

Design and Analysis of Rocket Motor Casing by Using Fem Technique

Siva Sankara Raju R, Karun Kumar Y, Pragathi Kumar G

ABSTRACT- This paper deals with the design of solid rocket mainly consists of determining the thickness of motor casing which includes the domes at head end, nozzle end and flange for bolted joints. Modeling of solid rocket motor components and its assembly is done in CATIAV5R19. Stress distributions are due to the effect of working stress developed in the components. The maximum working stress is compared with allowable yield stress of the material. Final conclusion brings out a well designed solid rocket motor for the effective storage of propellant for obtaining the required impulse. 2D Axi -Symmetric structural analysis for solid propellant rocket motor Casing is performed to determine the stress level of all components using ANSYS 12.0..

Keywords - Design, Analysis, Rocket Thrust Motor.

I. INTRODUCTION

A Rocket is a vehicle which obtains thrust by the reaction of the rocket to the ejection of jet of fast moving fluid exhaust from rocket engine. Solid propellant rockets creates their exhaust by the combustion of solid propellant grain. The resulting gases are expanded through the nozzle whose function is to convert this internal pressure in to a supersonic exhaust velocity.

As rule of [1] ASME Pressure vessel code section VIII division 2, such a rocket motor has the following five major components.

The typical solid rocket motor case [2], the first component, is basically a double-domed right circular cylinder with opening at both ends and cylindrical extensions called skirts. The solid rocket motor case is essentially a minimum-weight pressure vessel whose design is complicated by the pressure of significant levels of thrust and bending and locally concentrated loads from the skirts and attachments. Tactical motors typically operate from 3 to 25 MPa.

The general shape of the nozzle [3], the fourth component, includes three major parts: the convergent zone, which channels the gas flow; the throat, whose dimension determine the operating pressure of the rocket motor; and the exit cone, which increases the exhaust velocity of the gases in their expansion phase, consequently improving the propulsive effect. In tactical systems [4], the nozzle is sometimes placed at the end of the tube, called blast tube, in order to provide space for different devices such as those that activate the steering controls of the missile.

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* Correspondence Author (s)

Siva Sankara Raju, Department of Mechanical Engineering, working as assistant professor at GIET, Odisha, INDIA.

Karun Kumar Y Department of Mechanical Engineering, working as Assistant Professor in GIET, Gunupur, Odisha, INDIA.

Pragathi Kumar G Department of Mechanical Engineering, GIET, Odisha, INDIA

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The propellant grain [5] is the next component. Grains are made of solid propellant shaped according to a given geometry during manufacture. To prevent combustion, their surface may be locally restricted or may be inhibited with a flame resistant adhesive material, an inhibitor. The regression of the free propellant surface, once it has begun to burn, normal to this surface and dictates the evolution of the pressure and thrust.

The thermal insulation [6] is the next component. The motor case interior is converged with an insulator which provides thermal protection and flow erosion resistance to gases whose temperature ranges from 1500 K to more than 3500 K, in regions where propellant burns to the wall before the entire grain is consumed.

The last component, the igniter system [7], brings the energy necessary to the surface of the propellant to start burning. There are two basic types in igniters i) pyrotechnic igniters and ii) progeny igniters. In industrial practice, pyrotechnic igniters are defined as igniters using solid explosives or energetic propellant like chemical formulations as heat producing materials.

II. LITERATURE REVIEW

ASME [1] Pressure vessel code section VIII division 2 gives the equations for the calculation of shell and dome thickness.

Alexander flake [5] developed equation for the calculation of minimum required area of the bolt and the thickness of flange. This approach is called as Schneider approach.

NASA SP-8025 [6] has given the details about the material properties for the various solid rocket motors. Based upon these material properties the material is selected for the solid rocket motor to withstand the pressures that are going to act on the motor casing.

NASA [7] has given the details of the solid rocket motor preliminary design review and structural analysis of the solid rocket motor factory joint including metallic and non-metallic components. A structural analysis is performed to verify the structural integrity of the solid rocket motor at certain working temperature.

NASA [8] has given the solid propellant performance prediction and analysis. Based upon this the performance of the solid propellant rocket motor the design is done by considering the loads that are going to act on the solid rocket motor casing. The effectiveness of this process is predicted and assessed by evaluating the reaction thrust developed through the pressure-imparted momentum of the expanded exhaust gases. Mathematical modeling used to simulate solid rocket combustion-chamber internal flow fields is reasonably good for steady-state and transient flow prediction.

David Heckman [9] in 1988 has explored that the finite element analysis is an extremely powdery tool when used correctly.

For pressure vessels finite element analysis provides an additional tool for use in analysis. However, it must be compared to other available data, not taken as being correct just because it looks right.

III. EXPERIMENTAL DETAILS

I. Requirements for Rocket Motor Design

The main required parameters that are considered for the design of solid rocket motor are

- Total impulse
- Duration of flight and
- Outer diameter of the motor

Based on the above required parameters the design of solid propellant rocket motor is classified [17] in two ways given below

- Internal ballistic design and
- Rocket motor hardware design

Internal ballistic design mainly consists of designing of propellant of propellant and nozzle contour which includes the exit diameter of nozzle and throat diameter of nozzle.

ASME Pressure vessel code section VIII division 2 (1) given the formula for the calculation of shell and dome thickness and is given below

Thickness of the shell is given by

$$T = \frac{P \cdot D \cdot \text{Mismatch Factor}}{\text{biaxial gain} \cdot 2 \cdot (SE - 0.6P)} \text{ ----- (1)}$$

Table 1: Materials used in solid rocket motors (metallic) and their properties

Material properties	15C DV6	Modified 15CD V6	Maraging steel (M250)	Cobalt-free MS	3Ni-Cr-2Si
UTS(MPa)	980	1600	1765	1765	1950
0.2% Yield strength	835	1470	1725	1725	1650
Elongation (%)	10	8	5	5	11
Fracture toughness	100-120	90-100	90	90	80-90
Weld efficiency (%)	12.8	21.7	23.1	23.1	25.5

IV. PROBLEM DESCRIPTION

The rocket motor is mainly designed to obtain a particular thrust which mainly depends on exhaust product mass flow rate, exit exhaust velocity, exit exhaust pressure, ambient pressure and nozzle exit area. Out of which the thrust mainly depends on the propellant and motor characteristics. Propellant [10] and motor characteristics may include burning rate, density, burning surface area and gas temperature and various geometric characteristics of the nozzle. The burning of propellant gives structural (pressure) and thermal loads (temperature). The liner has designed for thermal loads produced due to the burning of propellant.

The paper aims to the design of rocket motor casing based on the volume of the propellant it has to store and to withstand the combustion chamber pressure neglecting the thermal loads produced due to the burning of propellant inside the casing.

The design of solid rocket motor mainly consists of determination of the thickness of motor casing which includes the domes at head end, nozzle end and flange for the bolted joints.

V. MATERIAL PROPERTIES

High strength 15CDV6 steel material is chosen [8] NASA SP-8025 for motor casing and nozzle due to its availability and well established fabrication procedure. The specification of the material is (table 2) given below.

Table 2: material properties

Property	(Tangential) Along the grain	(Transverse) Across the grain
Tensile Strength (MPa)	1080 (min.)	1020 (min.)
Yield Strength (MPa)	930 (min.)	850 (min.)
% elongation (on 50mm min.)	10	10
Hardness	290-360	290-360
Impact toughness (J) 2mm charpy 'U' notch	60(min.)	60(min.)

VI. GENERAL METHODOLOGY FOR THE DESIGN

In the present paper the following steps is followed to design the solid rocket motor hardware components.

Step 1: Determination of the thickness of the casing shell.
Step 2: Determination of the thickness of the domes at head end and nozzle end.

Step 3: Determination of the thickness of the flange for the bolted joints.

Step 4: Determination of torque required for tightening the bolts.

VII. ROCKET MOTOR SYSTEM DESIGN

The motor casing is designed as per ASME pressure vessel code. Flange design at head end and nozzle end are designed using Schneider's approach. Flange thickness is calculated using flat plate closure formula as per ASME pressure vessel code [1]. Tori-spherical dome configuration is selected of easy fabrication for head end and nozzle end domes and thickness is calculated using ASME pressure vessel code.

DESIGN OF MOTOR CASE

Motor case is made of three ring forgings with welded joints the motor case thickness is calculated using conventional formula from ASME Pressure vessel code [1]. For this case of cylindrical shell, the thickness is calculated using formula UG-27(c) (1). The weld configuration of the motor shell consists of thread joint welded in/out outside of the shell with butt joint. The weld efficiency is selected as 90%.

Min. thickness of the shell,

$$T = \frac{P \cdot D \cdot \text{Mismatch Factor}}{\text{biaxial gain} \cdot 2 \cdot (SE - 0.6P)} = 4.77 \text{ mm ----- (2)}$$

DESIGN OF HEAD END DOME

Tori-spherical type is considered for head dome [19] for easy fabrication. The design is carried out as per ASME Pressure vessel code [1] and Design of mechanical joints by Alexander Blake [1]. The OD of motor is 1000 mm and opening diameter at head end is 190 mm.



The minimum thickness of dome is calculated using the formula,

$$T = \frac{P \cdot L \cdot M}{2.0 \cdot (SE - 0.1P)} = 5.67 \text{mm} \text{ ----- (3)}$$

DESIGN OF NOZZLE END FLANGE

Flange design is carried out using Schneider’s approach [4, 5]. The PCD of the bolts is 680 mm. The no. of bolts and size of bolt are initially selected as 48 and M 16 X 2.0. The minimum area of bolt is calculated using the formula
The minimum area required/bolt is calculated using the formula:

$$A = \frac{P R_m^2 (1.0 + l/b_{max})}{2.0 \cdot \sigma_{bolt} \cdot N (R_m + l)} = 119.54 \text{ mm}^2 \text{ ----- (4)}$$

Flange thickness:

$$T = 1.1 R_m \left[\frac{3.0 \cdot P \cdot l}{\sigma_f (1 - N \cdot d) (R_m + l)} \right]^{0.5} = 16.43 \text{ mm. ---- (5)}$$

DESIGN OF HEAD END IGNITER FLANGE

The minimum area required/bolt is calculated using the formula:

$$A = \frac{P R_m^2 (1.0 + l/b_{max})}{2.0 \cdot \sigma_{max} \cdot N (R_m + l)} = 58 \text{ mm}^2. \text{ ----- (6)}$$

VIII. MODELING OF SOLID ROCKET MOTOR

Motor casing as shown in the fig1 is basically a double-domed right circular cylinder with openings at both ends and cylindrical extensions called skirts. The aft opening interfaces with the nozzle, and the forward opening accommodates the safe and arm device as well as the igniter.

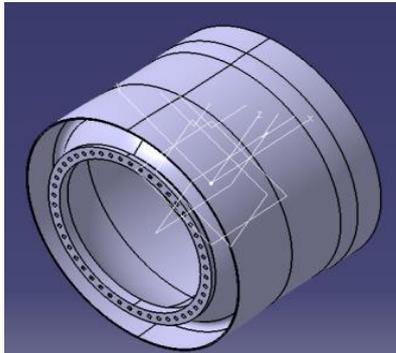


Fig.1: Motor Casing

Intermediate dome as shown in fig 2 is the metal component which is used to connect the nozzle assembly to the casing with bolted joints. The main use of this component is to reduce the load on the casing due to the expansion of gases in the nozzle assembly.

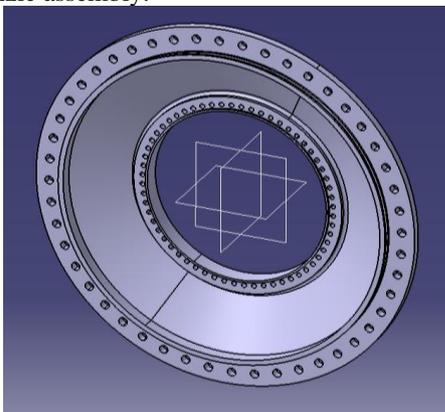


Fig.2: Intermediate Dome

Igniter closure plate as shown in the fig 3 is used to accommodate the igniter which is used to ignite the solid propellant to burn inside the motor casing.

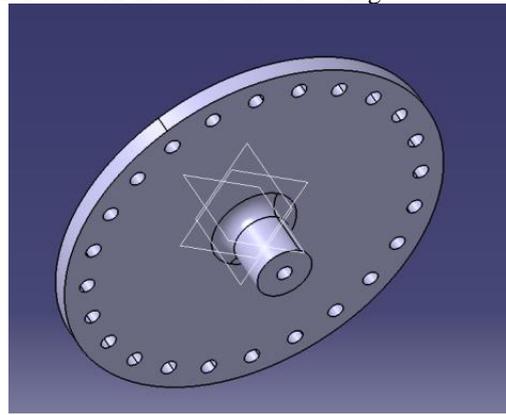


Fig.3: Igniter Closure Plate

A part from present thesis the modeling of other parts required for the solid rocket motor assembly is modeled as per the user industry specifications and requirements for the weight calculation purpose.

The liners shown in the fig 4 and 5 are composite materials mainly used to absorb the temperature up to a range of 20000c produced by the burning of propellant [14]; the main use of these liners is to absorb the heat without transferring to the casing materials.

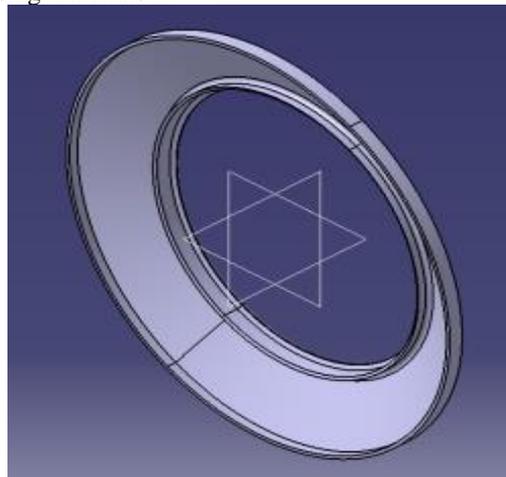


Fig. 4Intermediate Dome Liner

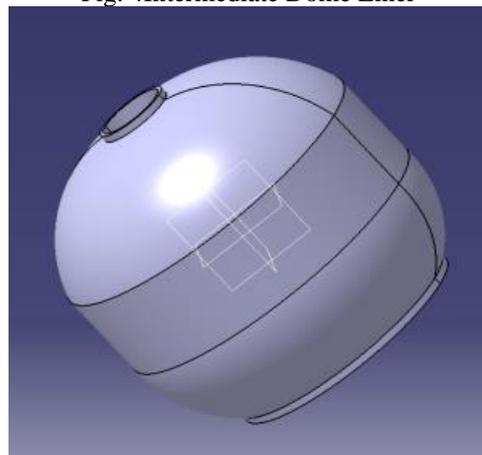


Fig 5 Casing Liner

Flex seal assembly [16] as shown in the fig 6 consists of 7 shims, rubbers bonded in between a fit end ring and fore end ring. The main use of flex seal assembly is to the load transfer between the motor casing and the nozzle assembly by absorbing the loads that are produced in the nozzle assembly while expansion of gases and also the loads that are produced in the casing.

Nozzle assembly [8] as shown in the fig 7 includes three major parts: the convergent zone, which channels the gas flow, the throat, whose dimensions determine the

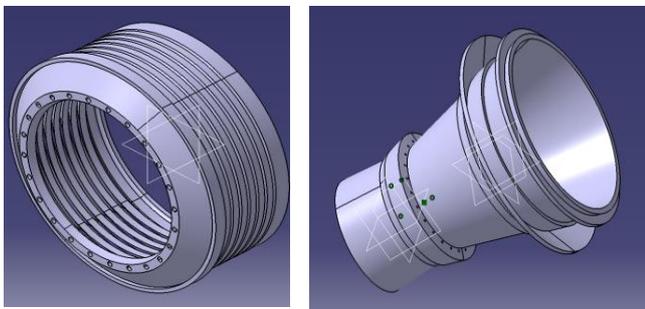


Fig.6: Flex seal assembly Fig.7: Nozzle assembly

Operating pressure of the rocket motor and the exit cone, which increases the exhaust velocity of the gases in their expansion phase which consequently improving the propulsive effect.

Rocket motor assembly as shown in the fig 9 consists of Casing assembly, Intermediate dome, Flex seal assembly, Nozzle assembly and Igniter assembly. Solid propellant rocket motor creates the exhaust by the combustion of solid propellant [12, 13] grain. The resulting gases are expanded through the nozzle whose function is to convert this internal pressure into a supersonic exhaust velocity.

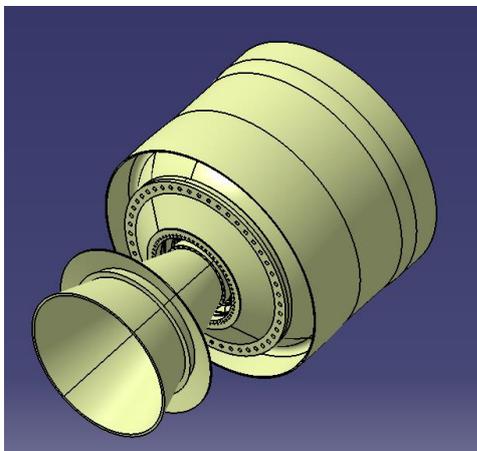


Fig.9: Rocket Motor Assembly

IX. RESULTS AND DISCUSSIONS

A. FINITE ELEMENT ANALYSIS OF ROCKET MOTOR CASING

Axi-symmetric Finite Element model of solid rocket motor is prepared by using 8 noded Axi-symmetric element, (plane82) [15]. Stress analysis of model is carried out for internal pressure of 65 Bar. To predict factor of safety of motor before firing, [11] Thermal and pressure load analysis is required. The present project covers the pressure load analysis with the original dimensions of motor.

The equivalent area of pre-pressure of 648 MPa (60% of yield strength steel bolt, 12.9 classes,). Flange joint is

modeled by arresting relative nodal displacement in appropriate direction. Analysis had been carried out for maximum operating internal pressure of 65 bar.

B. Loads and Boundary Conditions

The analysis [9, 18] has been carried out with a pressure load of 65 bar (6.5 MPa) and pre-tension of 648 MPa applied to the bolts.

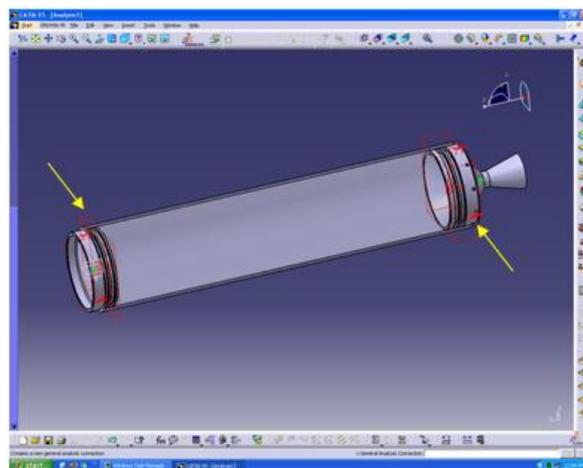


Fig 11: Clamp and Connection at Both Ends

For casing 'O' ring: The uniform temperature is taken as 1 °C and the temperature that is obtained [17] in order to obtain the desired pre-tension values are

$$t = -33.1354 \text{ } ^\circ\text{C for M10 bolt}$$

$$t = -32.7145 \text{ } ^\circ\text{C for M16 bolt}$$



Fig12: Applying Loads and Displacements

The maximum stress is observed to be 621.459 MPa, which is well below the yield values of 15CDV6 material (648 MPa). In the shell region, it is observed to be 552.768, which again is Shell below the yield value of 15CDV6 material (648 MPa).

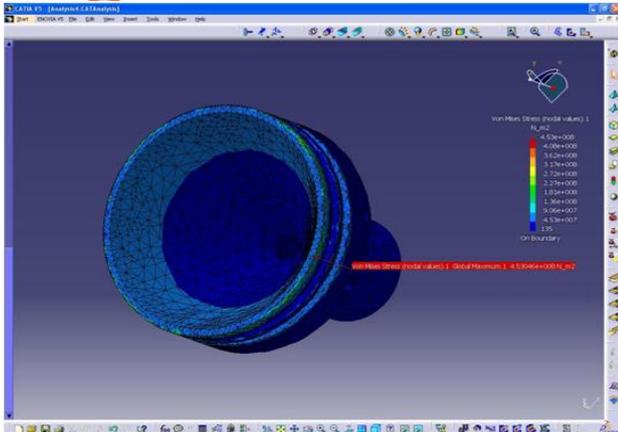


Fig 15: Critical Area of Highest Vonmises Stress for Nozzle

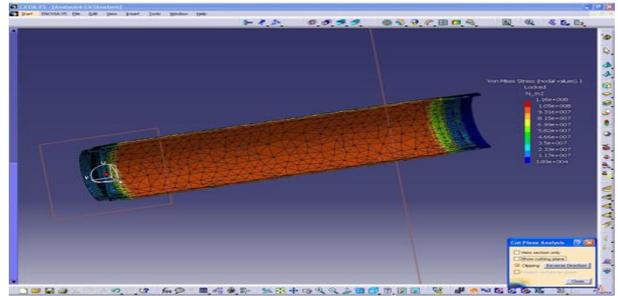


Fig16: Vonmises stress across the casting tube

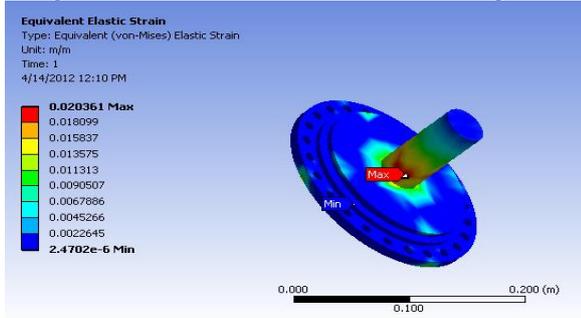


Fig 17: Equivalent Stress across the ignite plate

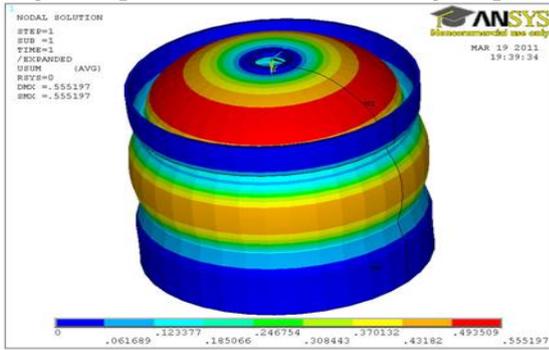


Fig 19: Total Displacement acting on the object

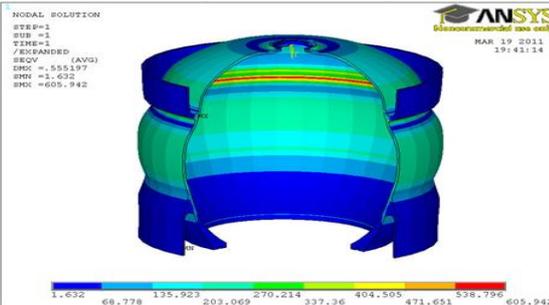


Fig.20 Von Mises Stress Of the Nodes

CONCLUSION

In the present study the Solid rocket motor design is carried out as per ASME pressure vessel code for MEOP of

6.5 MPa and for the pre stress value of 648 MPa for the bolt. The flange design is carried out following the Schneider's approach. The values calculated in the present study are listed below

- The thickness calculated for the different regions are the thickness of the shell is 4.8 mm, head end dome is 5.8 mm, nozzle end dome is 7.0 mm, nozzle end flange is 17.0 mm and igniter flange is 12.0 mm. The 'O' ring groove are configured by considering 25% squeeze of 'O' ring diameter.
- The values of Von misses stress are determined by conducting the finite element analysis for the calculated thickness. The maximum stress is observed to be 621.549 MPa. In the rest of the region stress is observed to be in between 605.942 MPa which is well below 648 MPa (yield stress value of 15CDV6 material). So the thickness calculated for the motor casing and the flanges are safe for the desired pressure load and pre-tension of the bolts.
- The expansion of 'O' ring groove dilation at all the locations ranges from 19.885 to 25% which is greater than 15%. So the depth and width of the 'O' rings designed are safe for the desired internal pressure load.
- The performance of 'O-ring can be describe in table 3. The expansion of 'O' ring grooves at all the locations from 19.88% to 25% which is greater than 15%.

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Siva Sankara Raju R Department of Mechanical Engineering, working as assistant professor at GIET, Odisha, INDIA. Having teaching experience 2.8yr, core experience 3.5yr. Exposed area of interest in CAD/CAM, Rapid prototyping and Aluminum metal matrix. Journal publication on international: 1, National: 4. Membership in ISTE.



Karun Kumar Y Department of Mechanical Engineering, working as Assistant Professor in GIET, Gunupur, Odisha, INDIA. Having teaching experience 5.2 yr, core experience 3 yr. Research proposed in Industrial Engineering, Six Sigma, and Optimization Techniques. Journal publication on international: 1, National: 2. Membership in ISTE.



Pragathi Kumar G Department of Mechanical Engineering, GIET, Odisha, INDIA .having teaching experience 10.5 yr, core experience 5 yr. Department of Mechanical Engineering, working as Associate Professor in GIET, Gunupur Odisha, INDIA. Research proposed in CAD/CAM, Machine Design, and Finite Element Method.