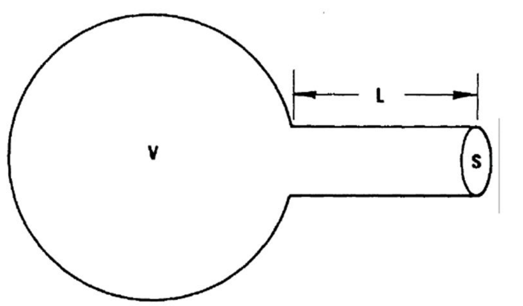
S = cross-sectional area of the intake pipe in sq. in

L = length of the pipe in inches

V = piston displacement in cu. In

R = compression ratio of the cylinder

Thus, using the data of the engine's specification we can calculate the length of the pipe.



Helmholtz resonator. $V$ = volume of the cavity; $L$ = length of neck, and $S$ = cross-sectional area of neck.

Now the volume of the cavity shown in the above figure it can be assumed as plenum. Plenum is situated after the restrictor and can be deduced as air storage unit in the intake manifold to complete the air requirement at sudden throttle. The resonance pipe can be done as the runner. Runner is the last part in the intake manifold.

Thus, by using the Helmholtz resonator theory we can calculate the runner's dimension and the plenums volume as well. Generally, the plenums volume should be kept at least 3 times the engines capacity if you are running our engine on stock tuning map that has been provided by the company.

Thus, the shape of the plenum can be considered by using the different constraints offered by the frame of the formula student car. In this paper, we have used a U-shaped double plane design to get maximum efficiency and to meet the rules mentioned by the competition.

*1)* Restrictor: As the design calculation of the intake manifold are completed, it is very necessary to get an optimized structure. The three components of the intake manifold that are restrictor, plenum and runner are designed to get the maximum supercharging effect. The restrictor that is selected is a venturi type convergent-divergent nozzle. The restrictor is a component which is used to limit the mass flow rate. The restrictor is designed to get an optimized amount of velocity at the outlet without having many fluid contours.

The restrictor of 20mm throat diameter is the rule stated by the competition. Thus, it was up to us that which type of restrictor we can use

### *C. Selection Procedure*

We have two options to restrict air flow using a 20mm diameter constriction and these are both a simple orifice and a converging diverging nozzle.

Following is difference between both:

| Parameters | Orifice | Nozzle |
|---|---|---|
| Coefficient of discharge | 0.60 | 0.975 |
| Pressure loss | Medium | Low |
| Viscosity effect | High | High |
| Accuracy (% of full scale) | 3 | 1 |
| Cost | Low | Medium |
| Manufacturing | Easy | Difficult |

Thus, for higher efficiency we select the restrictor of convergent-divergent nozzle type. For the inlet diameter we can get the constraint from the diameter of the throttle body. The mating in the manifold should be accurate so as to avoid the formation of any contours in the flow.

We can calculate the mass flow rate of the restrictor i.e. the mass flow rate at chocked condition.

Mass flow rate at throat of Restrictor:

M = A[(p0/(T0)$^{.5}$) *(¥/R)$^{.5}$ *(2/ (¥+1) $^{(¥+1)/2*(¥-1)}$)]

A = area of cross section of throat (Where Mach No. = 1)

p0 = 1.01325*10$^{2}$kPa,

T0 = 310K,

¥ =1.4,

R = .287 kJ/kg-k,

A = (pi/4) (20*10-3)2

M = 0.00227kg/s

Thus, the mass flow rate was found to be 0.0027kg/s.

This is obtained by the throat diameter and other conditions and thus the length of the restrictor is remaining.

For the length of the restrictor we performed CFD analysis to get an overview on how the flow happened. The final design was brought by number of flow analysis on the restrictor which yielded a convergent angle of 16.65$^{0}$ and divergent angle of 6.66$^{0}$. Analysis procedure has been discussed below.

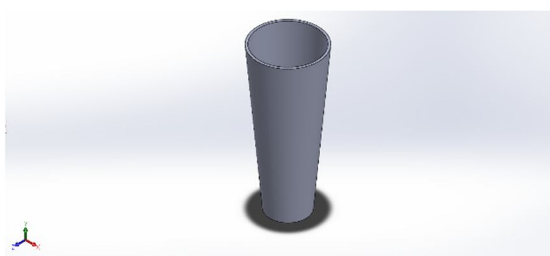
*1)* *Plenum:* This component is considered as storage of air for fulfilling the surges of air requirement at sudden throttle. Therefore, the volume of the plenum should be twice or thrice the volume of the engine. Due to which at the time of sudden air requirement, the engine does not lack the required volume of air needed. The design of the plenum is done by keeping in mind that the air coming inside the manifold is a fluid and according to the fundamentals of the fluid dynamics, any sudden change in the direction of flow or rigorous change in the cross-sectional area of the flow would results in reduced flow.

Points to keep in mind while designing the plenum

*a)* The volume of the plenum must be greater than the engine capacity.
*b)* The volume of the plenum must be at least 3 times the engine capacity if running the engine at stock settings.
*c)* The plenum must not contain any sharp bends which can hinder the flow of the air to the runner.
*d)* There must not be any sudden increase in the cross-sectional area in the flow to avoid the formation of contours which will retard the flow.
*e)* After designing the plenum, run some CFD analysis on the same to get the location of where the flow is maximum, because due to some bends and change in cross-sectional area there will be some formation of contours.
*f)* Thus, locating the region, we can get the mating region of the runner to the plenum.
*g)* It is not necessary that the opening for the runner will be a concentric hole at the end of the plenum. Mating the runner offset to the centre of the plenum can be done to get the maximum flow to the runner.

Following these procedures, one can design the plenum according to the requirement of the frame, structural soundness, rules and maximum efficiency. The design that we got after iterations for the 4-stroke engine of 390cc capacity.

*2)* *Runner:* The dimension of the runner can be calculated by the Helmholtz theory stated above. The diameter and the length of the runner pipe can be determined to attain the maximum compression pressure and thus attaining the acoustical supercharging effect.



Also, tapering the runner will increase the velocity at the end of the runner and thus increase the performance.
Cross-verification of the length of the runner can be done by using the David-vizards theory. David Vizard's rule tell to begin with a runner length of 17.8cm for a 10,000rpm peak torque location, from the intake opening to the plenum chamber. You add 4.3cm to the runner length for every 1000rpm that you want the peak torque to occur before the 10,000rpm.
After the cross-verification the length we found from the Helmholtz resonator theory and David vizards theory was quite near to each other.

*3)* *Fluid Approach:* While designing the manifold following points should be considered:
*a)* The incoming air is a fluid and thus the manifold be designed accordingly.
*b)* The manifold should not contain any sudden change in the direction as it can retard the flow.
*c)* There should not be any abrupt change in the area of cross-section of the fluid flow so as to avoid the formation fluid contours in the flow and to prevent the retardation of the fluid flow.
*d)* The restrictor is a competition implemented rule and needs to be optimized to get the maximum performance. The points stated above for the calculation of the restrictor can be used for designing.
*e)* While designing the manifold, special care should be taken for the mounting and it can change according to the frame.
*f)* While designing the manifold, use the above theory and perform number of iterations of the fluid analysis as it will give the actual results and loopholes for improvisation.

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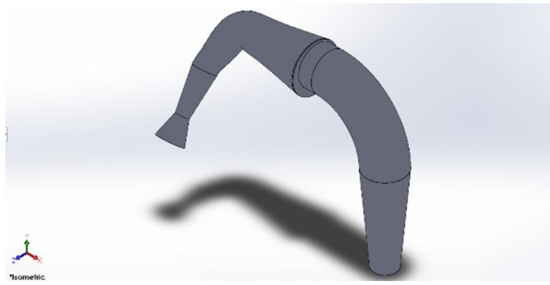
Thus, after designing all the components, assemble the components. Now the assembly should be according to the frame of the of the formula student car. There are several templates that the intake manifold must follow in order to clear the scrutineering.
The final assembly of our intake for the KTM 390 engine was a double plane U-shaped design.



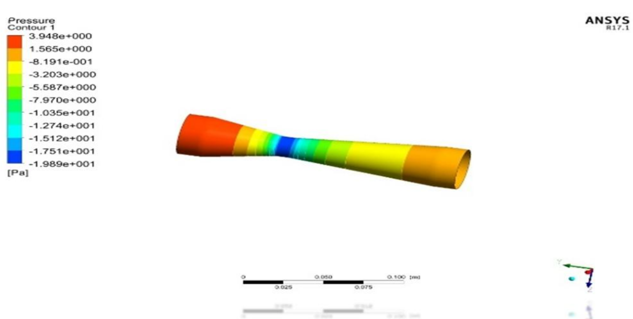
The manifold we designed was a double plane U-shaped. The double plane design was adopted for the compliance of the rules mentioned by the SAE supra formula student competition in India.
The double plane design also offered greater facility for the mounting of the intake with the frame.
The bent that is present between the plenum and the runner joins these two components and gives us the desired U-shaped design. The dimension was calculated so as to comply for the acoustical resonance. But the design of the runner that we adopted is optimized and thus the bent does not need any further calculation. Only calculation needed is to set the initial diameter of the runner as the final diameter will get the desired constraint from the throttle body assembly. The bent and the runner should consist the total length of acoustical resonance length that we obtained above. The initial diameter can be found by the analytical iterations which will tell the plenum average maximum flow diameter. Also, necessary condition that should be remembered is that the tapering should not be too much, as it can reduce the mass flow into the cylinder.
Thus, the first phase of the paper of discussing the design and its calculation has been done and the analysis of the same is mentioned below.

## III. ANALYSIS AND RESULTS

### *A. Methodology*

In order to ensure that we had made a quantifiable improvement in the flow behaviour of fluid, we began by identifying the key components in our design and optimizing each individually. Based on our assessment, we found four major components connecting the air filter and the engine in the following order:
We established the design parameters for each component and after assembling the initial prototype, used flow analysis to optimize the final system.

1) *Restrictor:* We had identified the inner diameter of the restrictor throat as fixed at 20mm and the length with longer diverging section and the other one with a bit narrower diverging section With this as our starting point, we began by analysing the optimum angles of convergence and divergence in case of the restrictor to minimize the loss in flow. We were working with an average inlet speed of 25m/s. We were also changing the converging and diverging angle of the restrictor and the final converging and diverging angle we got was about $16.65^0$ of convergence angle and $6.66^0$ of diverging angle. Based on our analysis, the optimum values of the inlet and outlet diameters were found to be 48mm and 40mm respectively.



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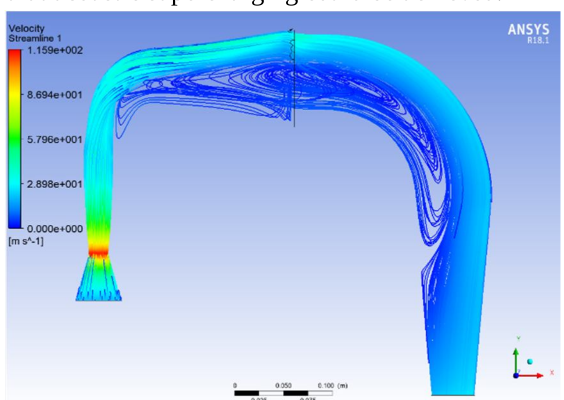
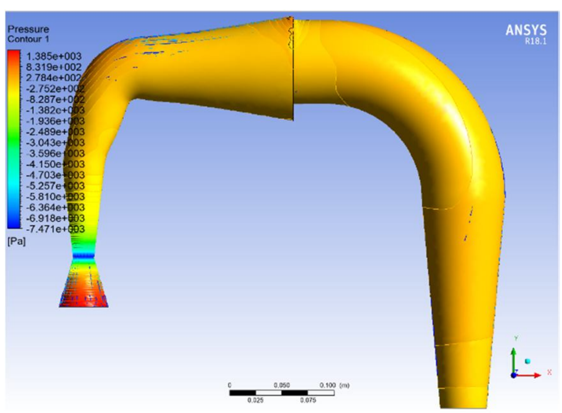
This is our final analysis that we performed on our final iteration of the restrictor.
Before this, we iterated the design of the restrictor by changing the dimension of the restrictor and observed the changes that took place after changing the given dimensions
First, we iterated a restrictor with a longer diverging section. The total length of the restrictor was about 180mm
Second, we decreased the length of the diverging section comparatively from the one mentioned above and keeping the converging sections length almost same. The total length of the restrictor was about 150mm

2) *Plenum:* We began by analysing the requirement of the engine per unit time for operation at the specified condition. Based on this as well as the space available, we decided to optimized for a volume 3 times the cylinder volume. By means of flow analysis on the initial prototype, we adjusted the position for the inlet and outlet orifice. With this we were able to significantly reduce the deterioration in flowlines of the fluid. This also allowed us to optimize the plenum further, resulting is reduction in its size.
3) *Bent:* With the area of the orifice being fixed based on the results from the plenum analysis, we had to design an optimum locus for the centres of the cross section from the inlet to the exhaust. We used geometrical considerations as well the subsequent flow behaviour to finalize the flow path of the liquid.
4) *Runner:* The runner was designed to be slightly converging to ensure that no sudden flow variation occurred as well as to capitalise on the flow resulting from the converging cross section. The length of the runner bent system was calculated are verified by many theories to ensure that acoustic supercharging could be achieved.




Velocity profile of the flow

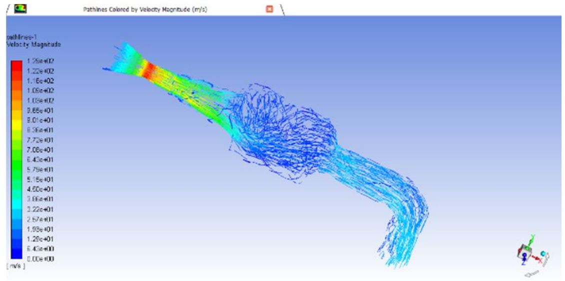
The image above shown is the velocity profile that is being created in the manifold. The inlet velocity of the air given was around 20m/s and at the end of the manifold it was around 28m/s. thus there is an increase in the velocity of the air and the fluid contours are optimized by the design so that it does not disturb the flow at the end.




Pressure profile of the flow

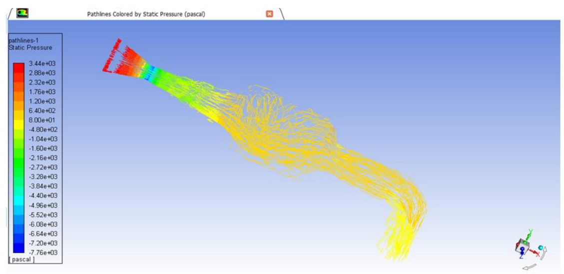
The pressure profile indicates that the flow does not disrupts the desired pressure profile nature of any ideal manifold. A uniform pressure distribution indicates a steady flow and thus while iterating the design through analysis, above mentioned pressure profile should be observed.

The design was compared to the previous year design. The previous year design was a manifold with its centreline being on a single plane. Some of the CFD analysis of the previous year design is shown below.



Velocity profile of the flow

The image shows the flow characteristics which tells us about the formation of complex fluid contours and thus the flow is retard and the velocity obtained at the end of the runner also contained some fluid contours



Pressure profile of the flow

The pressure as seen above shows some irregularities which gives a bit of uneven flow and thus this minor flaw was then optimized in the design.

Thus, this type of analysis iterations should be performed which gives corrective measures to the design and hence improves performance.

After the completion of the design, proper thickness was provided and the entire assembly was analysed to ensure that pressure did not exceed the material strength.

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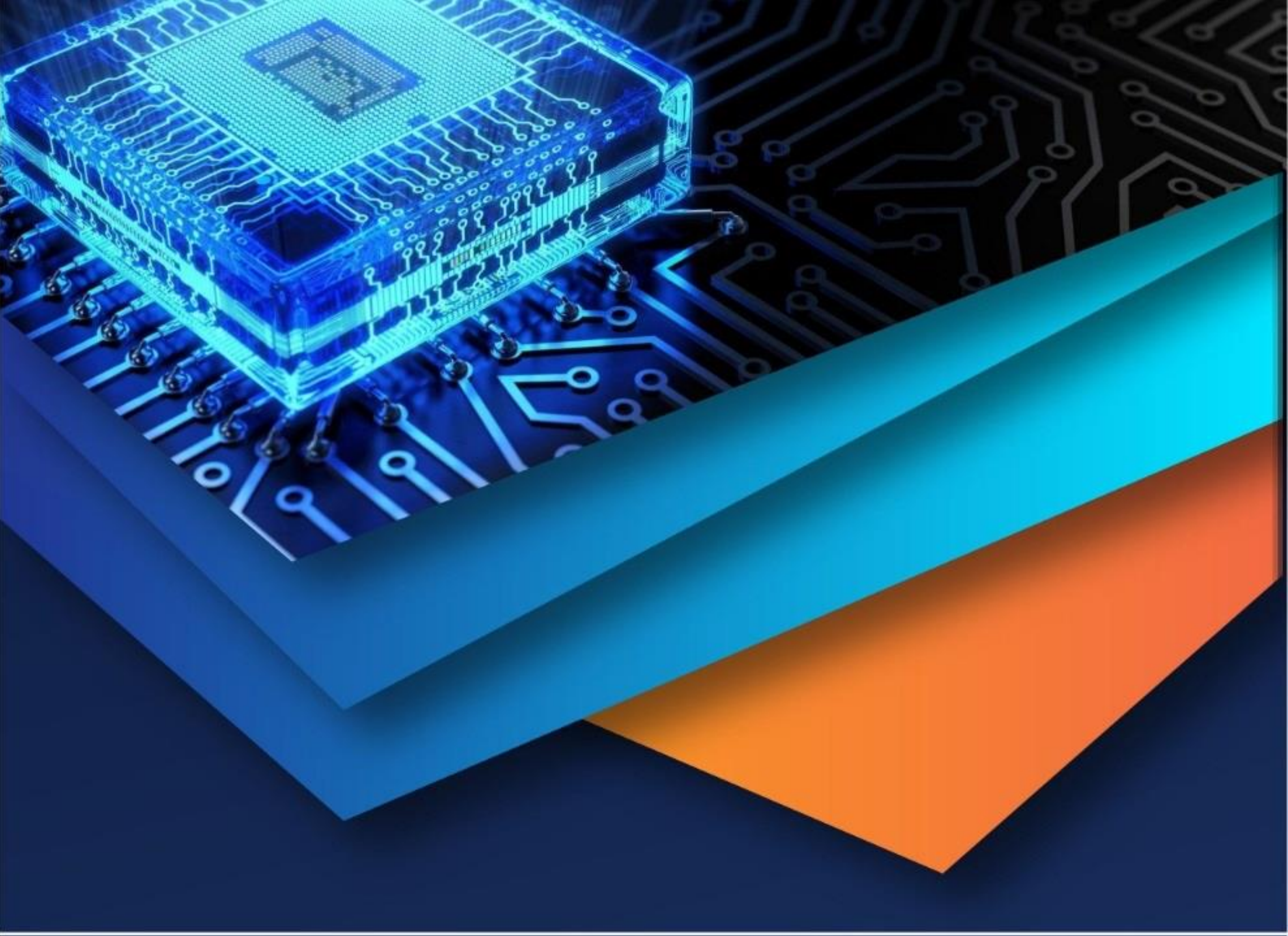

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