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# Analysis and Control of Combustion Instabilities in Rocket Engines

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***Abstract: Sound is the transmission of energy that is produced when two particles or objects undergo collision. It is one of the forms in which energy modulates and travels in a medium. Vibration is a phenomenon in which an object of mass executes a periodic oscillatory displacement when certain energy is transferred to it. Combustion is a chemical reaction in which a lot of molecules collide. Combustion instabilities occur in a reacting flow. It is a physical phenomenon. Combustion instabilities have mostly been studied in a particular flow but they also occur in real life. Real engines often feature specific unstable modes such as azimuthal instabilities in gas turbines or transverse modes in rocket chambers. Eddy simulation has been the major tool to study this type of instabilities so far but recently it has been proved to be insufficient to completely understand the complex nature of these instabilities [3]. These instabilities involve large Reynolds number, high pressure, densities in real engines. Combustion instabilities can occur at any part of the rocket propulsion system like nozzle, combustion chamber, injectors, feed systems and lines. Theory plays an important role in understanding and analysing these instabilities and the amount of damage they can cause to a particular object. In this paper we will look at different types or modes of combustion instabilities and active and passive ways to control them in real situations.***
***Keywords: Combustion instabilities, Modes, Amplitude, Flow rate, Chamber pressure***

## I. INTRODUCTION

Combustion is a chemical reaction in which molecular composition of reactants are broken off and products are formed. Chemical reaction breaks and makes a chemical composition of matter without altering atomic structure. Molecular collision therefore produces sound and vibration. Essentially sound by interacting with a medium (propellent and gases or flame tube wall) and vibration of control volume which is rocket and combustion system [2]. This phenomenon tends to interact with injection of liquid propellants into the combustion chamber triggering combustion associated instabilities. Combustion instabilities produces oscillatory behavior of pressure, temperate and velocity. Pressure oscillations of sufficient strength can cause sever oscillations in the combustion chamber leading to explosions/detonations. The subject of combustion instability has received much attention in the early 1900's but the solution to completely eliminate them is yet to be designed.

A physical interpretation was given by Rayleigh describing the interaction between unsteady heat release and sound waves for inviscid, linear perturbations

$$R = \int_{T} p'(t)q'(t)dt \qquad (1)$$

Where T is the period of oscillation, p I is the fluctuation in pressure, q I is the fluctuation in heat release rate and R is the Rayleigh's index. A positive Rayleigh's index is indicator of an amplification of the pressure oscillation due to the fluctuating heat release rate while a negative Rayleigh's index denotes a dampening of the oscillations.

This paper presents a preliminary effort to summarize previous effort and to provide conclusions to combustion instability. The ultimate goal is to understand combustion instabilities and analyse the methods to control them in rocket engines

## II. STANDING WAVES IN COMBUSTION CHAMBER

Combustion chamber of a rocket is in form of a cavity. Any disturbance created in a cavity in any local zone such as flame zone will travel throughout the entire cavity. Consider motion of a sinusoidal wave travelling along the axial length of cavity with a velocity 'a'. Wave travels a distance by time interval 't' to occupy new position. This also causes fluctuations which can be represented by an equation with the help of a graph.

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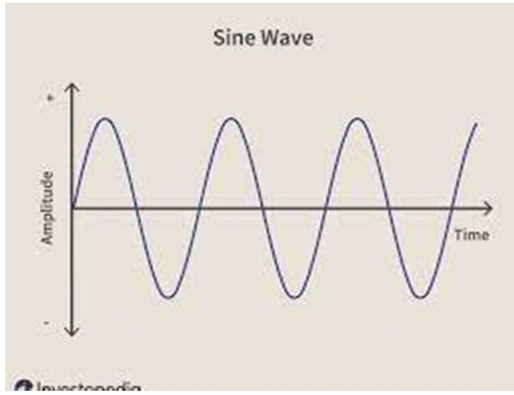


Fig 1: represents a sinusoidal wave in the form of a graph [1]

The pressure fluctuations in this wave after travelling and attaining a new position can be represented by

$$P' = A\, sin\, \frac{2\Pi}{\lambda}(x - at) \tag{2}$$

- A is maximum pressure amplitude and $\lambda$ is the wavelength of the wave
- For weak pressure waves such as sound waves the velocity is given by speed of sound

Wave gets reflected at the end of cavity causing changes in pressure

$$P' = -A\, sin\, \frac{2\Pi}{\lambda}(x - at) \tag{3}$$

The interaction between incident and resultant wave in the combustion cavity gives

$$P' = A\, sin\, \frac{2\Pi}{\lambda}(x - at)\ - A\, sin\, \frac{2\Pi}{\lambda}(x + at) \tag{4}$$

After introducing the constant 'K' the equation becomes

$$P' = -2A\, cos\, kx\, sin\omega t \tag{5}$$

- The above equation does not contain the travelling component
- At location where cos kx =0, the pressure perturbations are minimum
- At location where cos kx =0, the pressure perturbations are maximum
- The combustion chamber in in form of a cylinder with one end open(nozzle)
- The rapid acceleration causes the gas to reflect waves into the chamber causing interaction between incident and reflected waves which makes the rocket chamber ass good as with closed ends [4]
- The pressure perturbations are maximum at closed ends

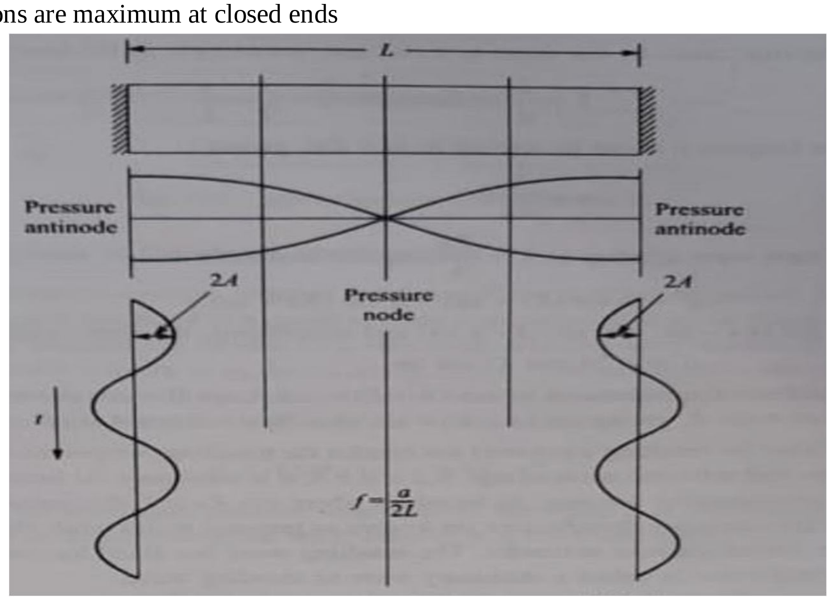


Fig 2: standing waves in fundamental mode

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## III. BULK MODE OF COMBUSTION INSTABILITY IN ROCKET ENGINE

Accumulation of propellants in chamber during combustion delay period is responsible for oscillations in the chamber.
The rate of mass accumulation in the chamber can be given by the equation

$$\frac{dm}{dt} = m_c \dot{-} \dot{m}_n \tag{6}$$

Where $\dot{m}_c$ is the gases in the combustion chamber and $\dot{m}_n$ are the gases leaving the nozzle
The rate of gases produced will be equal to the flow of propellant

$$\frac{dm}{dt} = c_d A_0 \sqrt{2\rho(P_{inj} - P_c)} - \frac{1}{c}(P_c A_t) \tag{7}$$

1) Due to reduced pressure in the chamber the rate of chemical reaction slows down, leading to increase the combustion delay time.
2) Usually healing rate of propellant surface is proportional to chamber pressure.
3) However due to thermal inertia of heated propellant at higher pressure the combustion pressure persists some time which generates mass corresponding to higher pressure (during characteristic thermal time) this lowers chamber pressure.
4) Reduced rate of chemical reaction reduces pressure resulting in lower values of gas flow rates which in turn increases resistance time.
5) Increased resistance time therefore enhances chemical reaction which tends to increase the heat release.
6) Combined effect of increased resistance and existing thermal resistance of propellant increases mass generation leading to rise in chamber pressure.
7) Increased pressure accelerates gas flow rate causing a smaller resistance time.
8) Combined effect of smaller resistance time and reduced thermal depth produces a lower rate of gases which in turn results in lower chamber pressure [8].
9) Lower chamber pressure lowers the flow rates out, increasing the resistance time again.
10) This is a cycle that goes on creating oscillation in the combustion chamber as bulk mode of combustion instability.

Equation 7 can be expressed in differential form in terms of amplitude of non-dimensional pressure perturbations and resistance time as

$$\frac{d\phi}{dt} + \frac{\phi}{t_{res}} = -\frac{\beta}{t_{res}}\phi(t - t_c) \tag{8}$$

## IV. EFFECT OF CHAMBER LENGTH ON INSTABILITY

If chamber length is small, resistance time is also small. If resistance time is small combustion may not reach completion. Further if resistance time is small, it may affect the degree of completion of combustion reaction and cause significant changes to the mass of gas leaving the combustion chamber.
If the resistance length is large a small change in Tc will not affect the degree of completion of reaction, so the masses leaving the combustion chamber will not be largely affected. Solid propellant rockets having small resistance time value are more prone to fluctuations and hence likely to exhibit bulk mode of instability. Bulk mode of instability is also referred to as $L^*$ instability. Lower chamber is most likely to cause $L^*$ instability. The most important parameter that affects bulk instability is chamber pressure.

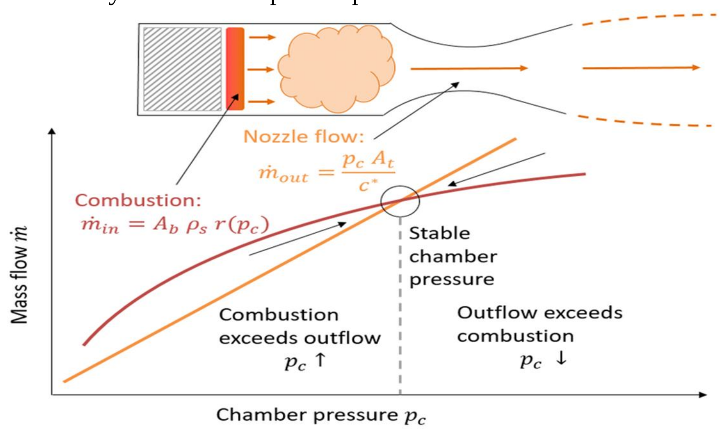


Fig 3: Graph between chamber pressure and mass flow of solid rocket motor [5]

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## V. WAVE MODE OF COMBUSTION INSTABILITY

When wave length of oscillation is smaller than the characteristic dimension of chamber, wave propagates in chamber with higher frequencies of oscillations. Hence it becomes necessary to consider variations of perturbations at different locations of chamber. The pressure variations therefore are function of both

1) Spatial coordinates
2) Time

While in bulk mode of instability the pressure oscillations are only a function of time. The burning process in the combustion chamber results in development of different amplitudes of pressure at different locations that leads to development of large amplitude waves. Such type f waves and its growth characteristics is called as wave mode of combustion instability. The motion of wave thus formed in the chamber results in formation of standing waves. Wave equation describes perturbations in a limit of small amplitudes and small values of mass flow velocity in the chamber. The flow is considered to be homentropic flow. Homentropic assumption gives

$$\frac{D}{Dt}(S) = 0 \quad (9)$$

a) For small amplitude of pressure oscillation and negligible mean velocity, the wave equation can be written as

$$\frac{\partial^2 p'}{\partial t^2} = a^2 \triangle^2 p' \quad (10)$$

b) The solution to the above wave equation in form of Bessel function is

$$P' = A\cos\left(\frac{n\pi x}{L}\right)\cos(m\theta)\left[BJ_m\left(\frac{\beta_{m,j} r}{R}\right) + CY_m\left(\frac{\beta_{m,j} r}{R}\right)\right]\sin(\omega t)$$

(11)

$J_m$ : Bessel function of first kind
$Y_m$: Bessel function of second kind
A, B, C: constants
n: mode of oscillations along x (longitudinal) direction
m: mode of oscillations along x (tangential) direction
: mode of oscillations along x (longitudinal) directional

c) Values of $\beta_{m,j}$ are determined for different tangential modes and radial modes of standing waves using values of standard Bessel function.

| | $l = 1$ | $l = 2$ | $l = 3$ | $l = 4$ |
|---|---|---|---|---|
| $m = 0$ | 0 | 3.832(1st radial) | 7.016(2nd radial) | 10.173(3rd radial |
| $m = 1$ | 1.841 (1st tangential) | 5.331 (combined 1st tangential and 1st radial) | 8.526 (combined 1st tangential and 2nd radial) | 11.706 (combined 1st tangential and 3rd radial) |
| $m = 2$ | 3.054 (2nd tangential) | 6.707 (combined 2nd tangential and 1st radial) | 9.970 (combined 2nd tangential and 2nd radial) | 13.170 (combined 2nd tangential and 3rd radial) |
| $m = 3$ | 4.200 (3rd tangential) | 8.014 (combined 3rd tangential and 1st radial) | 11.348 (combined 3rd tangential and 2nd radial) | 14.586 (combined 3rd tangential and 3rd radial) |

Fig 4: non dimensional frequencies of standing waves in different modes.

d) For m = 0, L = 1,2,3: - It is radial modes
e) For m = 1, L = 1: - It is tangential mode
f) For m = 2, L = 1: - It is second tangential mode
g) For m = 2, L = 2: - It is third tangential mode
h) For m = 1, L = 2: - It is combined first tangential and radial mode

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## VI. CONTROL OF COMBUSTION INSTABILITIES

Combustion instabilities arise due to the coupling between the heat release rate perturbations and the acoustic disturbances within the combustion chamber. Although linear models may be accurate at low perturbation levels, the dynamics of real unstable combustors become dominated by nonlinear mechanisms once amplitudes grow sufficiently. In many combustors, including gas turbine and aeroengine combustors, it is notable that even during large amplitude oscillations the behaviour of the acoustic waves remains linear. These instabilities are nearly always undesirable as they cause large oscillation amplitudes and damaging structural vibrations of the combustion chamber. The stability of a combustion chamber is determined by the balance between the energy gained from the flame/acoustic interactions and various dissipation processes. Control of combustion instabilities can be achieved through both active and passive means. Passive control techniques are most typically found on hardware currently operational, and include such techniques as resonators, pilot fuel, and fuel staging. Active control isn't typically found in industrial hardware, but it's noteworthy that the sole field utilization of active control on an outsized frame engine was applied to a transverse instability [6]. Active feedback control can be used to interrupt the coupling between the acoustic waves and unsteady heat release and prevent or suppress instability. Passive control techniques, including Helmholtz resonators, quarter-wave tubes, and perforated plates, are wont to damp acoustic oscillations by both resistive and reactive processes. Perforated plates damp acoustic oscillations by transferring fluctuating acoustic energy into vortical motion at the sides of the plate's holes. Typical combustor liner configurations contain many perforations to permit cooling air to enter the combustor, and also act to damp acoustic oscillations. Helmholtz resonators and quarter-wave tubes are dominantly reactive devices, although the large amplitude oscillations at the resonator outlet generally also lead to an amplitude dependent resistive acoustic damping as well. Commercial combustor with quarter wave tubes in the combustor plenum used for damping transverse oscillations. Damper tubes of either type are used widely across the industry and have been used on rocket engines as well.

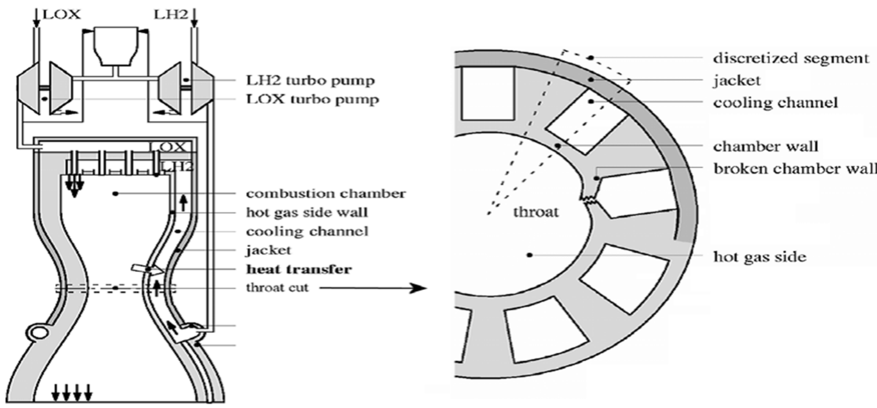


Fig 5: Regeneratively cooled rocket engine

Design and placement of such resonant devices is critical for their effectiveness. Stow and Dowling showed that the required number of resonators must be at least one greater than the highest azimuthal acoustic mode number in order to effectively damp azimuthal oscillations. While a range of resonator locations effectively damped the oscillations, the resonator efficacy is sensitive to the resonator volume [9]. Two circumferential baffles located above and below the middle burner, known as "heat shields". In addition to their other functions, these shields serve as baffles for high frequency radial modes. These baffles have an analogous function to their usage for transverse rocket instabilities. Radially-aligned baffles were examined by Dawson and Worth, who showed that the addition of one or two baffles had little influence on oscillation amplitudes, but forced the acoustic mode to a standing-wave pattern, and eliminated traveling waves and some of the more random switching in wave patterns.

Asymmetric burner outlets (ABO) can also be used to change the axial development of large-scale vortices. Symmetry breaking with various levels of asymmetry in location of CBO's and ABOs can be used. Finally, active control techniques are tested for the control of azimuthal modes. These techniques employ external excitation, either acoustic forcing or pulsing of fuel or air delivery to the combustor, to damp the self-excited mode. These actuators can stabilize the system by pulsing either at the forcing frequency with a phase-shift, or far away from the forcing frequency.

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## VII. CONCLUSIONS

Combustion instability results from complex dynamic interactions between acoustics, heat-release, and vortex dynamics.

Combustion instability in rocket engines plays a significant part in effectiveness and efficiency of the rocket. If left undealt this can cause severe damage to the engine. Instability causes oscillations in the combustion chamber which multiply in different types. Variation in chamber pressure is the main factor for these instabilities and unstable flow properties make the pressure decrease or increase rapidly. Traditional approaches to controlling instability in combustion turbines have focused on passive mechanisms—no feedback control. Active instability control (AIC) method uses external acoustic excitation by a loudspeaker to suppress the oscillations of a flame. Passive control is found on hardware currently operational which uses resonators, fuel staging. Advances in combustion control are essential for developing engines for propulsion and power generation with high efficiency, increased performance, and low emissions. Lean-burning combustors are needed to meet stringent low-emission requirements and other design criteria, but such combustors are prone to instability.

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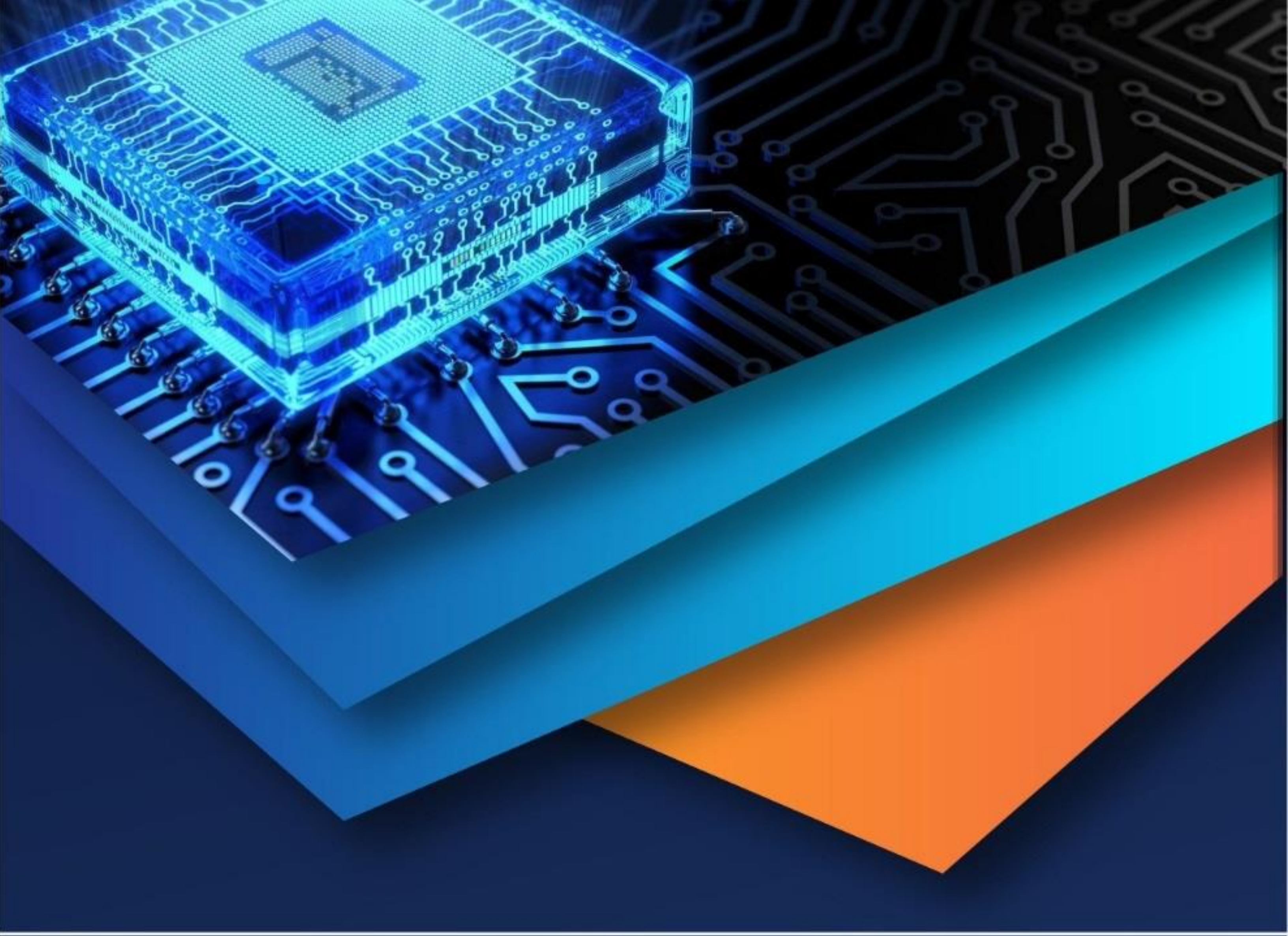


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