DESIGN OF A 4M CLASS LOW-COST RADIO TELESCOPE

M.Sc. Thesis

By

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DEPARTMENT OF ASTRONOMY

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A THESIS

Submitted in partial fulfillment of the
requirements for the award of the degree
of
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by

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **Design of a 4m Class Low-Cost Radio Telescope** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF SCIENCE** and submitted in the **DEPARTMENT OF ASTRONOMY, ASTROPHYSICS AND SPACE ENGINEERING, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from **July 2023** to **May 2025** under the supervision of **Dr. Narendra Nath Patra, Asst. Professor, Dept. of Astronomy, Astrophysics & Space Engineering.**

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

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14.05.2025

Signature of the student with date
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This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

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DEDICATION

Dedicated to Mother India

Abstract

The development of a low-cost radio telescope is essential for a large-scale radio interferometry for higher resolution, where a huge number of affordable radio telescopes are required. This thesis presents a detailed process for designing a 4-m class radio telescope with an estimated cost of 4 lakhs INR per unit, with limited resources, manpower and manufacturing accessibility. This project is aimed for facilitating the construction of large array interferometer at a scale 100 numbers of antenna for scientific research and to provide access low-cost telescope for schools and colleges.

The design process begins with the creation of a parabolic dish, with a 4-meter diameter and 0.435 f/D ratio. Dimensions and parameters were referenced from other radio telescopes (GMRT, NCRA Pune & IIRI Indore). The dish's weight and inertia were calculated using CAD and then required torque, gear ratio & friction correction were calculated analytically. Subsequently a study of a supporting base truss was conducted using FEA to ensure structural integrity and safety of the design. The analysis confirmed that the structure will withstand the load and avoid catastrophic failure.

Future work involves developing a control system for the telescope using low-cost components that will offer performance comparable to higher-end systems. This system will include a PID feedback system for antenna positioning and tracking. Additionally, a robust backend system for data acquisition and processing will be established using RFSoC FPGA. This low-cost, scalable design provides a promising solution for building large interferometric arrays with affordable individual telescope units.

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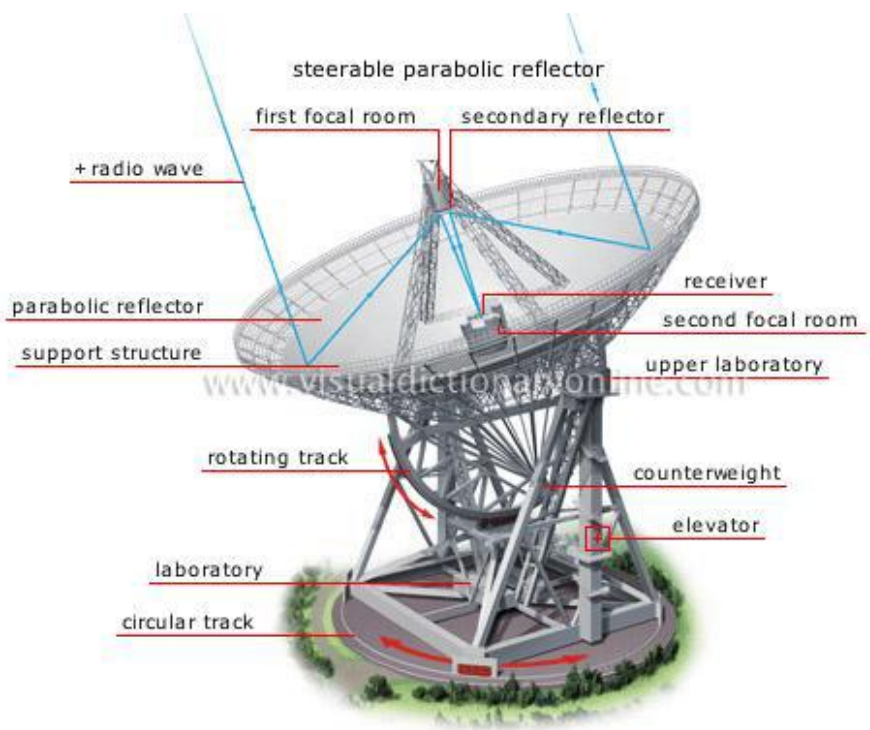
Chapter 1

Introduction

Radio Telescopes are one of the greatest wireless technologies ever invented. They are key instrument in Astronomical Research, helps in producing image, spectrum and other information about extra-terrestrial objects. In this document we will see how to build one Radio Telescope in Home from scratch. So, let’s begin…

1.1 Model of Radio Telescope

There are many types of Radio Receivers, but we are using the dish reflector type as a Radio Telescope for its wave focusing capability. An image of a same is shown in the right. The parabolic dish reflects and focuses the radio waves from galaxies, stars, compact objects and other sources from the space into a feed located at its focal point, which develops a voltage wave that can be amplified and processed to get information. The dish can rotate to point at any point in sky and many electronic systems are involved in controlling and data acquisition which we will see further.



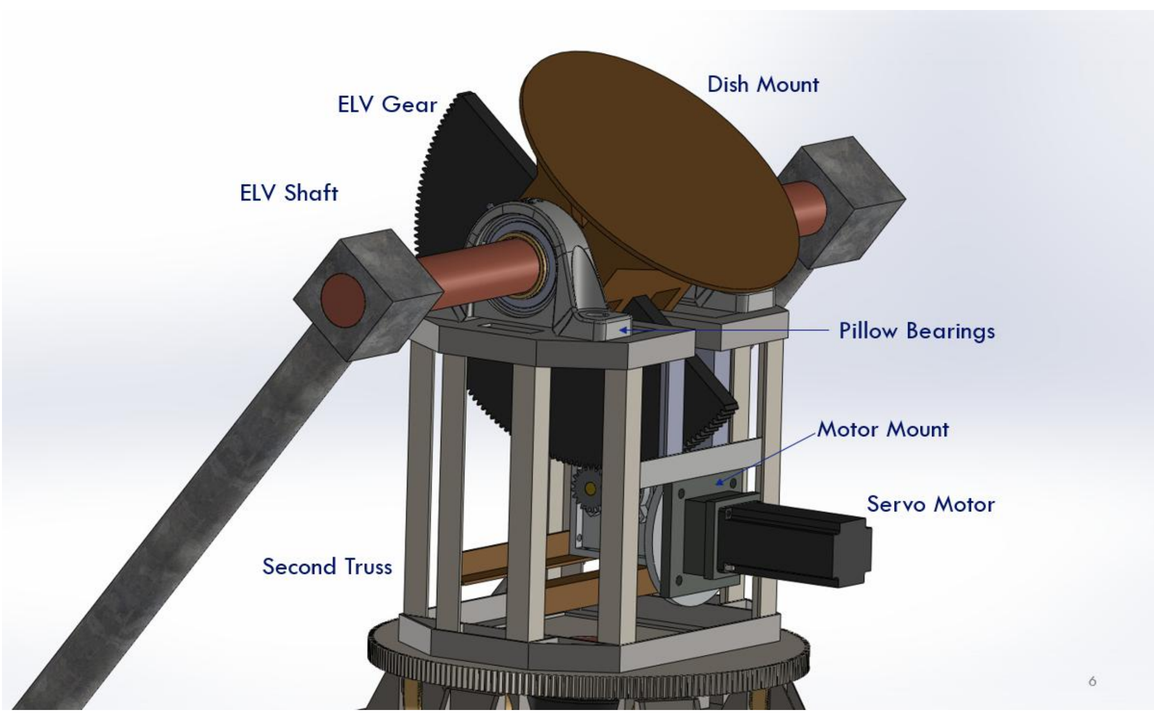
Other than the dish, parts like sturdy base, azimuthal drive and elevation drive are also crucial parts. They came in a huge range of sizes from few meters to hundreds of meters. As there no universal design, a general sketch is shown to get us some idea of how to build it.

Getting inspired from the model and some other telescopes, we are designing and building a small 4m reflector type radio telescope which can be mounted on a sturdy truss support and electronically steerable, a model is shown on the right. The base and first truss are sturdy and fixed to the ground where the second truss can rotate azimuthally. The second truss has elevation movement system, allowing the dish to cover the whole aerial domain of sky.

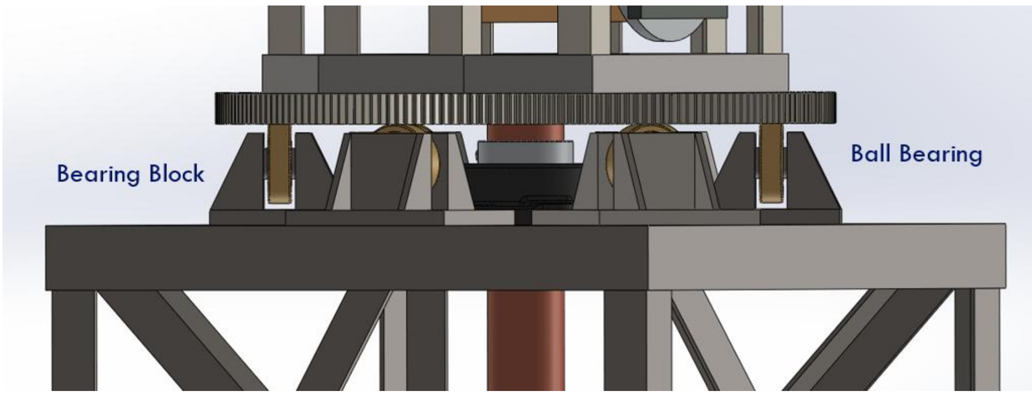
It will be made from simple materials like steel angle bars, rods, pipes and perforated steel plate. Some small plastic or aluminium materials may be added as per need. Now let's look into more detail of its motion and electronic system.

1.2 Motion System

The movement of the telescope is controlled via gears made from steel and we are using spur gears as it's easier to make although worm gears and jack screw are more ideal choices. An image of elevation assembly is shown.



As you can see the dish can be mounted on top which is supported by a solid shaft called ELV shaft. It’s connected to a ELV gear and held by 2 pillow bearings. The ELV gear is rotated by a pinion gear connected to the output of a ULM-40 gearbox whose input is connected to a servo motor. The ELV gear and pinion gear has a gear ratio of 1:10 and the gearbox has the gear ratio 1:100, so overall 1:100 gear ratio in total. The whole system is mounted in a Truss called Second Truss (crossbars are not shown) and the whole system is mounted on a horizontal azimuthal gear. It’s also rotated by a similar system as on the elevation one. The Az gear is supported by 3 ways, 1. Coaxially by an AZ shaft, 2. Concentrically by some more pinion gears from sides (not shown in diagram) and 3. Vertically by 6 ball bearings to support the weight of it and everything above it.



The bearing block is the part that supports bearings and can move up or down by nut bolts to align the Az gear horizontally. From this point everything is fixed to the ground.

1.3 Electronic System

The electronic system of the Radio Telescope is divided into 2 sub-systems: 1. Control Mechanism and 2. Data Acquisition System. The control system involves precision motors, processor & controller, feedback sensors, Network Connections and I/O systems. This system monitors Telescopes pointing and health. Data Acquisition System (DAQ) reads the signal from the antenna and converts it into information. It consists of filters, amplifiers, Frequency Synthesizers, FPGA like RF components. Auxiliary or I would say mandatory system like MCB, EMI filter, Cooling Fans are necessary, not only in this but also in all components.

1.4 Aim of this Research

The radio telescope we are building has three aims. First one is to make it in a low cost of around 4 Lakh INR. It will enable to make a huge observatory in between a crore or something. The second aim is to keeping the electronics part same as IIRI (IIT Indore Radio Interferometer), 4 although the programming the control system and DAQ are beyond scope of this research, keeping the hardware same may enable someone to copy its program code to update IIRI, which may resolve the current faults in it.

The third and most important aim is gaining and applying the knowledge of building and manufacturing infrastructural knowledge of a Radio Telescope. It will make us free from the dependence of foreign departments and companies and place our country in Technological Advanced Field.

The End

Chapter 2

Engineering Materials I

To build something, finding the suitable material is a fundamental step. Some materials are strong, some are soft, some are smooth, some are abrasive, and some materials have special property. However, every material has its own characteristics property, for which they find their respective place in this world. It's good to know some general properties & widely used materials which are used for engineering processes. In this chapter, we will learn some raw materials, their properties and their applications. So, let's begin…

2.1 Raw Materials

By Raw Material I mean matter that available to us in either Element or Compound form which can be transformed to some useful items which can be used to build something later. Solid Raw materials are mainly divided into 4 categories: Metals, Non-Metals, Composites & Polymers.

2.1.1 Metals

Metals occupy most places in the periodic table. They have many characteristic properties like metallic luster, metallic sound, thermal & electrical conductivity, malleability, ductility etc. Most metals are moderately or highly reactive to their surrounding (air, water, other elements), thus naturally found as oxides, sulphides, carbonate ores. But metals like **Au & Pt** are very inert and found in pure state in nature. **Cu and Ag** can also be found in pure state but sometimes found in sulphide ores. The Platinum Group Elements like **Pt, Pd, Rh, Ru, Ir, and Os** are found naturally in alloy state.

At room temperature, all metals are solid except Hg. To show their metallic property, the metal should be in pure elemental alloy form. Metal Oxides, sulphides, carbonates don't show metallic property. As they are very reactive, preventive measures are taken to prevent corrosion and rusting, like dripping in or covering with oil/grease, coating with paint, surface oxidation / galvanization etc.

We will see in more details about metals in further few sections, here are examples of some engineering metals: Iron, Aluminium, Copper, Tin, Titanium, Chromium, Manganese, and some metal alloys: Steel, Brass, Bronze etc.

2.1.2 Non-Metals

In the periodic table, there are total 93 Metals, 18 Non-Metals and 7 Metalloids. Non-Metals seems to show exact opposite behavior of metals like poor thermal and electrical conductivity, brittle, low melting point, exist in all 3 states at room temperature etc. They don't need to be in pure elemental form to show their properties. Even their compounds show non-metallic property. Non-Metals are widely used for heat/electric insulation, storing chemicals and some special applications as phosphorous in match stick. Some widely used non-metals are: Glass, Wood, Ceramics, Carbon, Sulphur, Helium, Nitrogen etc.

2.1.3 Composites

Composites are the materials formed by binding two or more materials which has enhanced properties that are better than the individual materials. One material is called Matrix/Binder and others are called reinforcement. Binder binds the elements together where reinforcements give specific properties like strength, stiffness, resistivity etc. Here are some example composites:

Composite	Matrix	Reinforcement	Application
Fiberglass	Polymer resin	Glass fibers	Boats, helmets, car bodies
Carbon Fiber	Epoxy or polymer	Carbon fibers	Aerospace, racing cars, drones
Concrete	Cement	Sand, gravel, steel bars	Buildings, bridges
Plywood	Glue (resin)	Layers of wood veneer	Furniture, construction
Kevlar composites	Epoxy	Kevlar fibers	Bulletproof vests, helmets

2.1.4 Polymers

Polymers are long chains of repeating atoms/molecules that form the basis of all plastics and rubbers. The individual repeating units are called monomers. They can be natural or synthetic. Now a days they are widely used because desired properties can be set by choosing the monomer. Some Natural polymers are Rubber, Cellulose, Silk etc. & some widely used synthetic polymers are given below:

Polymer	Type	Use Case
Polyethylene (PE)	Thermoplastic	Bags, bottles, packaging
Polyvinyl Chloride (PVC)	Thermoplastic	Pipes, cables, doors

Nylon	Synthetic	Fabrics, ropes, gears
Teflon (PTFE)	Synthetic	Non-stick cookware, gaskets
Bakelite	Thermoset	Electrical insulators, switches
Rubber (Natural/Synthetic)	Elastomer	Tires, seals, gloves

Thermoplastics are polymers that softens on heating and hardens on cooling. They can be reshaped by heating. Thermosets are polymers that hardens permanently after heating. Here is the difference between polymers and composites.

Feature	Composites	Polymers
Made of	Two or more materials	Long chains of repeating monomers
Purpose	Combine strengths of components	Lightweight, flexible materials
Examples	Carbon fiber, concrete	PVC, Nylon, Rubber
Nature	Heterogeneous	Usually homogeneous

2.2 Structural Properties of Materials

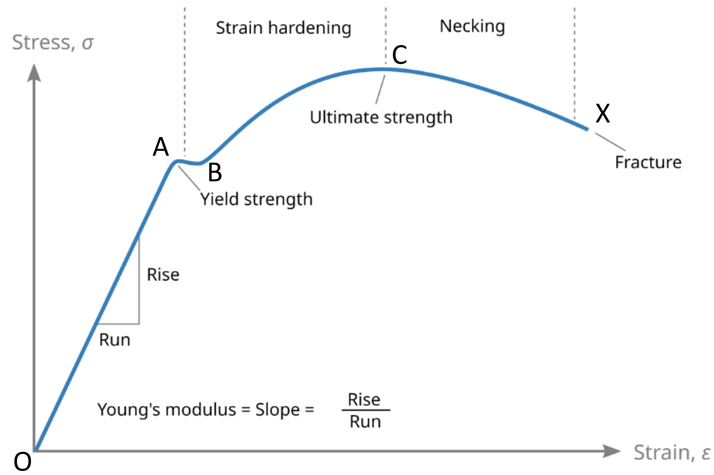
Different materials react differently upon the action of load. On these behavior materials are classified into brittle, ductile or elastic. When a load is applied, the material experiences stress and results in some strain. In increasing the load, the material first deforms which can be reversed after the removal of the load, but after reaching a point, it deforms permanently and cannot be reversed. I the load increases more, the material breaks or rupture.

We study the stress-strain curve of the material to know about its structural properties in more detail. The material is put in a “Universal Testing machine” which pulls it and measures the stress at different elongation points (strain). As the material is pulled, at first it deforms which can be reversed by removing the load. After a point, deformation doesn’t return back to its original state. If the elongation increases more, at a point the material breaks/fractures. The stress ~ strain graph is plotted which is useful in knowing many material properties.

2.2.1 Ductile Materials

These materials are generally metals. They have the ability of deform to different shapes by application of external force or impact, called ductility, hence ductile materials. Up to a strain and so corresponding to a stress limit, they undergo elastic deformation, that means the deformation reverts to its original shape after removal of the load. This region obeys Hooke's Law "Stress is directly proportional to strain."

After the stress limit, the deformed material doesn't revert to its original shape even after removal of the load. We call it the material deformed or failed. This type of deformation is called plastic deformation. The stress point after which plastic deformation starts is called Yield Strength of the material. After a stress point the material spontaneously deforms under load and eventually breaks or facture, the point after which the material spontaneously breaks is called Ultimate strength. Here is a stress ~ strain curve of a metal.

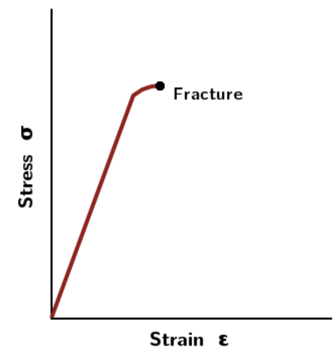


Here's a table mentioning the behavior of the material at a given region:

Region	Description	Material Behavior	What Happens When Stress Increases	What Happens When Stress Decreases
O–A	**Elastic region**	Linear behavior, obeys **Hooke's Law**	Material stretches elastically. Returns to original shape when stress is removed.	Material contracts elastically. No permanent deformation.
A–B	**Elastic–Plastic transition**	Start of **yielding** (may show upper and lower yield point)	Material begins to yield; slight increase in strain with little stress increase. Permanent deformation begins.	If stress is removed here, some **permanent strain** remains (plastic deformation).
B–C	**Plastic deformation / strain hardening**	Material deforms plastically, stress continues to increase	Dislocations form and interact; metal becomes stronger (strain hardening).	If stress is reduced, material retains its new shape. No recovery to original form.
C–X	**Necking + Failure**	After **ultimate tensile strength** is reached	Localized narrowing (necking) begins at C. Stress appears to drop due to reduced cross-section.	Decrease in stress occurs naturally until fracture at X. Cannot reverse deformation.
X	**Fracture point**	Material breaks completely	Complete separation of material.	N/A — material has failed.

2.2.2 *Brittle Materials*

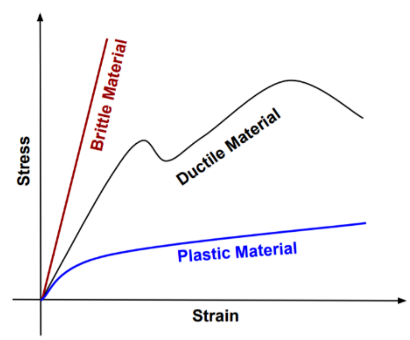
The brittle materials are generally Non-Metals. They typically don't have a plastic deformation region, more clearly the yield and ultimate strength point are very close, that means no plastic deformation or necking, thus sudden fracture. Two more characteristic property are they have very high compressive strength and crack propagation is fast and catastrophic. Here's a stress strain curve of brittle metal:



Examples: Cast Iron and some metals in low temp, Glass, Metal Oxides, Acrylic, Polystyrene, Stone, Concrete etc.

2.2.3 *Elastic Materials / Rubbers*

The elastic materials are those that expand significantly compared to the stress applied and also return to original shape after removal of load until it exceeds elastic limits. They have very high strain rate compared to the stress and also a high strain limit. They have low slope in their stress strain curve. Some of them plastic deformation and some suddenly failure. Here's a graph of all 3 materials for comparison.



Examples: Rubber, Silicone, foams

All the material properties we have seen are only applicable in solid state, in liquid state or gaseous, they obey very different physics. Now let's proceed with metals.

2.3 *Metals*

We have learned some structural properties of metals, before we get into more properties, it's essential to learn about some atomic properties of the metals as well. This may explain some thermal and electric/magnetic properties as well. And we will also see how the structural properties arise from it, so let's start with crystal structure of metals.

2.3.1 *Metallic Crystal:*

We know crystalline solids are those solids which have a regular arrangement of atoms on constituents. Metals also form a crystalline solid structure, for some specific properties of metal atoms and their metallic bonds, they show metallic properties, thus it's called metallic crystal.

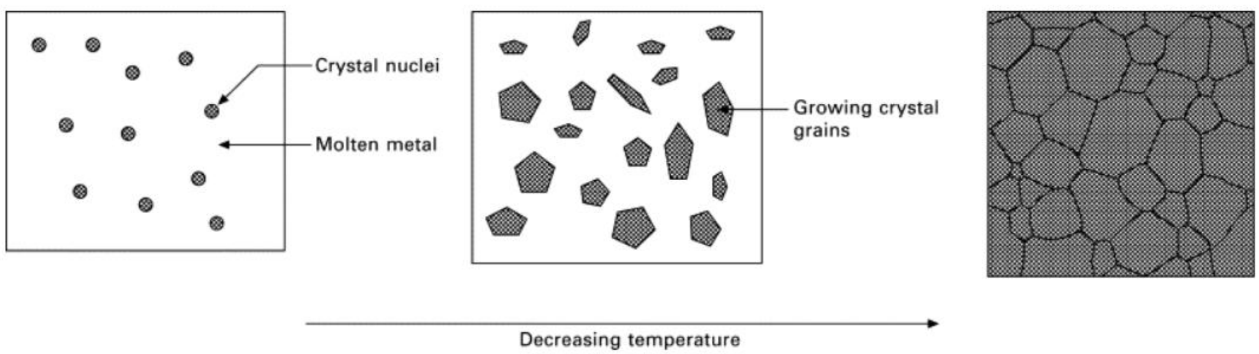
Key features of Metallic Crystal:

Lattice Structure – Atoms are constituents of the crystal, not metal compounds, even a small impurity can cause a significant change in physical property. The arrangement is highly regular and repeating.

Delocalized Electrons – Electrons are not bound to any specific atomic nuclei; they are free to move across the crystal lattice like a liquid; allowing electrical & thermal conductance and metallic luster.

Flexible Bonds – The atoms often slide across each other by breaking and making bonds, this changes the structure of the metal, thus explaining ductility and malleability.

Metallic Grain – Although the metallic crystals are highly ordered, but usually while solidification, crystallization starts from multiple points having different directional lattice, and they end up in grains instead of a single whole crystal.

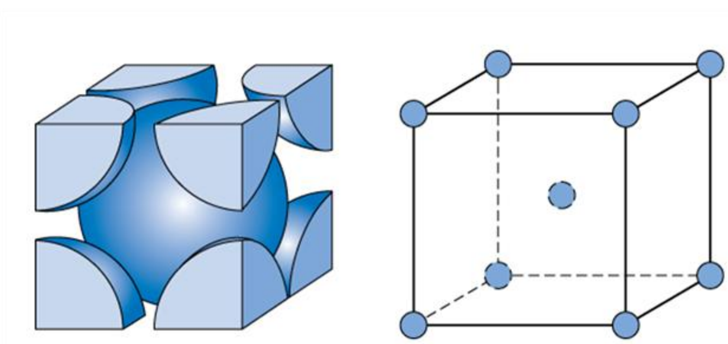


2.3.2 *Crystal Structures*

The metals show mainly BCC, FCC and HCP close packings. These arrangements have effects on properties and behavior of the metal.

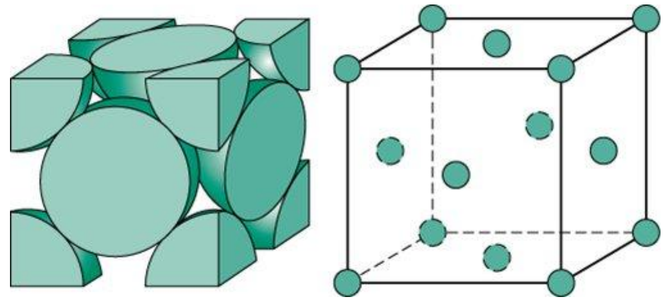
Body Centered Cubic – BCC:

Atoms are arranged in all corners of the cube and 1 at the center. Packing efficiency 68%. Slip systems 48, but harder to activate due to lower atomic density. These metals are harder but brittle, their strength increases with lowering temperature.



Ex: Iron (Fe), Chromium (Cr), Tungsten (W), Molybdenum (Mb)

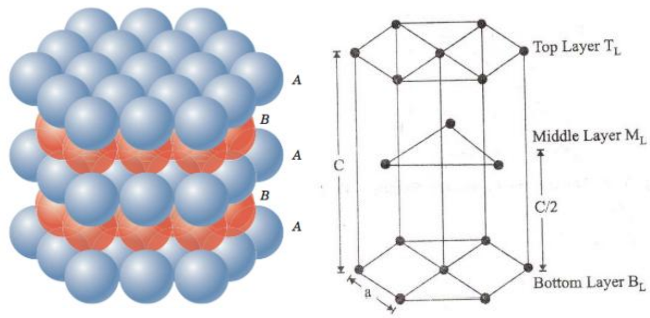
Face Centered Cubic – FCC:



In this structure atoms are arranged in all corners as well as center of all faces. Packing efficiency 74%. Slip systems 12, thus these materials are very ductile and easy to shape.

Ex: Aluminium (Al), Copper (Cu), Gold (Au), Nickel (Ni), Lead (Pb)

Hexagonal Close Packing – HCP:



Atoms are arranged in hexagonal prism with alternating layers (ABAB stacking). Packing efficiency is also 74%. Slip system is typically 3-6, so less ductile. These materials are also strong and brittle, but deformation is difficult without heating.

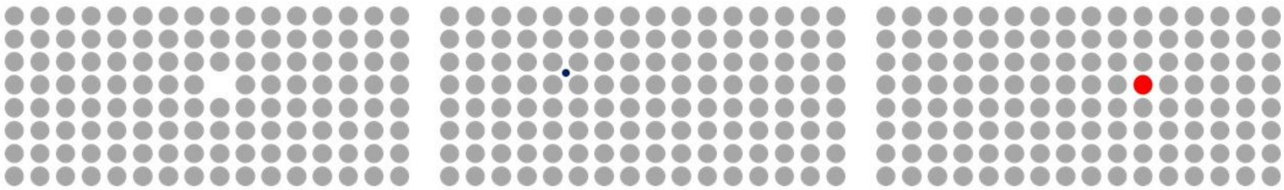
Ex: Titanium (Ti), Magnesium (Mg), Zinc (Zn), Cobalt (Co)

2.3.3 Crystal Defects

Crystal defects mean an imperfection in the perfectly ordered crystal lattice. It may arise due to external substance or external force. It's very hard to get a perfect crystal and understanding the defects is crucial in understanding many properties of the material. There are many types of crystal defects:

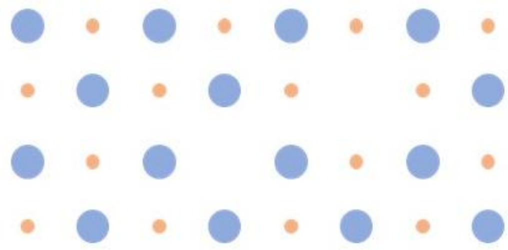
2.3.3.a Point Defect

In a crystal lattice some atoms are missing or replaced by foreign atom or a foreign atom present in void spaces. They are called vacancy defect, interstitial defect and substitutional defect respectively. Metallic crystals have these three-point defects.

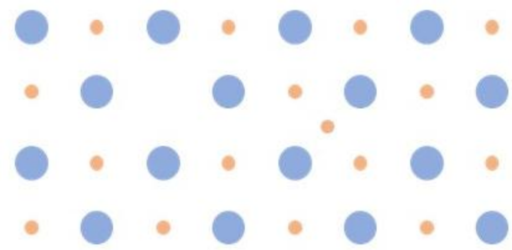


Vacancy Defect Interstitial Defect Substitutional Defect

Two different kind of point defect are *Schottky defect where an anion and cation are missing from the crystal lattice* & *Frenkel defect where a cation is placed in an interstitial point. These are primarily shown in in compounds.*



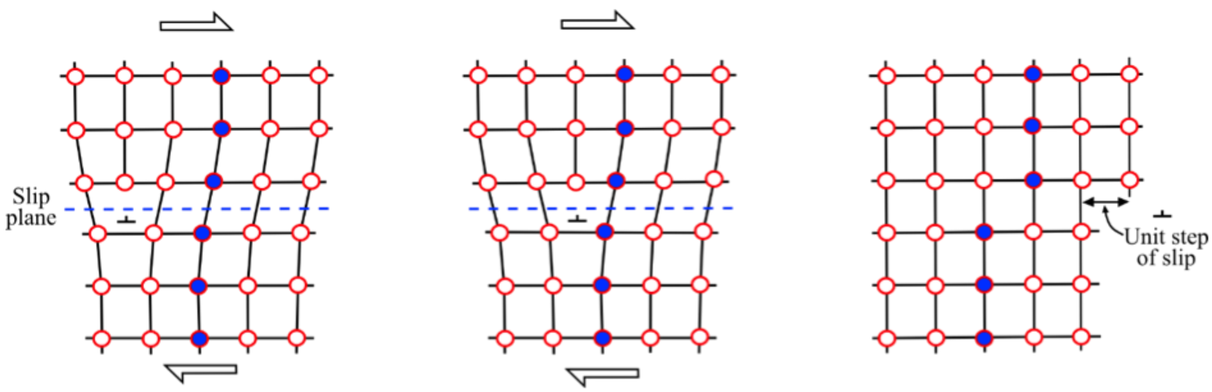
Schottky Defect



Frenkel Defect

2.3.3.b Line Defects

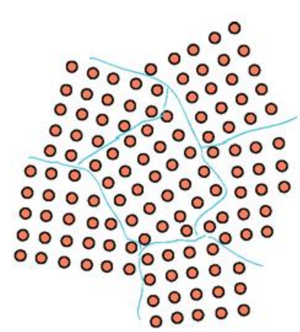
Sometimes a whole row of atoms misaligns with the crystal lattice giving a line defect. This defect arises due to external force. The atomic bonds break and binds again with different atoms due to the same. Figure below shows how external force disrupts the crystal lattice that arises line defect.



This effect arises due to external force in first place, the number of unit step emerged from one side is from the number of unit steps got pushed from the other. This explains the ductility of metals.

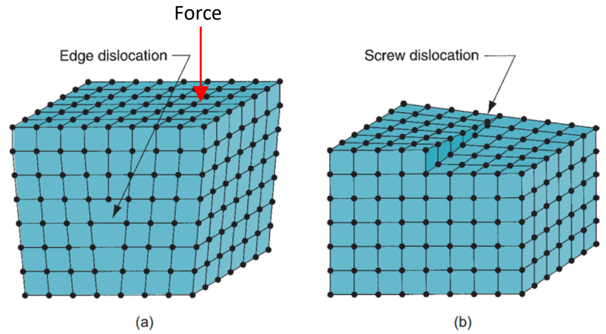
2.3.3.c Planar Defects

It's same as line defect, just in this case a whole plane gets misaligned due to external force. The line defect was 1 dimensional defect where planar is 2 dimensional. It can be thought of line defect in 2 dimensions. This also explains ductility of metals. At the boundaries of metallic grain this type of defect is seen.



2.3.3.d Bulk Defect / Volume defect

Volume defect is when a whole bulk chunk of crystal lattice is misaligned. These can be screw dislocation, where atoms are linked in a helix or interstitial voids or presence of foreign particle.



Screw dislocation arises where there is already a line dislocation. An external force realigns the atoms in a helix path when applied to one side of edge dislocation, thus screw dislocation.

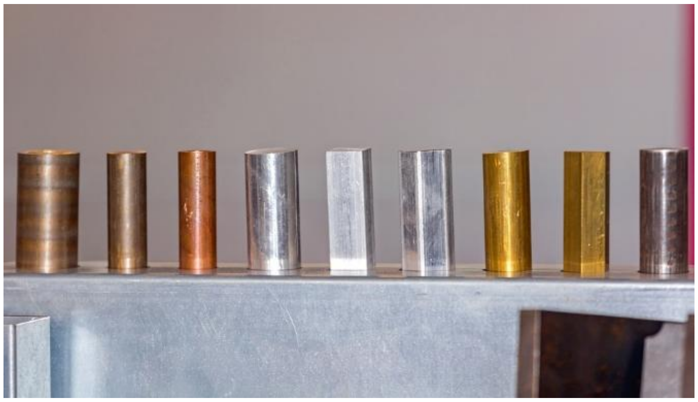
The line, plane and bulk defect are the result of external force, which implies metals deform under the application of external load. This explains the ductility of the metals. As the deformation is due to defects in the crystal lattice, many methods are used to enhance the strength of pure metal crystal as introducing foreign particle or improving grain number significantly prevents these crystal defects, hence making the material stronger. It also makes the material gain some new property. Let's see some of the methods.

2.3.4 Enhancement of Metals

As you can see pure materials don't usually show the properties that we see in our daily life. The pure metals generally weak as the crystals planes can slide or dislocate due to applied force. That means real life application metal items are quality enhanced metals, result of numerous techniques, some of them are discussed below:

2.3.4.a Alloying

Alloying refers to mixing a base metal with other metals / non-metals to improve its properties like strength, hardness, corrosion resistance and machinability. Example: Mixing Iron and Carbon to give Steel (Increased strength). Adding chromium and nickel to steel give stainless steel (Corrosion Resistant) etc.



In substitutional alloying atoms of the alloying element replace atoms of the base metal in the crystal lattice. It requires atoms of similar atomic radii metals. In interstitial alloying, small atoms of the alloying element fit into the interstices (gaps) of the base metal's crystal lattice. Typically, non-metals are added in this method.

Properties of the alloy depends on the base metal but changes are due to the alloying material that has been added. Here are some alloying materials and the property they add to the base metal:

Goal	Achieved Through Alloying
Increased strength	Add elements that hinder dislocation movement (e.g., C in steel).
Improved hardness	Elements like V, Cr, or Mo form hard carbides.
Enhanced corrosion resistance	Cr in stainless steel forms protective oxide layers.
Better wear resistance	Ni and Cr improve surface durability.
Improved ductility	Add Ni to steel to improve toughness and ductility.
Magnetic/electrical tuning	Add Si to Fe for electrical steels.
Lightweight strength	Al-Li or Mg-based alloys for aerospace use.

Sometimes the alloys show up intermediate property of both alloying elements, sometimes higher or lower than both, it depends upon the process of making and proportion. This helps in precisely adjusting the quality of the alloy for dedicated use. Given below a table of various alloys and their application:

Alloy	Alloying Elements	Application
Bronze	Cu 90% + Tin 10%	Daily use items and instruments, coins
Brass	Cu 67% + Zn 33%	Precise mechanical parts
Steel Alloys	Fe + C + More	Various high strength applications. Available in many grades
Aluminium Alloys	Al + More	High strength/weight and corrosion resistance applications. Available in many grades
Invar	Fe 64% + Ni 36%	Length doesn’t change upon temp. change
Pewter / Solder	Pb + Sn	Low melting point, used for luxury items casting (Pewter). Connecting electrical connections (Solder)

Alnico	Fe (Base) + Al + Ni + Co	Magnetic, used in motors, generators, speakers etc.
Duralumin	Al + Co + Mn	Aircraft body manufacturing
Nichrome	Ni + Cr	Resistant wires and heating elements
Sodium-Potassium	Na + K	Highly explosive (no application)
Neodymium Magnet	Nd + Fe + B	Highest magnetic property
Tungsten Carbide	W + C	Highest strength material. Used for making high grade machining tools.
Stainless Steel	Fe + C + Cr + Mn	Corrosion resistant structures
Titanium Alloy	Ti + (Al / V / Mo)	Higher strength / weight ratio applications

In our daily life we often see metal alloys, as pure metals are highly reactive and alloying simply gives a better result and so. But there are also some metals like gold and silver that are used in pure form. In simple words alloying adds solute atoms in metallic lattice changing the properties of atomic bonds and hence changing the material properties. It also prevents dislocation in the lattice making the material stronger, along with making the grain size smaller which makes it harder to dislocate the structure. It's very common process of enhancing metals known before the crystal structures, and has been used since millennials.

2.3.4.b Heat Treatment

In this process the material heated above some critical temperature, holding it for some time and then controlled cooled to achieve desired the grain structure, which in turn alters hardness, strength, ductility etc. There are many processes of heat treatment given below taking Steel as an example:

Annealing

It softens the material by relieving internal stresses; thus, it improves ductility. Steps are heating the steel around 600-700 °C and let it be for some period (Soaking Period) and then cool it down inside furnace (slow cooling).

Normalizing:

It raises the strength of the material by making the grain size smaller / finer. First the steel is heated above 850 °C (the critical point of steel). It dissolves the grain of steel making it paramagnetic and repel to magnet. After the soaking period, the steel is air-cooled to produce more finer grains. The finer grains obstruct the slipping of crystal plane, making the material gain more strength.

Quenching:

In this process also the steel is heated above 850 °C, but it's rapidly cooled by submerging in water / oil / brine. This rapid cool introduces huge number of grain formation points which makes the grain size even smaller, which results in a very hard but brittle steel. The resulting steel is known as Martensite.

Tampering:

It's done to reduce the brittleness of hardened steels. It's done after quenching or normalizing. It involves heating the steel in low temp (150 °C – 600 °C) and then cooled in air.

2.3.4.c Surface Treatment

Surface treatments are done to protect the material from corrosion and wear. The processes are given below:

Anodizing:

In this process an oxide layer of the material is formed on the surface which protects it from corrosion. It's primarily done to Aluminium (Al), Titanium (Ti) and Magnesium (Mg). The metal is submerged in an acidic electrolyte where the target metal acts as anode. The current causes oxidation on the surface giving it a good corrosion resistance. The metal develops many colors depending duration and many other parameters.

Electroplating:

In this method a layer of Nickel (Ni) or Chromium (Cr) is formed on the surface of the metal. In this method the target metal is submerged in a saline solution of the coating metal (Ni, Cr, Cu, Ag) and is connected to the cathode of the electrode. In this process, cations from anode dissolves in the solution and cations from the solution gets deposited on the cathode or target metal. At the end the anode gets dissolved and a new layer is formed on cathode.

Galvanization:

In this process a zinc coating is applied to the steel. Zinc forms a ZnO layer on the surface which protects steel from rusting. A common method is to dip the steel in molten zinc.

Painting:

Applying colors to the surface blocks the oxygen contact with steel which prevents rusting. Other alternatives are applying oil or grease.

Carburizing:

In this process steel is heated to 800 – 1000 °C and then either carbon rich gas (CH_4, CO_2) is blasted on it or direct charcoal powder is poured onto it or it's dipped in molten salt bath or carbon. In this process, the carbon atom gets fused to the surface making the surface harder and wear resistance while the inner core remains tough.

Nitriding:

In this process Nitrogen (N) is diffused into the surface by exposing the heated metal to Ammonia (NH4) or nitrogen rich mixture. It also increases hardness of the surface of the metal. Other methods are as salt Bath Nitriding, Plasma Nitriding / Ion Nitriding or Laser Gas Nitriding.

Black Oxide Coating:

In this process surface layer of iron and steel is converted into Magnetite (Fe3O4) known as Black Oxide / Iron III Oxide. It gives a smooth finish to the surface and it's also corrosion and wear resistant. It's achieved by a chemical reaction of the metal with Nitrates, Nitrites and Sodium Hydroxide (NaOH). Its commonly seen in Allen bolts & keys.

2.4 Steel

Steel is the most manufactured metal in the world because of its high strength and ease of availability. It's an Alloy of Iron (Fe) and Carbon (C) for increased strength, with a small amount of Mn, Cr, Ni, Mo are added to modify properties. Some properties of Steel are given below:

- Greyish Color
  High Strength 200 – 900 MPa
- High Melting Point 1371 °C – 1540 °C
- High Density 7.8 g/cc
- Moderate Chemical Reactivity
- Moderate Heat Conductivity
- Good Electrical Conductivity
- Allotropy
- BCC Crystal Lattice in room temperature

In nature Iron comes from 2 ores: Hematite and Magnetite; from which Iron is extracted by smelting. Then carbon is added to them in various amounts to give different type of steel. Most commonly available steels are Mild Steel or Low Carbon Steel (MS) and Stainless Steel (SS) with yield strength 248 MPa and 205 MPa. Some other elements are also added to produce many grades of steel like carbon steel, alloy steel and tool steel. The type and grade of steel is determined by American Iron and Steel Institute (AISI) which is used in India, other standards are ASTM and EN. Given below some types of steels.

2.4.1 Classification as per Composition:

As per composition, the steel is mainly divided into 3 categories:

2.4.1.a Carbon Steel:

These types of steel only have iron and carbon as their composition with min 98% Fe and max 2% C. They have wide range of application in structural engineering. They come with moderate strength (250 MPa) and suitable for general purpose construction. They also have 4 varieties:

- Low Carbon Steel: up to 0.05 – 0.30 % w/w. Known for good ductility and formability.
- Moderate Carbon Steel: up to 0.3 – 0.6 % w/w. Has a balance of ductility and strength.
- High Carbon Steel: 0.6 – 1.0 % w/w. High hardness, strength but brittle.
- Ultra-High Carbon Steel: 1.25 – 2.0 % w/w. More hardness for special applications.

2.4.1.b Alloy Steel

Alloy steels have some other elements like Mn, Cr, Ni, Mo, Cu, V, Ti etc. along with Fe and C to improve its quality. Each metal adds some of its own characteristics to the steel. They are also categorized into low-alloy and high-alloy steel as per more or less than 8% alloying elements. These types of steels are used in specific applications where carbon steel couldn't fulfill the need. These generally have more yield strength (350 – 900 MPa) and higher melting point and some specific property like corrosion, wear resistance and more.

2.4.1.c Stainless Steel

Stainless steel is a very specific type of alloy steel that is highly resistive to corrosion and rusting. It's made from at least 10.5% Cr with Fe and C. It generally has lower strength (200 MPa). Its high corrosion resistance helps it to be used in wide range of applications like: plumbing and bath ware, kitchen ware, plates and cutlery, spoons, straws, food packaging, food & water storage, medical equipment, blades and implants, aerospace devices and many times for aesthetics for its shiny and mirror like surface finish.

Its high Chromium content forms a transparent Chromium Oxide (Cr_2O_3) layer around the steel which protects it from oxidation, rusting and many other stains and also makes it safe for edible items, medical equipment and many more, that's why the name Stainless Steel. Some of widely used stainless steel is AISI 304 & AISI 316.

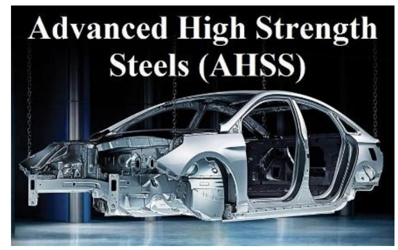
2.4.2 Classification as per Application:

As per application, there are many categories:

2.4.2.a Structural Steel

- Grades: S235 (min. 235 MPa yield), S275, S355
- Features: Excellent weldability and ductility; cost-effective for beams, columns, plates.
- Processing: Typically, hot-rolled and normalized to refine grain size and improve toughness.
- Application: Construction material and manufacturing

2.4.2.b Advanced High Strength Steels – AHSS



- Variety: Dual-Phase (DP), Complex Phase (CP), Transformation Induced Plasticity (TRIP), Twinning Induced Plasticity (TWIP)
- Features: Combines high tensile strength (up to 1200 MPa) with good elongation (>20%); energy-absorbing crash performance.
- Processing: Precise thermo-mechanical control (TTT curves) to produce mixed ferrite-martensite microstructures.
- Application: Automotive Industries, Safety Components

2.4.2.c High Strength Low Alloy – HSLA

- Grades: Ti-6Al-4V, ASTM A572, A656 with grade 42, 50, 55 etc.
- Features: Light weight, high fatigue strength, and fracture toughness; corrosion resistant in aerospace environments.
- Processing: Quench & temper for steels; solution treatment and aging for titanium alloys.
- Application: Aerospace and other Industrial level manufacturing

2.4.2.d Tool Steels

- Grades: D2 (high Cr), M2 (high W/Mo), H13 (hot-work)
- Features: Exceptional wear resistance, red hardness, and thermal fatigue resistance.
- Processing: Oil or water quenching followed by high-temperature tempering to optimize hardness / toughness.
- Application: Making cutting tools, machine dies, woodworking tools, hand tools etc.

2.4.2.e Stainless Steel

- Grades: 304, 316, duplex (2205)
- Features: ≥10.5% Cr forms passive oxide; Mo in 316 resists chlorides; duplex steels add strength and crack resistance.
- Processing: Annealed or solution-treated to maximize corrosion resistance and formability.
- Application: Food sectors, medical sectors, Household items, Marine and Chemical sectors and Aesthetic Architecture.

2.4.2.f Alloy Steels

- Grades: 4140 (Cr-Mo), 4340 (Ni-Cr-Mo), EN24
- Features: High yield and tensile strength (>600 MPa); good fracture toughness; fatigue resistant for shafts, gears.
- Processing: Quench & temper to achieve desired mechanical balance.
- Applications: Specific Industrial Applications

2.4.2.g High Speed Steel

- Grades: M2, M42
- Features: Maintain hardness (~62 HRC) at cutting temperatures >600 °C; excellent wear resistance.
- Processing: High-temperature tempering cycles to optimize red hardness.
- Applications: Wood and Soft metal machining tools

2.4.2.h Electrical Steels

- Grades: 3% Si non-oriented; grain-oriented for transformers.
- Features: Low core loss (<1.5 W/kg), high magnetic permeability for motor and transformer laminations.
- Processing: Recrystallization anneal in H_2 atmosphere; application of insulating coatings.
- Applications: cores of electro-magnetic devices – Motors, Generators, Transformers

2.4.2.i Specialty Steels

- Maraging Steels: Ultra-high strength (>2000 MPa) via Ni precipitation; excellent toughness.
- Weathering Steels (Corten): Alloyed to form stable rust layer that protects core; no coating needed.

Apart from specialty of steel, its strength also needs to be considered for structural studies. Here is a table showing the structural strength and grade of the steel.

Steel Grade	Yield Strength MPa	Steel Grade	Yield Strength MPa
1023 Carbon Steel	282.68	Chrome Stainless Steel	172.399
201 Annealed Steel	292	Galvanized Steel	203.94
A286	275	Plain Carbon Steel	220.59
AISI 1010	180	Stainless Steel ferritic	172.33
AISI 1015	325	Wrought Stainless Steel	206
AISI 1020	351.57	ASTM A572 Grade 42	290
AISI 1035	282.68	ASTM A572 Grade 50	345
AISI 1045	530	ASTM A572 Grade 55	380
AISI 304	206.80	ASTM A572 Grade 60	415
AISI 316 Annealed	137.89	ASTM A572 Grade 65	448
AISI 316	172.36	ASTM A709 Grade 36	250
AISI 321 Annealed	234.42	ASTM A709 Grade 50	345
AISI 347 Annealed	275	ASTM A706 Grade 60	420
AISI 4130 Annealed	460	ASTM A706 Grade 80	550
AISI 4130 Normalized	460	ASTM A576 1070	390
AISI 4340 Annealed	470	ASTM A576 1018	310 – 420
AISI 4340 Normalized	710	ASTM A576 1118	315
AISI 316L	170		
AISI A2	1270 – 1590		
Alloy Steel	620.42		
ASTM A36	250		
Cast Alloy Steel	241.27		
Cast Carbon Steel	248.16		

Source: SOLIDWORKS

2.5 Aluminium

Aluminium is the second most used metal for engineering works. Its main advantage is its high strength to weight ratio. It's a silvery-white, lightweight metal. It can be directly used in element form as well as alloy. It's extracted from Bauxite ore. Some of the properties are given below:

- Aluminium Yield strength: 7 – 11 MPa
- Aluminium Alloy Yield Strength: 200 – 600 MPa
- Melting point: 660.3 °C
- Good Conductor of Electricity and Heat
- Itself corrosion resistance by its own oxide layer
- 100% recyclable: can be recycled indefinitely without loss of any property
- Highly malleable and ductile: Very thin wires and sheets can be formed from it
- FCC crystal lattice

A wide range of products are formed from aluminium and also many construction materials. Its highly used in aircrafts to reduce weight of it. It normally has very low strength but alloying with other elements significantly increases its strength. It has FCC crystal lattice. A table below shows some aluminium grades and their yield strengths:

Aluminium Grade	Yield Strength MPa	Aluminium Grade	Yield Strength MPa
1060 Alloy	27.57	1100-O Rod	34.5
1060-H12	75	1345 Alloy	27.57
1060-H12 rod	57	1350 Alloy	27.57
1060-H14	90	201.0-T43	225
1060-H16	105	201.0-T6	349
1060-H18	125	201.0-T7	344
1060-H18 rod	108	2014 Alloy	96.5
1060-O	30	2014-O	95
1100-H12 rod	99.28	2014-T4	290
1100-H16 rod	122.72	2014-T6	415
1100-H26 rod	118.58	2018 Alloy	317

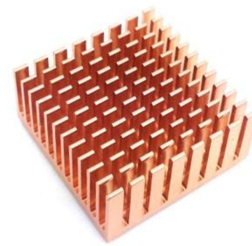
2024 Alloy	75.82	4032-T6	316
2024-O	75	5052-H32	195
2024-T3	345	5052-H34	215
2024-T361	395	5052-H36	240
2024-T4	325	5052-H38	255
2219-O	70	5052-O	90
2219-T31	250	5052-O rod	72.40
2219-T37	315	5086-H32	193.05
2219-T62	290	5154-O	139.27
2219-T81	350	5454-H111	180
2219-T87	395	5454-H112	125
2618-T61	372	5454-H32	205
3003 Alloy	41.36	5454-H34	240
3003-H12	125	5454-O	115
3003-H14	145	6061 Alloy	55.15
3003-H16	170	6061-O	62.05
3003-H18	185	6061-T4	227.52
3003-O	40	6061-T6	275
3003-O rod	36	6063-O	50
3004-H34	200	6063-O	41.36
3004-O	69	6063-T1	90
356.0-T6	152	6063-T4	90
7050-T73510	435	6063-T5	145
7050-T7451	470	6063-T6	215
7050-T7651	490	6063-T83	240
7075-O	95		
7075-T6	505		
7079 Alloy	572		
AA356.0-F	159		
C355.0-T6	207		

Source: SOLIDWORKS

2.6 *Some Other Metals:*

2.6.1 Copper

Copper is another elemental metal, mostly used in pure form. It's a soft metal with very high electrical and thermal conductivity. It's primarily used as wires, PCB connections in electronics and heat sinks, heat pipes in thermal applications. It's a reddish-brown appearance, 1085 °C melting point, 8.96 g/cc density, 40 – 50 MPa and good corrosion resistance in various environments including salt water, thus, making it suitable for marine applications. Alloying with Zinc and Tin results Brass & Bronze respectively. It also has natural microbial properties, useful in water containers and kitchen wares. It's also durable to pressure and temperature, ideal for plumbing, air conditioners and cryogenic systems.



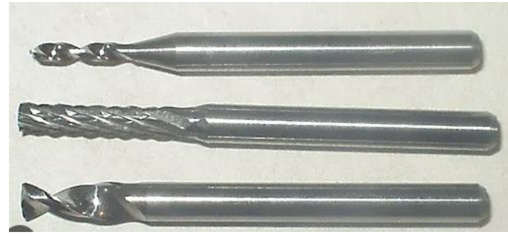
2.6.2 Titanium

Titanium is a lustrous silvered-colored metal with high strength, melting point and high strength to weight ratio. It also has high corrosion resistance properties and highly used in aerospace, medical and industrial applications. The yield strength is 170 – 480 MPa in pure form and can reach 1260 MPa in Alloy form. Its density is 4.51 g/cc and melting point is 1725 °C. For these properties it's great choice for jet engines and rockets. Additionally, Titanium Dioxide (TiO_2), a white compound, is used in paints and coatings and UV resistances.

2.6.3 Tungsten

Tungsten is the hardest metal on planet earth. It's a silvery grey metal and has the highest melting point among all metals, for which it was used in incandescent bulbs. It's also used it heating elements, jet engine and turbine blades are also made from it, due to its high density and strength Armor piercing shells of tank are also made from it. Another most noticeable application is, it's used in cathode ray tube to produce X-Ray. Yield strength of tungsten is 750 MPa and density is 19.35 g/cc.

It can be alloyed with other materials to make super alloys. One of which is Tungsten Carbide which is used for heavy duty machining works. Many cutting tools and bits are made for tungsten carbide for high strength steel alloys, also in mining and boring machine also tungsten carbide. Yield strength of Tungsten Carbide is 7000 MPa.



2.6.4 Lead

Lead is a very soft, bluish-white metal with high density (11.34 g/cc) and low melting point (327 °C), ideal for casting applications. It has high corrosion resistance properties due to the formation of Lead Monoxide. A mixture of Lead Monoxide and Lead on the surface gives a dull grey appearance. Alloying it with Tin gives a good conductivity and more low melting point alloy, widely used as Solder for electrical joints. It's considered to be poisonous and infectant when causes injury, therefore used in bullets.

2.7 Corrosion & Friction

These are two opposing forces to an ideal mechanical structure. Rusting is a main problem in Steel and Iron and variety of techniques are used to resolve the issue like applying grease, oil and some other techniques as mentioned in section 2.3.4.c. While some metals are naturally corrosion resistance, above mentioned techniques are widely used. Application of grease and lubes also reduces wear damage.

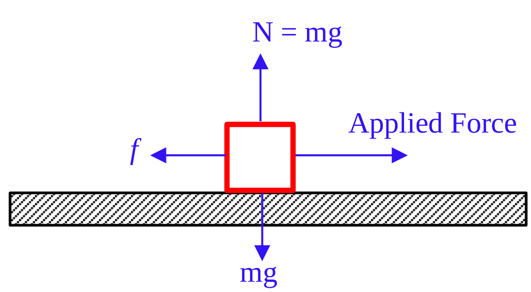
Friction in other hand opposes the sliding of parts in between them. In real world application we cannot neglect friction. Although the exact calculation is more complicated, we will do a rough estimation of the frictional opposition. The coefficient of friction is given by:

$$f \leq \mu . N$$

$$f: Frictional\ force$$

$$\mu: Frictional\ coefficient$$

$$N: Normal\ Force$$



One thing needs to keep in mind that:

$$f = \begin{cases} f_a & : \ f_a < \mu.N \\ \mu.N & : \ f_a \geq \mu.N \end{cases}$$

Friction also two types, static and kinetic, which is friction applies on the body when the body is at rest and in motion, respectively so the coefficient of friction is defined. The table of frictional coefficients of some materials are given:

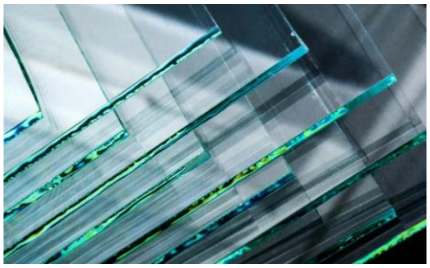
To encounter friction, grease, lubricants, oils, fine surface finish and bearings are used.

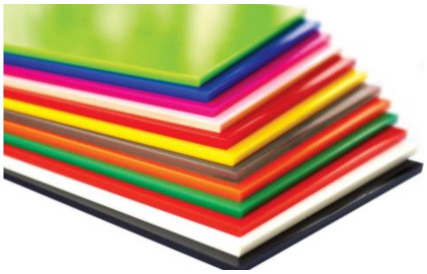
Surface Type	μ_s	μ_k
Steel on Steel	0.74	0.57
Aluminium on Steel	0.61	0.47
Rubber on Concrete (dry, wet)	1.0, 0.3	0.8, 0.25
Wood on Wood	0.25-0.5	0.2
Glass on Glass	0.94	0.4
Metal on Metal with Lubrication	0.15	0.06
Ball Bearings	--	0.001 to 0.002

2.8 *Other Useful Materials*

Other than metals many non-metals and polymers are also used for engineering applications. Some of them are mentioned below:

2.8.1 Glass, Acrylic & Polycarbonate:





Glass is a transparent, highly brittle, non-metal solid widely used as windows and aesthetics. Its Silicon Dioxide (SiO_2) that forms glass, it's heated above 1400 °C which makes the glass softer and then various methods are used to give it shape. Mainly two types of glass are there: Amorphous and Crystalline, as amorphous glass leaves sharp edges causing injury, crystalline glass is used in automotive vehicle windows, which breaks into grains preventing serious injury in accidents.

Acrylic and Polycarbonates are alternatives of glass. These are the group of plastic which come in transparent as well as many different colors. Polymethyl Methacrylate known as

Plexiglass is a common form of acrylic. It's a brittle material and widely used as aesthetic items. It's also used as waterproof color used for canvas painting.

On the other hand, polycarbonate is a stronger and lighter polymer than acrylic. It's known for its exceptional flexibility, impact resistance, heat resistance and UV protection factor. It also comes with many colors and widely used as roofing, windows and some protection shields.

2.8.2 Wood & Charcoal

Wood is a natural material, basically tree logs. They have moderate strength and weight and varies depends on the tree type. They are organic so safe to use as kitchen items as spoons and plates. Other than that, they are used to make many household items like cots, doors, windows, aesthetics and many more. Wood's main compositions is Carbon; thus, it's highly flammable. Anyway, flash point of 600 °C makes it safe to use as kitchen ware. Sometime heating it in airtight chamber, releases moisture and gas, leaving charcoal, which can be used further as fuel or activated charcoal as a good cleaning and anti-microbial agent in toothpaste and cosmetics.

2.8.3 Graphite & Diamond

Graphite is a Hexagonal Crystal of Carbon, characterized by its gray to black color, soft and smooth nature, excellent thermal and electrical conductance and very high melting point (3650 °C). It's widely used as pencil for writing for its grey color, in motors as contact brush for electrical conductance and lubrication properties, in batteries as anode, in Nuclear Reactors as moderator and as electrodes in Arc Furnace for its high melting point and electrical conductance.

On the other hand, diamond, the Tetragonal Crystal of carbon, is the strongest material on the planet. It has the highest refractive index, so its appearance like rocks, but transparent and shiny after processing. It forms naturally from fossils of trees under extreme ground temperature and pressure. It's very expensive so used as jewelries and some glass & heavy metal cutting tools.

Now, as at the end we have seen many materials, we will now see some more derived materials that are crucial for engineering applications in next chapter.

2.8.4 Carbon Fiber

Carbon fiber is a high strength low weight material developed in late 1950. It's a long thin filament of crystalline filament of carbon. Long chains of carbon fibers are bound by resin or other materials to form pipes or sheets. These sheets are basically composites and have a very high tensile strength and temperature tolerance. Also, they are extremely lightweight, for which they are used in Drones, Aircrafts, Hyper-cars, F1 cars and many more applications. As it's a brittle material, it's ultimate strength is its maximum allowed strength, which comes from 3000 to 7000 MPa with 1.6 to 2.0 g/cc density. It comes in the shape of bars, plates, pipes, sheets and more. They can be easily identified by a signature crisscross pattern. Although they are very strong, they come with a sky reaching price.

2.8.5 Fiber Glass

Fiber glass is also very thin glass fibers, bonded with resin or binding agent to form a composite material. They come with thin sheets with crisscross sewing like carbon fiber. Fiberglass has many interesting properties like they are stronger than many metals, they are very lightweight, they provide excellent insulation from heat, they are resistant to fire, corrosion and chemicals. In most cases they are used for reinforcement its other materials to provide more strength, protecting from heat, corrosion, chemicals and fire.

2.8.6 3D Printer Materials

In 3D Printer many types of filaments are used, we will see top 3 commonly used ones.

PLA: PLA stands for Polylactic Acid which is a biodegradable thermoplastic derived from corn, maize etc. It resembles clear polystyrene and provides a good aesthetic. It has medium range of strength and its very brittle material. But it's very common in 3D printers for its low cost and medium strength. It has hot-end temperature around 190 – 220 °C and bed temperature is 60 °C.

ABS: ABS stands for Acrylonitrile Butadiene Styrene; it's a thermoplastic commonly used for injection molding and also can be used in 3D printing. It has the highest strength among all common 3D printing materials. It's the same material that are used to make LEGO bricks. It's hot-end temperature is 250 °C and bed temperature is 110 °C.

PETG: PETG stands for Polyethylene Terephthalate Glycol, it's a flexible material to 3D print, to be noted flexible not elastic, means it can plasticly deform and come back to original state, but cannot be used as rubber. It's a bit translucent, and its hot-end temperature is 210 – 260 °C and bed temperature is 60 – 80 °C.

Other Materials: Now a days you can also get 3D printing of metals, carbon fibers, nylon and many more, but they don't use common conventional 3d Printers.

2.8.7 Aluminum Partitions

Aluminum partitions are aesthetic material used for interior wall. One good thing about it is it can be easily cut into pieces to assemble. It has a shiny surface because of aluminum but a soft core of composite or fibers. It's also resistant to fire from surface.

2.8.8 Polyurethane

Polyurethane are foam like sheets used for heat insulation is ac vents, home walls and in many electronic boxes which are exposed to sunlight and environment.

The End

Chapter 3

Engineering Materials II

In this chapter we are going to see some more derived materials, means products that are made from raw materials to be used in engineering and manufacturing applications. These materials we will call processed materials or inventory materials. Then we will see some more parts like bearing and Nut Bolts to sharpen the enthusiasm.

3.1 Processed Materials

Building something is pure geometry and we need proper geometrical shapes to be used in building something. But raw materials after being extracted from ore, they are very uneven chunks. So, industries process the raw materials into various shapes like rectangular blocks, cylindrical blocks, thin and thick plates, balls and angles etc. These new materials we will call processed materials, until we found a better name. As understanding the process of manufacturing these processed materials will be out of scope of this thesis, we will directly go and see them.

3.1.1 Rectangular Blocks:

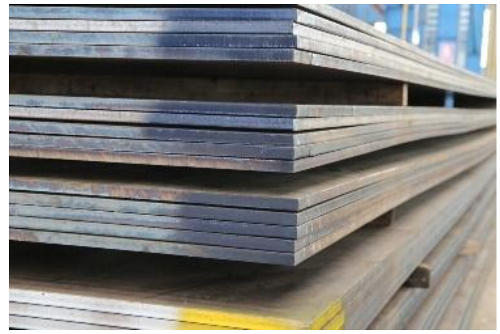
Rectangular blocks are primarily used for subtractive manufacturing by cutting into smaller pieces or by removing extra material to give it a shape. It’s used to crate parts from a single block, like carving an idol in stone. As a simple rectangle or more accurately orthogonal, we just need 3 parameters, length, breadth and height. If it’s a cube, we just need one parameter, just the side. Metal blocks can come in various size from few mm to many meters.

3.1.2 Rods

Rods come with 2 types: solid cylinders and hollow cylinders. Solid rods require 2 parameters to be fully defined: Diameter and Height, while hollow rods require 3: Inner Diameter (ID), Outer Diameter (OD) and Height (h). Cylindrical blocks are used to make shafts, axes, pillars and supports etc.

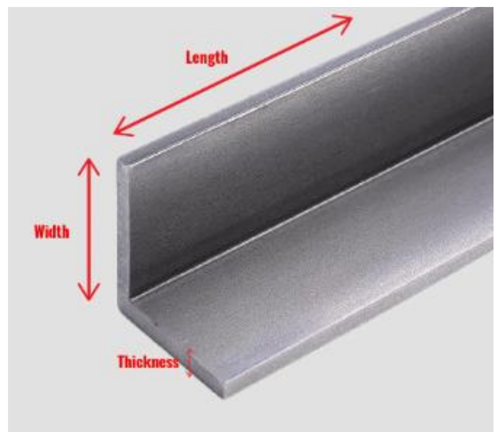
3.1.3 Plates

Plates are used for many purposes, they can be cut into smaller pieces and joined together to make complex geometry. Or they can be used to shield some parts or to provide an even base for other equipment. They also need three parameters to be defined: length × breadth and thickness. They can be available in really small thickness (~mm) which are called sheets. They also available in perforated design.



3.1.4 Angles

Angles are materials as shown in the diagram. They have excellent strength against bending due to their geometry. As a plate can be easily bent through its surface but hard from its edge, in this geometry there is always at least one side that experience bending force along its edge under external load, explaining their durability. They generally com with 90° angle and equal width on both sides. They also need 3 parameters to be defines: width, thickness and length. Many things like boxes, truss and frames can be made from them by cutting and welding.



3.1.5 Pipes

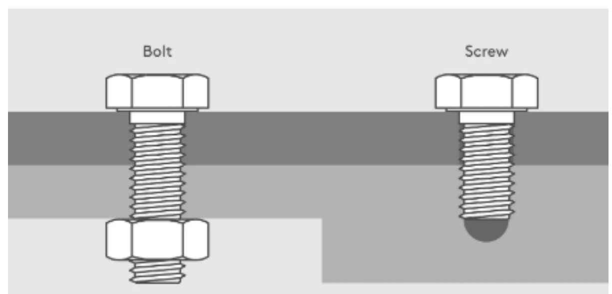
Pipes are basically hollow cylinders with very small thickness compared to diameter. They come with round as well as square and many other shapes. Round one need three parameters: diameter, thickness and length / ID, OD & h. The square one also has three: side, thickness and length. As the pipe gets any different geometry, number of parameters differs accordingly. They can be used for fluid transfer as well as support in many structures.

3.1.6 *Extruded Bars*

Extruded bars special lateral cross section designed for specific use. In the diagram an aluminium extruded bar is shown used to make CNC and 3D printer frames. They are formed by pushing a block through a nozzle, as a toothpaste forms a cylindrical shape on brush, the extruded bars take the shape of the nozzle. They are also used in making window supports, partition rooms, home & office interiors and many more.

As we have seen many processed materials, there are many more like I bars & steel balls. But it’s time to see some useful materials in structural engineering. They may be inferred as second processed materials.

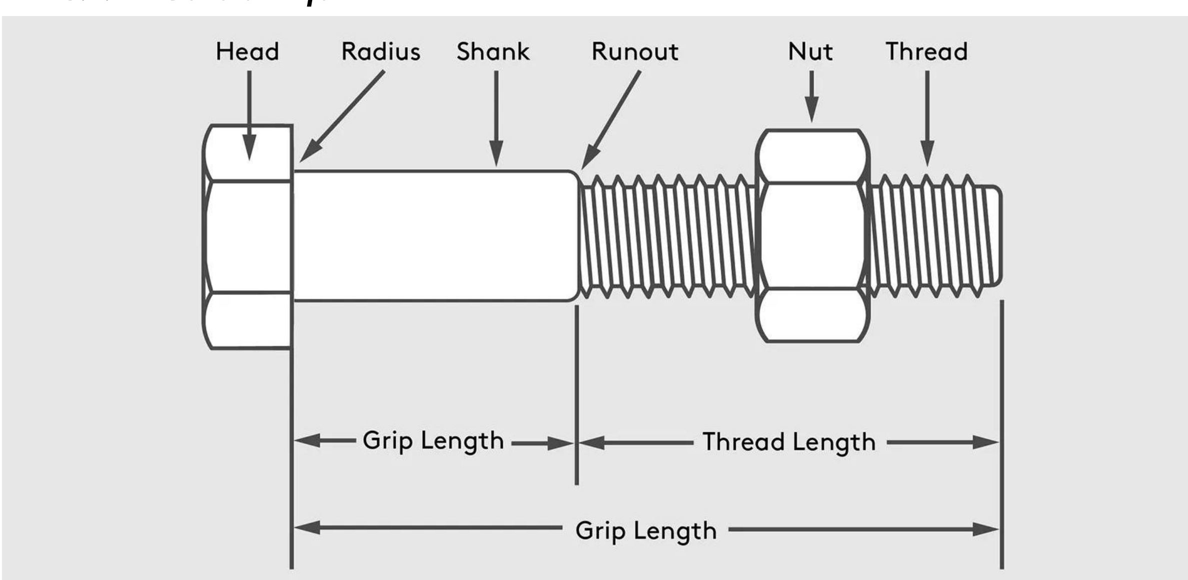
3.2 *Nut – Bolts*



Nut & bolts are very important inventions to the engineering field. They are helpful in joining materials. A picture of using nut-bolts is shown in the diagram. Another variety is called screw; this doesn’t require a nut and fastens itself to a material.

There any many types of nut & bolts which we will see later but before that there are a few things to know about a nut and bolt.

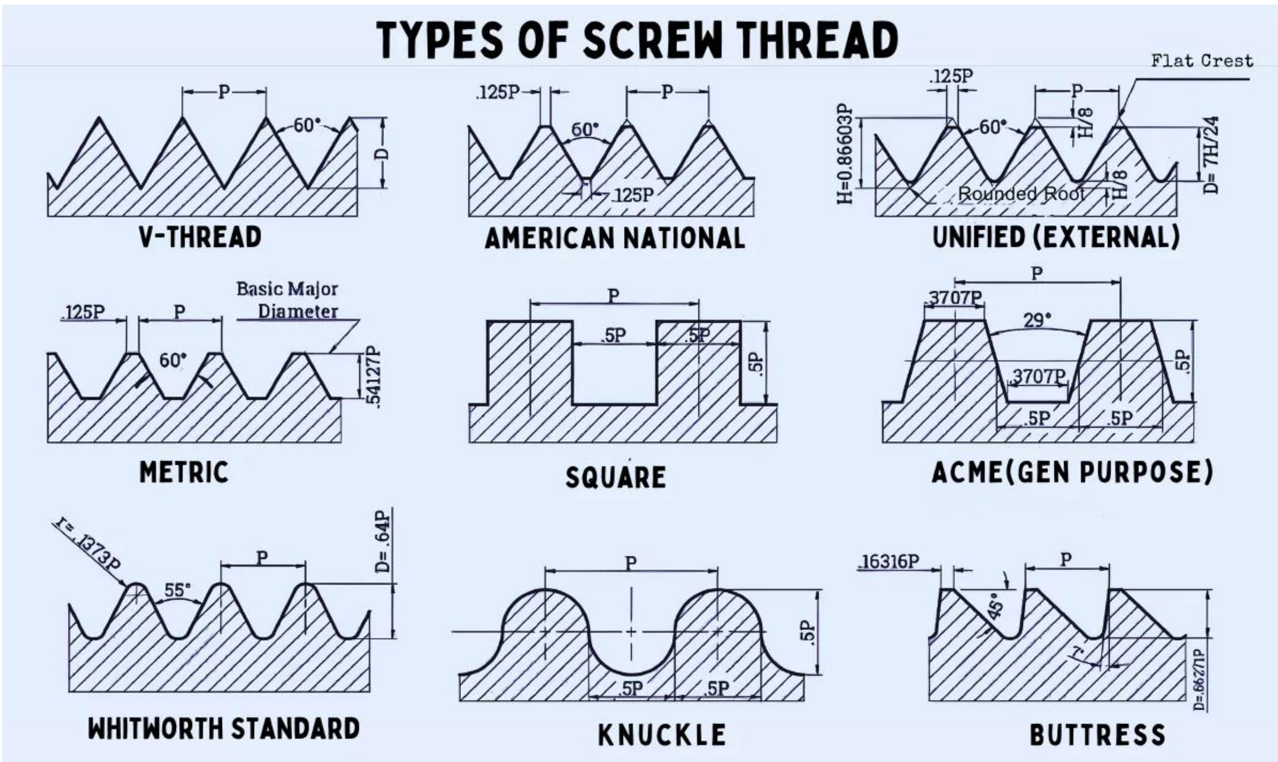
3.2.1 *General Info*



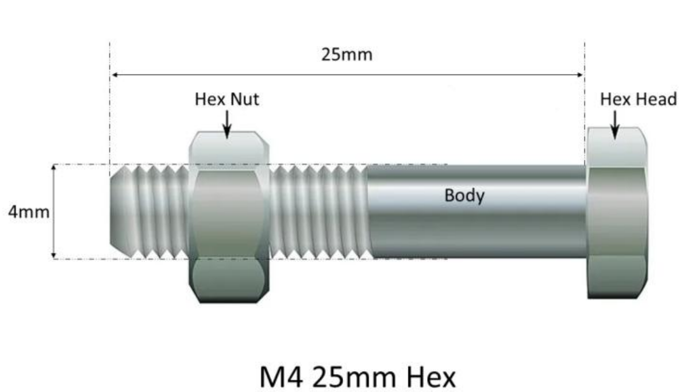
The above diagram shows a general bolt and nut fastened together. Various type of nut-bolt pair is there for many applications. For those who don't know how it works, due to the helical threading, the nut moves forward by rotating; to fasten 2 parts, the bolt is inserted through a common hole of 2 parts and the nut is rotated using a tool. Fastening more increases stress in the bolt which holds the two parts together.

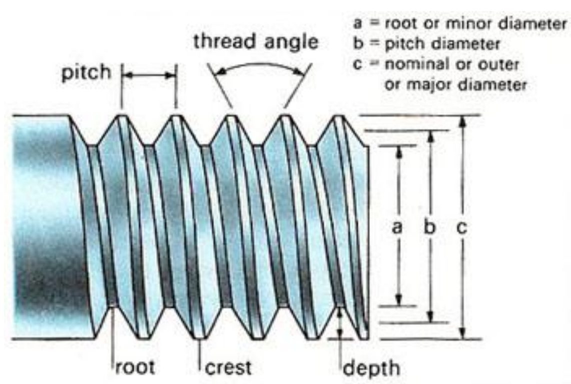
3.2.2 Threading

The nut bolts have many types of threads, shown in the diagram.



While all the threading type has their own purposes, but in general metric threading is used in most applications. The metric nut – bolts are named as M4, M5, M10 etc. While M stands for Metric threading and the number next to it represents the nominal diameter of the bolt in mm. Ex given for a M4 25mm nut bolt and some detail about threading is given:





Nut – bolts require minimum three parameters to be fully defined – Call name (M5, M4 etc.), length of the bolt and head type. The parameters can be increased to material type, head type and many more. One important thing to consider is a nut and a bolt will only fit if they have same type of threading.

3.2.3 Hex Nut Bolt

Hex nut bolt has a hexagonal head and hexagonal nut. They are fastened by wrench, spanners or ratchets.




3.2.4 CHHD Nut Bolt

CHHD stands for Cheese Head Hex Head Drive. They have a minus or a plus groove on its head. They can be fastened by nuts, but can also be fastened to materials directly with threading on it. If it’s used as a screw, screwdriver is needed to fasten it.



3.2.5 Allen Bolt

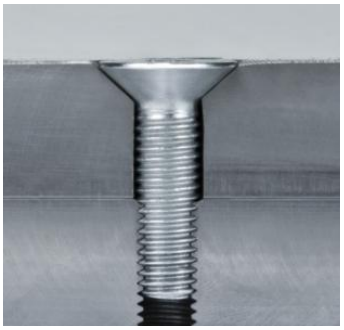
The Allen bolts have a hexagonal slot on its head. It can only be fastened with an Allen Key.




3.2.6 Countersunk Nut Bolt

The countersunk bolt has a tapered head; it allows it to fit into materials keeping the surface leveled. It also needs a screwdriver or Allen Key to be fastened.





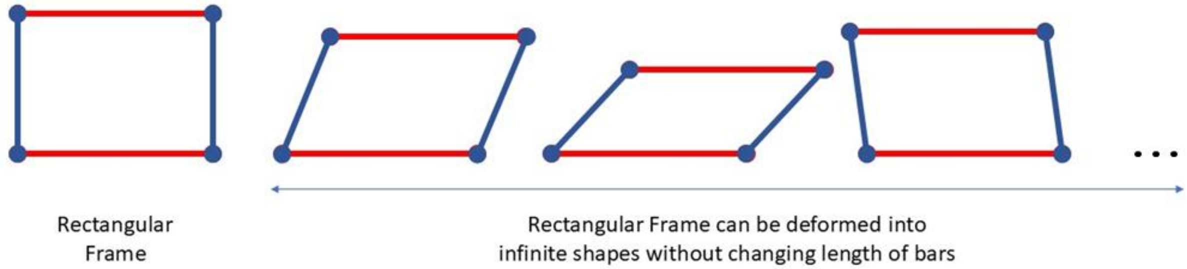
There are many more screw types and respective screwdriver to fasten them. In the underline of it, they all are fastened by rotating them.

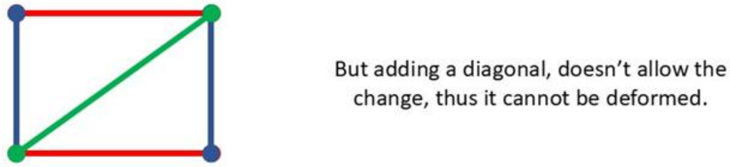
3.3 Truss

Trusses are everywhere. They are these triangular mesh structures shown in the diagram. They help save material cost and ultimately become lightweight and provide excellent strength.




One thing someone need to know is, trusses are made by joining bars at its end. So, at the joints, the bars can rotate and change angle. Thus, let us make something clear which is joints will definitely deform with many angles. Then:





That’s one to think about the strength of trusses. Trusses are very helpful when building large, lightweight structure with material and cost limitations. Many bridges, houses, large equipment and architecture showcase also prefer this.

3.4 Bearings

Bearings are used to fix axes or shafts; they provide tight support and low friction to rotation. One of a common design is ball bearing, the balls roll along to smoothly rotate the axis. Apart from ball bearing many other types of bearing available for various purposes.

Deep Groove Ball Bearing

Angular Contact Ball Bearing

Self-Aligning Ball Bearing

Cylindrical Roller Bearing

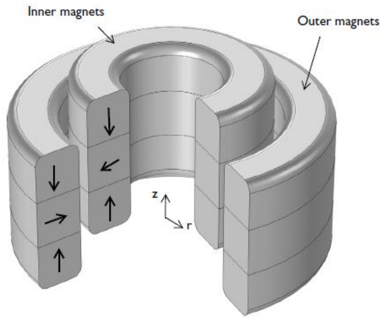
Tapered Roller Bearing

Spherical Roller Bearing

Needle Roller Bearing

Thrust Ball Bearing

Plain Bearing (Bushing)



Magnetic Bearing

Fluid Bearing

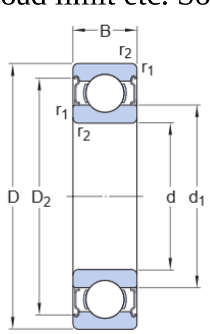
Jewel Bearing

Sometimes bearings come with their blocks. Two widely used block bearings are pillow bearing and flange bearing.

Pillow Bearings

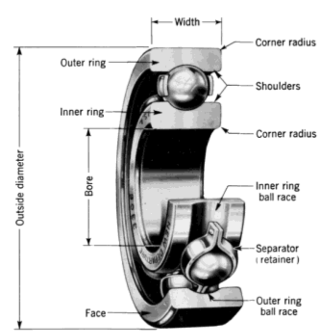
Flange Bearings

While selecting a bearing many factors needs to be chosen, like bore diameter, outer diameter, load limit etc. Some important information from SKF 6304 website is given below.



Dimensions

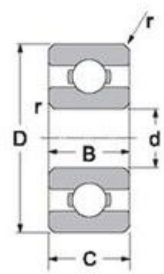
d	20 mm	Bore diameter
D	52 mm	Outside diameter
B	15 mm	Width
d_1	≈ 30.35 mm	Shoulder diameter
D_2	≈ 44.71 mm	Recess diameter
$r_{1,2}$	min. 1.1 mm	Chamfer dimension

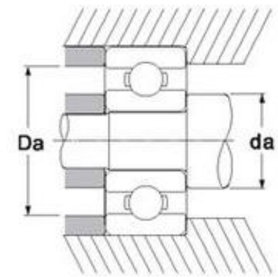


Bearings have a call name like 6202, 6000, 6305 etc. Detailed information can be found on SKF Website, they are a leading bearing manufacturer. Details various bearings with their dimensions and load limit can be found on https://www.skf.com/in. Here's a table of different bearings of 63XX series with dimensions:

DEEP GROOVE BALL BEARINGS

63 Series





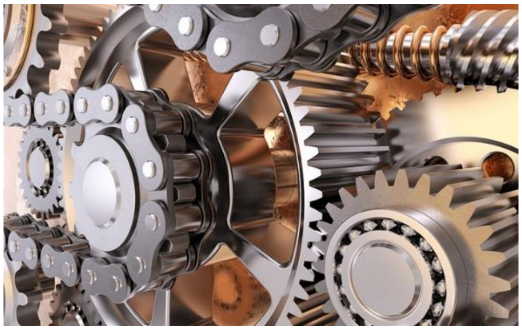
Any combination of closures is available

Basic Bearing No.	Nominal Bearing Dimensions						Preferred Shoulder Diameters							
	d		*D*		*B,C*		*r* (min)		*da* (min)		*da* (max)		*Da* (max)	
	mm	inch	mm	inch	mm	inch	mm	inch	mm	inch	mm	inch	mm	inch
635	5	0.1969	19	0.7480	6	0.2362	0.3	0.012	7.0	0.276	9.5	0.374	17.0	0.669
636	6	0.2362	22	0.8661	7	0.8661	0.3	0.012	...	...	...	...	...	...
637	7	0.2756	26	1.0236	9	0.3543	0.3	0.012	...	...	...	...	...	...
638	8	0.3149	28	1.1024	9	0.3543	0.3	0.012	10.0	0.394	...	...	26.0	1.024
639	9	0.3543	30	1.1811	10	0.3937	0.6	0.024	...	...	...	...	...	...
6300	10	0.3937	35	1.3780	11	0.4331	0.6	0.024	14.0	0.551	17.0	0.669	31.0	1.220
6301	12	0.4724	37	1.4567	12	0.4724	1.0	0.039	16.7	0.656	18.5	0.728	32.0	1.260
6302	15	0.5906	42	1.6535	13	0.5118	1.0	0.039	19.8	0.781	23.0	0.906	37.0	1.457
6303	17	0.6693	47	1.8504	14	0.5512	1.0	0.039	22.0	0.866	25.5	1.005	42.0	1.654
6304	20	0.7874	52	2.0472	15	0.5906	1.1	0.043	25.8	1.016	28.5	1.122	45.5	1.791
6305	25	0.9843	62	2.4409	17	0.6693	1.1	0.043	31.0	1.220	36.0	1.418	55.5	2.185
6306	30	1.1811	72	2.8346	19	0.7480	1.1	0.043	36.5	1.437	43.0	1.693	65.5	2.579
6307	35	1.378	80	3.1496	21	0.8268	1.5	0.059	42.9	1.688	47.0	1.850	72.0	2.835
6308	40	1.5748	90	3.5433	23	0.9055	1.5	0.059	48.0	1.890	54.0	2.126	82.0	3.228
6309	45	1.7717	100	3.9370	25	0.9843	1.5	0.059	53.0	2.087	61.5	2.421	92.0	3.622
6310	50	1.9685	110	4.3307	27	1.0630	2.0	0.079	59.0	2.323	68.5	2.697	101.0	3.976
6311	55	2.1654	120	4.7244	29	1.1417	2.0	0.079	64.0	2.520	74.0	2.913	111.0	4.370
6312	60	2.3622	130	5.1181	31	1.2205	2.1	0.083	71.0	2.795	80.5	3.169	119.0	4.685
6313	65	2.5591	140	5.5118	33	1.2992	2.1	0.083	76.0	2.992	86.0	3.386	129.0	5.079
6314	70	2.7559	150	5.9055	35	1.3740	2.1	0.083	81.0	3.189	92.5	3.642	139.0	5.472
6315	75	2.9528	160	6.2992	37	1.4567	2.1	0.083	86.0	3.386	99.0	3.898	149.0	5.866
6316	80	3.1496	170	6.6929	39	1.5354	2.1	0.083	91.0	3.583	105.0	4.134	159.0	6.260
6317	85	3.3465	180	7.0866	41	1.6142	3.0	0.1181	98.0	3.858	112.0	4.409	167.0	6.575
6318	90	3.5433	190	7.4803	43	1.6929	3.0	0.1181	103.0	4.055	118.0	4.646	177.0	6.968
6319	95	3.7402	200	7.8740	45	1.7717	3.0	0.1181	108.0	4.252	125.0	4.921	187.0	7.362
6320	100	3.9370	215	8.4646	47	1.8504	3.0	0.1181	113.0	4.488	113.0	5.240	200.0	7.913

★ We reserve the right to change specifications and other information included in this catalogue without notice.

056 HCH Bearings

3.5 *Gears & Timing Pulley*



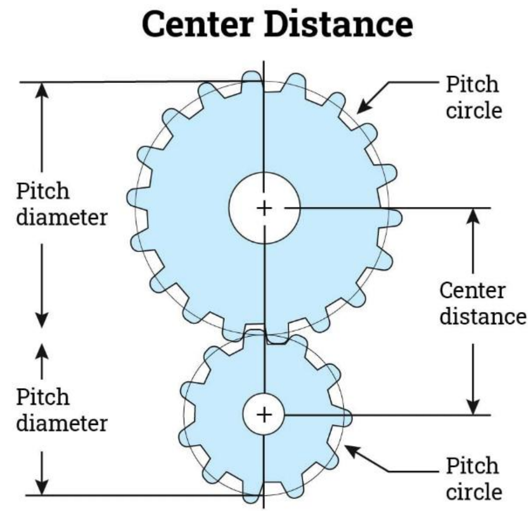
Gears are another important invention. They fall in the category of motion transmission. They use the technique of liver to get increased torque / speed / accuracy. They are used in almost every automotive and in many machines. They also come with various sizes and material. There are many types of gears, some of them are shown below:

In general spur gear are used as they are easy to manufacture and have great performance. Other types of gears are used for specific application. But learning something about spur gear will help a lot.

3.5.1 *Spur Gear*

Spur Gears are simple straight teethed wheels. They are connected to shaft which are parallel to each other. Bevel and mitre gears are intersecting axis gears where worm gears are off axis gears.

A spur gear must have minimum four parameters to be fully defined: **Module, No. Of Teeth, Face width & Bore diameter**. There are many more parameters as Hub diameter and width, keyway, pitch diameter etc. Let's see them in detail.



- Face width is the thickness of the gear
- No. of teeth is number of teeth in the gear.
- Bore diameter is the diameter of the bore.
- Module is a number which is basically width of a single teeth.

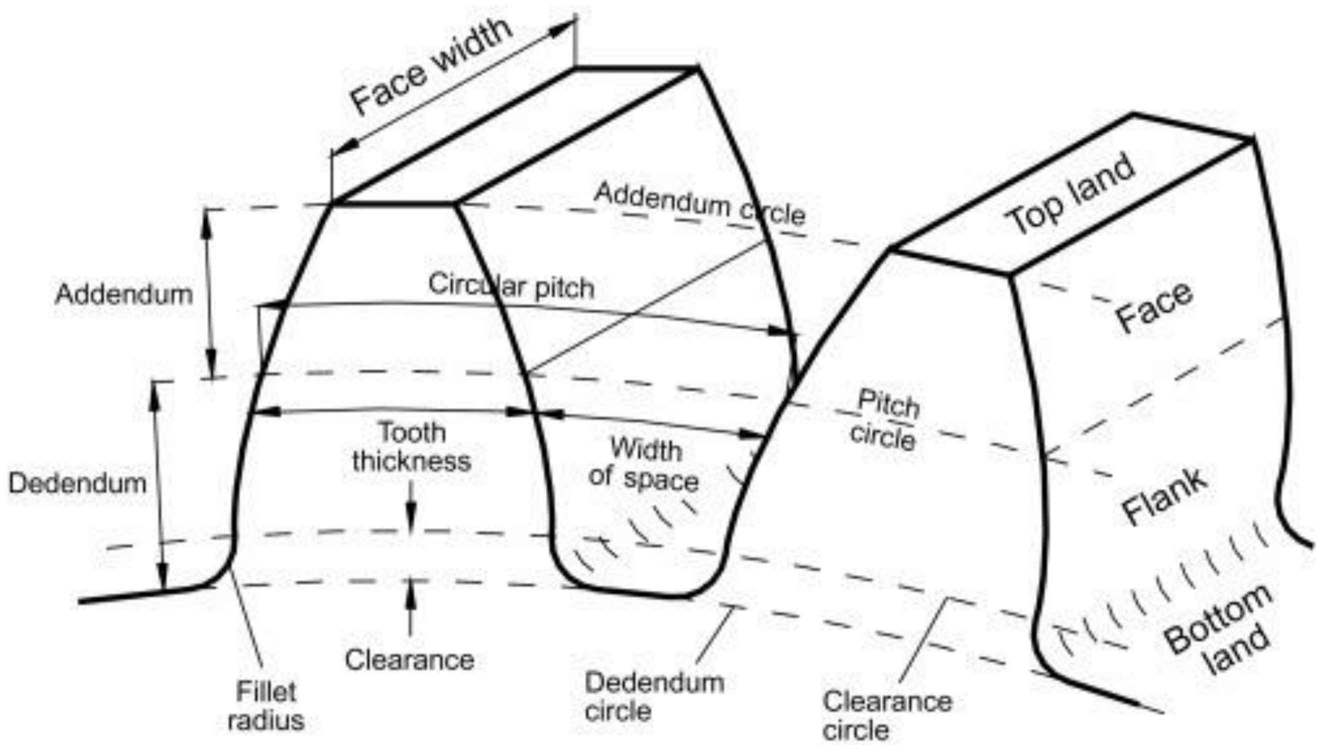
Module has a formula to be known:

$$\boxed{module = \frac{Pitch\ Diameter}{No.of\ Teeth}}$$

It can be derived as:

$$circular\ teeth\ width = \frac{pitch\ circle\ perimeter}{2 \times number\ of\ teeth} = \frac{\pi \times d}{2 \times n} = {}^{\pi}/_{2}\, m$$

Therefore, module is proportional to teeth width. It's independent of gear dimensions and for two gears fit perfectly, they must have the same module. Given below a diagram of more information about a gear.



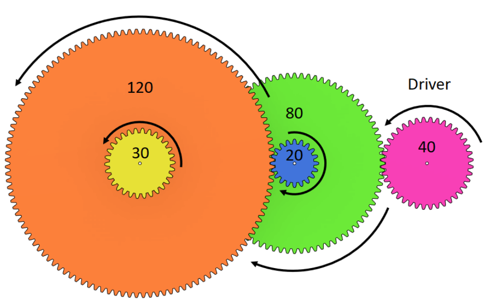
3.5.2 Timing Pulley

Timing Pulley use a similar type of teethed wheel, but instead of connecting directly to other wheel, they are connected by a timing belt. Timing belt has teeth and act as a pulley rope. A popular type of timing belt and pulley is GT2 given on the diagram. They also come in various size for different application. They are used in 3D printers and many small CNCs.

3.5.3 Gear Ratio

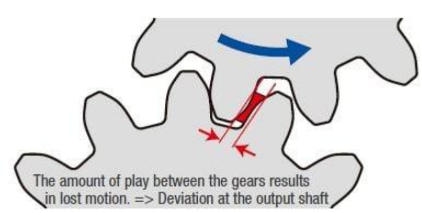
Gear ratio is the ratio of number of teeth of input gear and that of output gear. Mathematically it's also the ratio of pitch diameter of both gears. This also applies to timing belt. This shows how much the torque will increase & speed will decrease. For ex:

- Input gear has 20 teeth
- Output gear has 60 teeth
- Therefore, Gear ratio = 60:20 :: 3:1
- Therefore, input gear will rotate thrice for every one rotation of output gear. Therefore, speed will decrease 3 times, and torque will increase 3 times.



In a series of gear, gear ratio multiply, for ex given:
Gear ratio in first 2 gears = 80:40 :: 2:1
Gear ratio in last 2 gears = 120:80 :: 3:2
Therefore total gear ratio = 3/2 × 2/1 = 3/1 = 3:1

3.5.4 Backlash



Backlash is the gap between two teeth which is made during fitting. This backlash adds a loss of motion in output from input. In timing pulley it's absent as tight fitting of timing belt.

The End

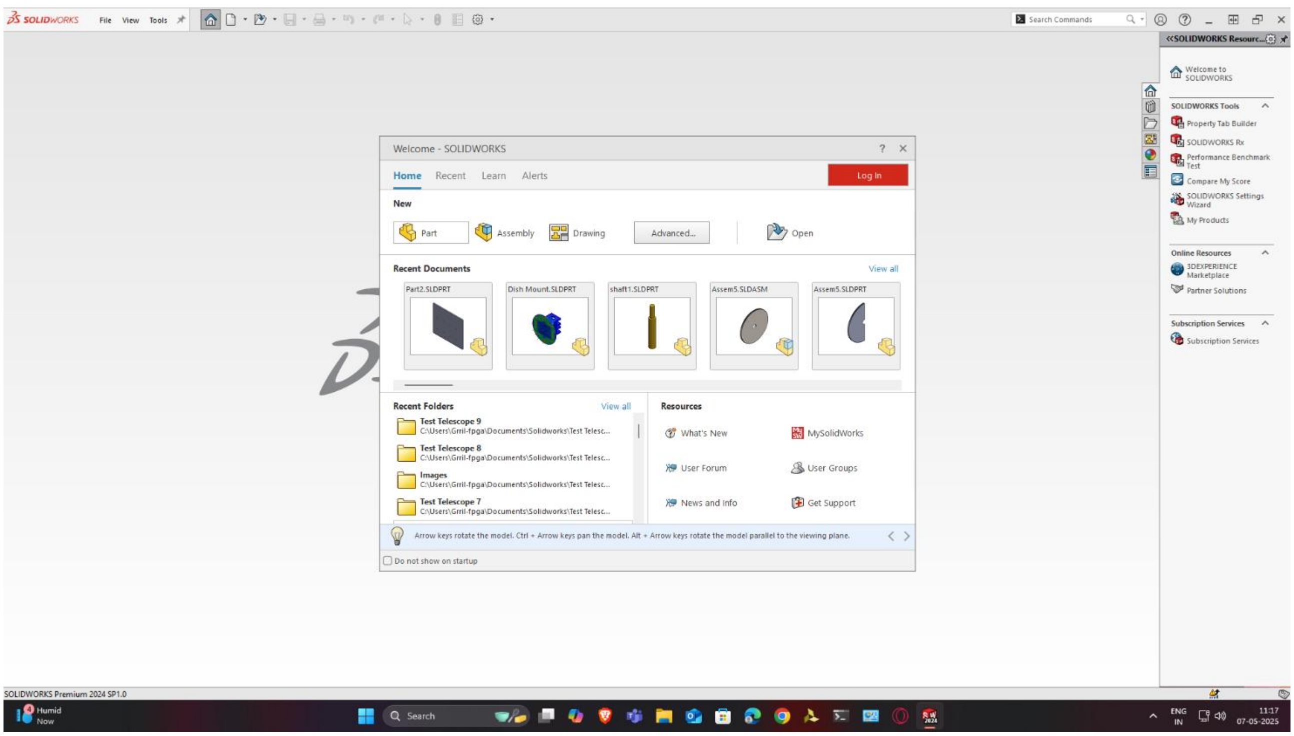
Chapter 4

Computer Aided Design

CAD is a computer program where we can create 3D geometries from 2D sketches using Extruded Boss and Extruded Cut like lot of features. It's important for mechanical engineers for designing machine, doing a motion study and analyze structural integrity. Here some basic functions are shown for CAD using SolidWorks. The opening interface is shown below.

4.1 Introduction to SolidWorks

SolidWorks was developed by Dassault Systems on 1^{st} Nov 1995 and was the first CAD software able to be run on a Personal Computer. After you open the software, you will see a pop window like below:



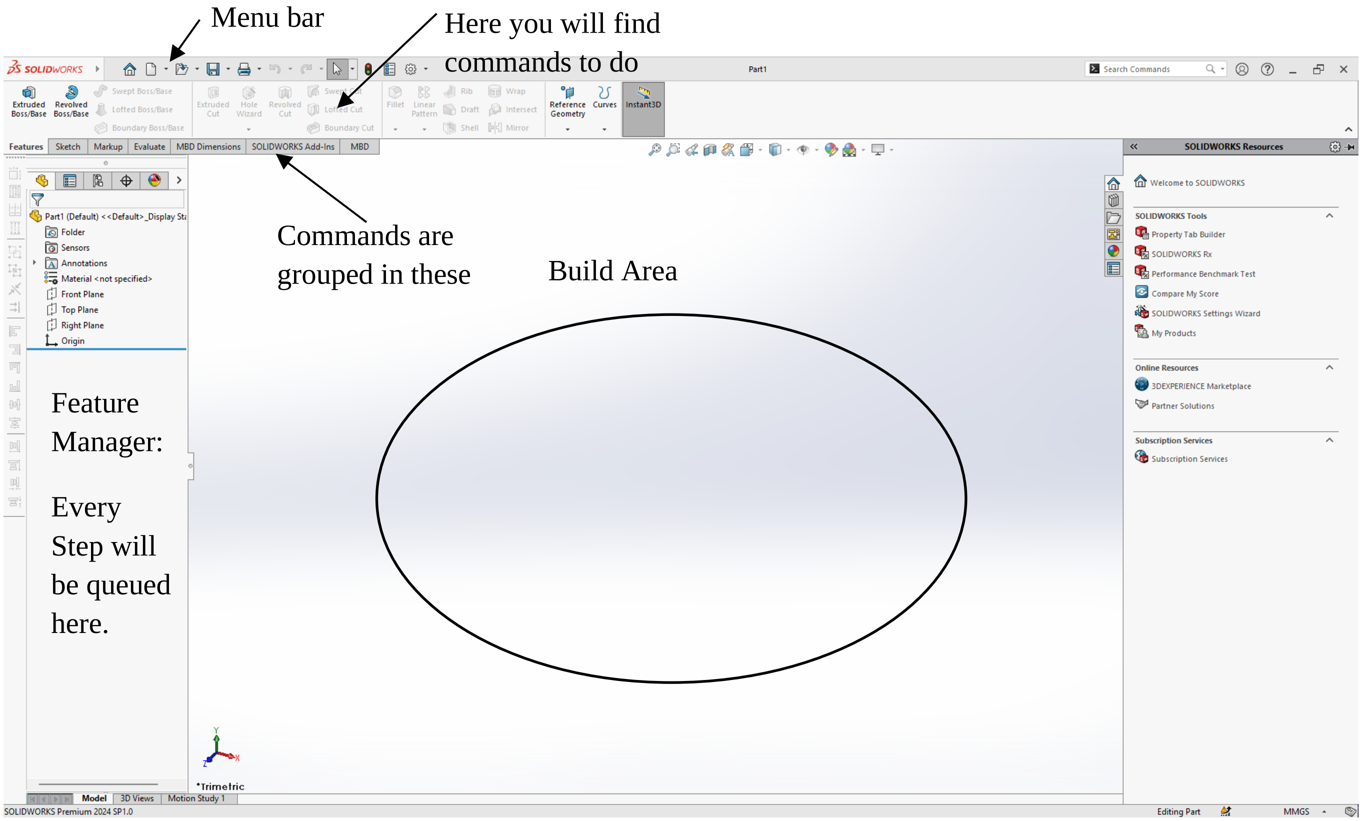
There are previous designs you can open, there are 3 more options:

Part: Click to build a new part

Assembly: Click to join previous made parts to form a full machine

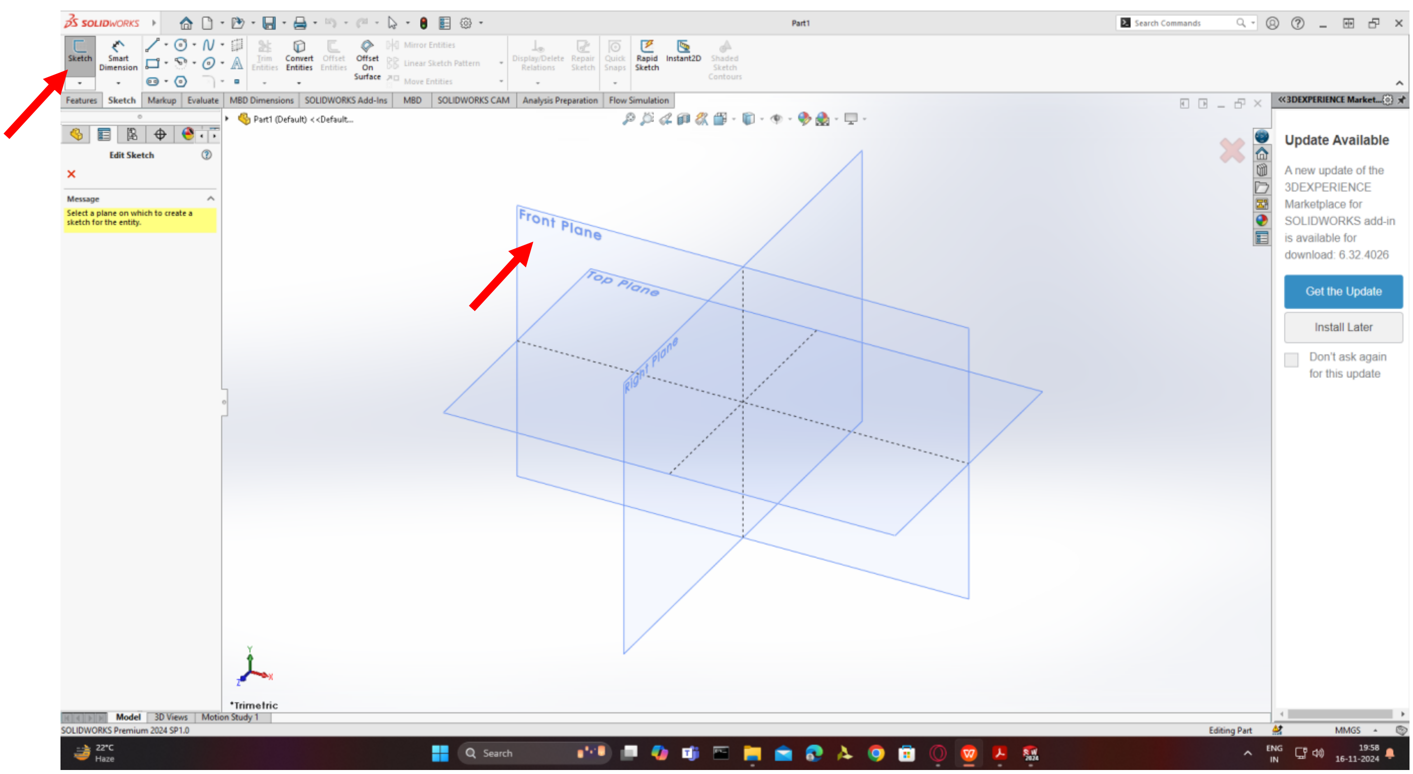
Drawing: Click to make an engineering drawing of a previous made part

So, when you click part for a new design, you will see an Interface as below:

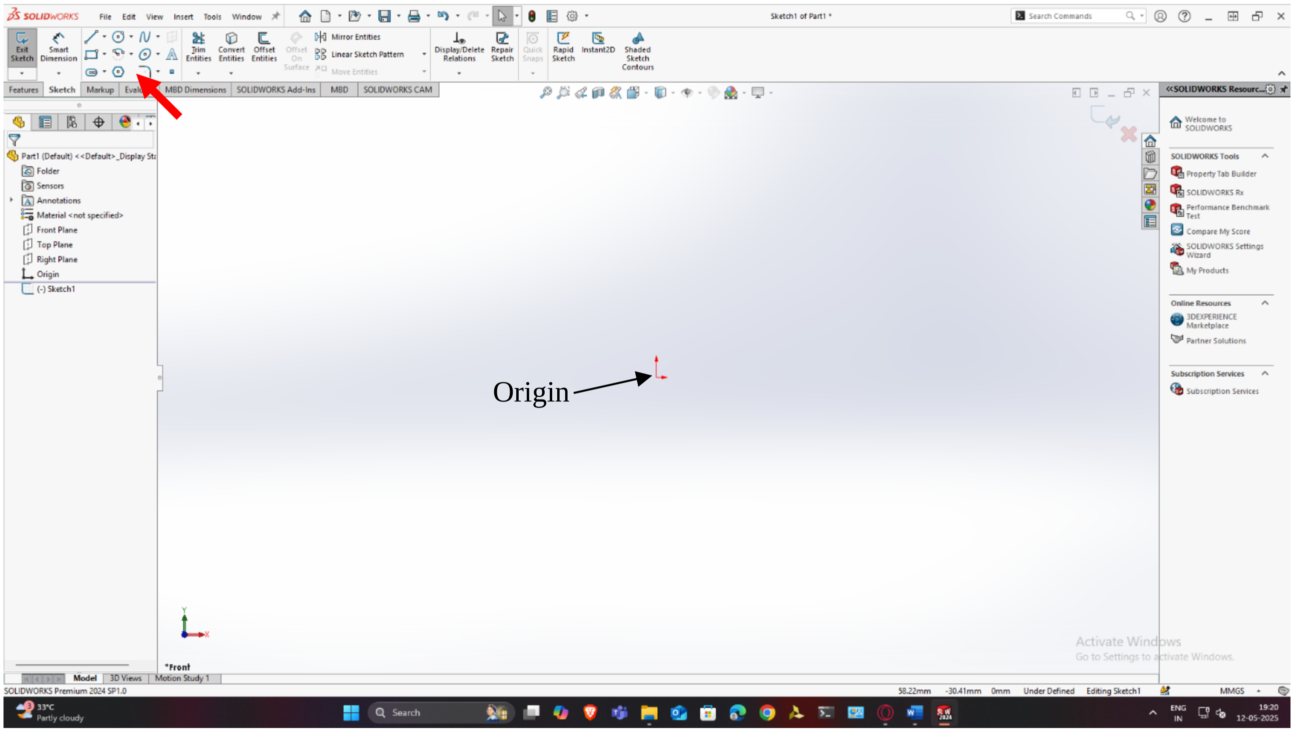


4.2 *Start With a Sketch*

First click the sketch tab → sketch. Following interface should open, then you need to select the plane, usually front plane is selected as x & y axis are on it. So, click on the front plane.



After clicking front plane, it will automatically align with the screen. You also will find a lot of drawings tools like line, circle, square etc. You can draw anything on it. Then you need to draw one face of the face of the part you need to draw, and you can then convert that 2d surface to a 3d part with Extruded Boss feature.

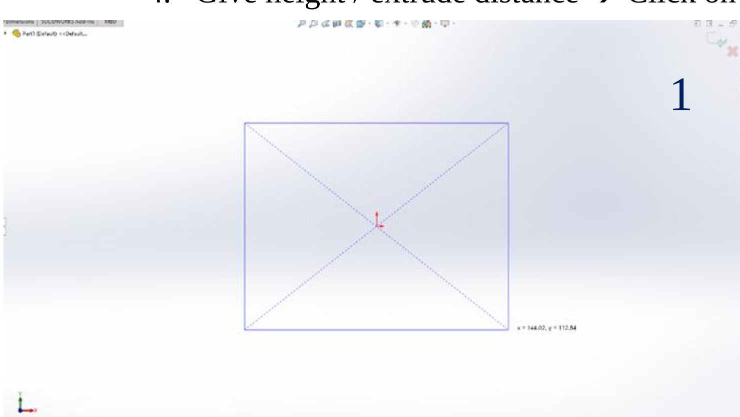


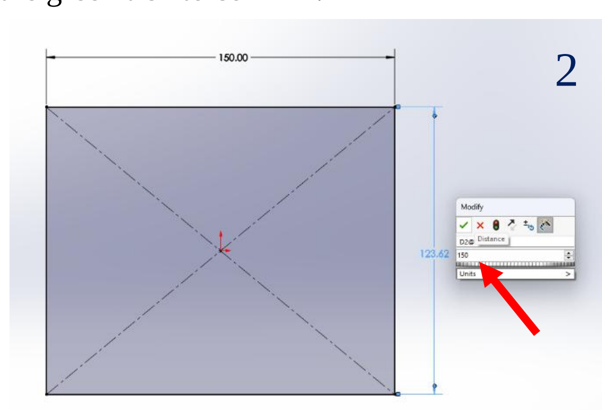
4.3 *Boss / Cut*

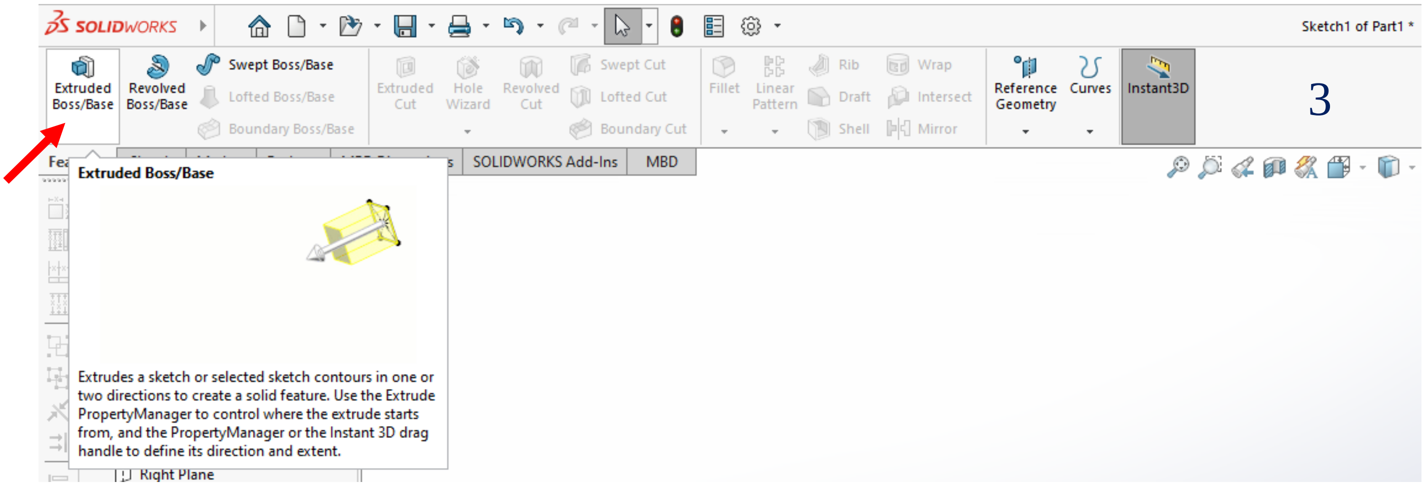
Boss and Cut are used to make 2d sketches into 3D. There are many types:

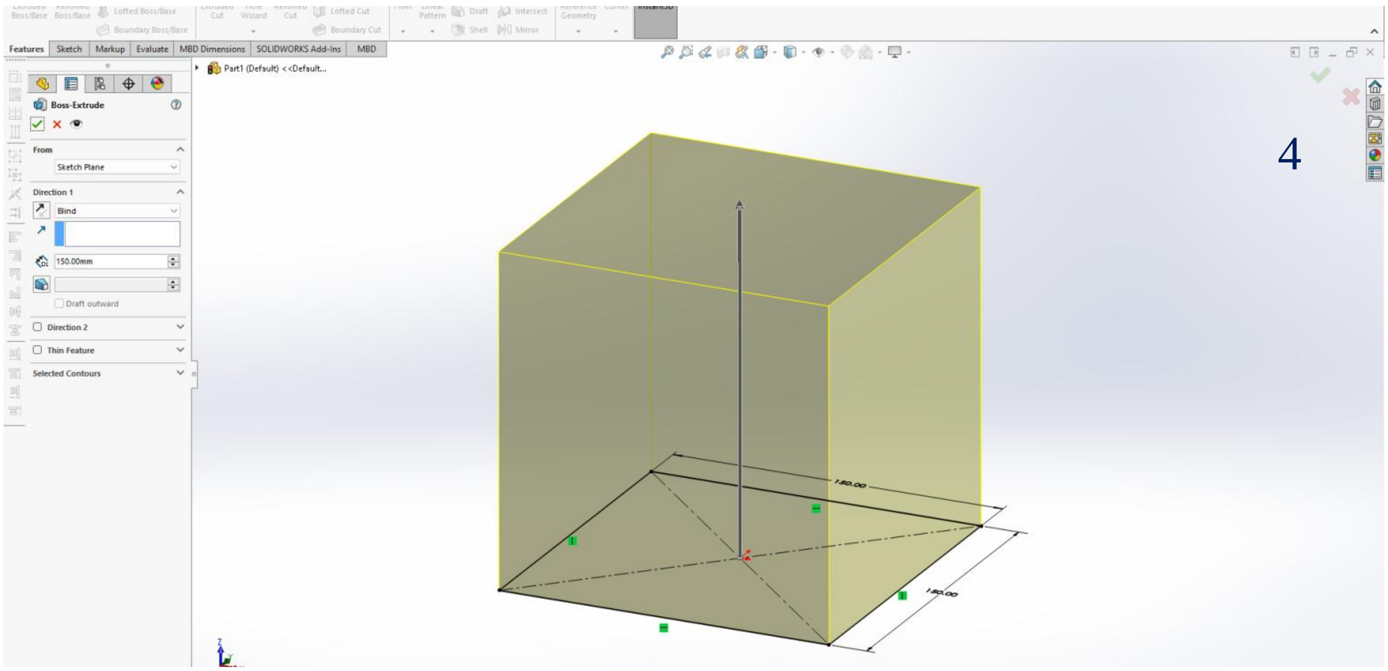
4.3.1 *Extruded Boss & Extruded Cut:*

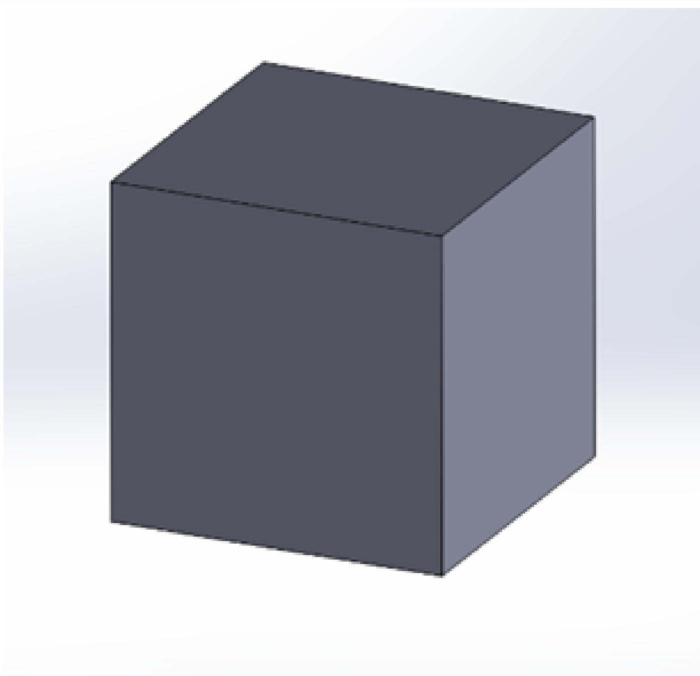
1. Draw a shape, rectangle for example using rectangle tool.
2. Use smart dimensions to give dimension to sides.
3. Click Features Tab → Boss Extrude.
4. Give height / extrude distance → Click on the green tick to confirm.





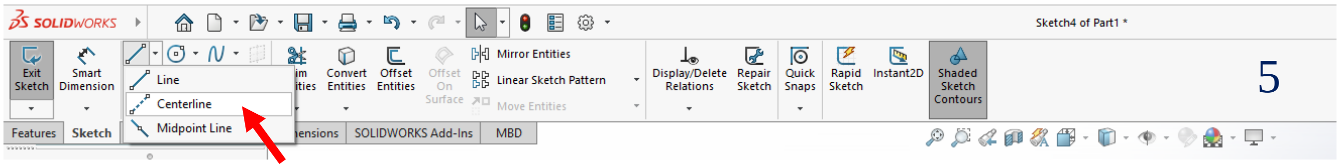


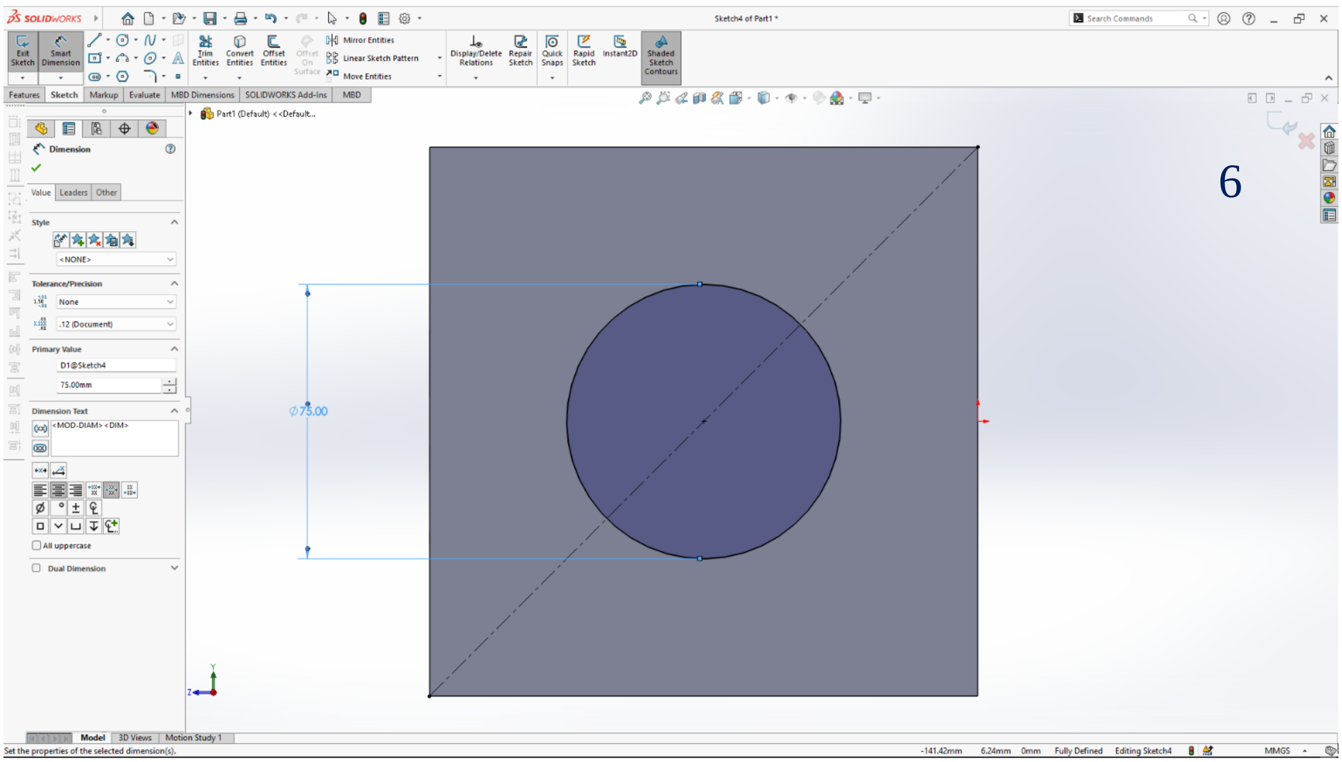


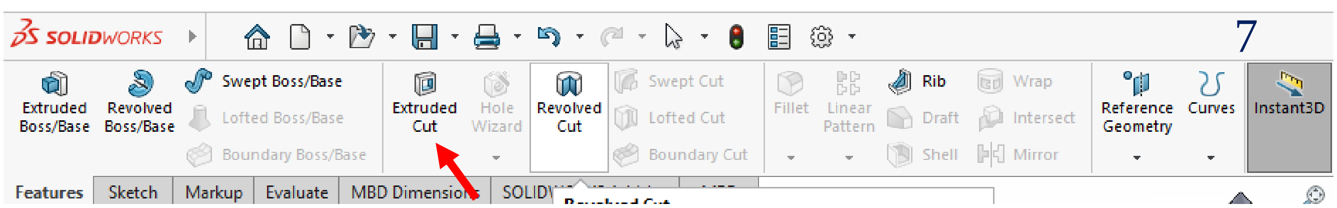


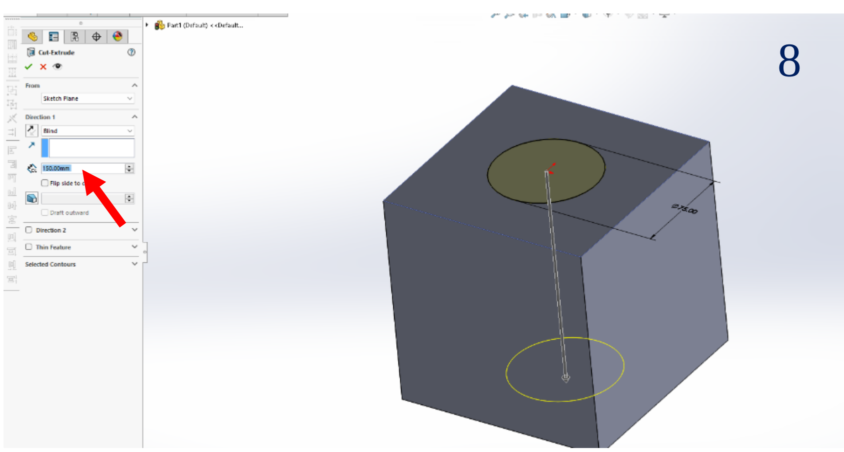
The resulted cube is shown in the diagram.

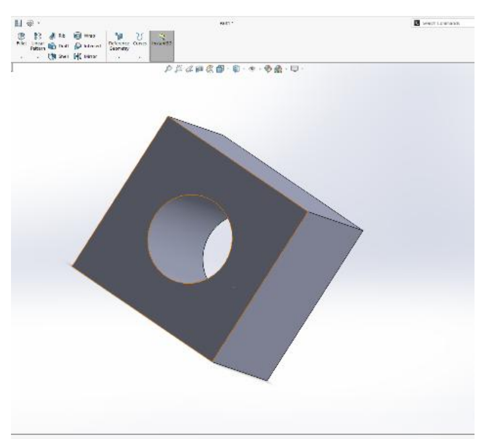
5. To get a reference point, draw a centerline a diagonal on the cube.
6. Draw a circle on it. Add dimension with smart dimensions.
7. Click Features Tab → extruded cut.
8. Give extrude value / depth. Then click the green tick.



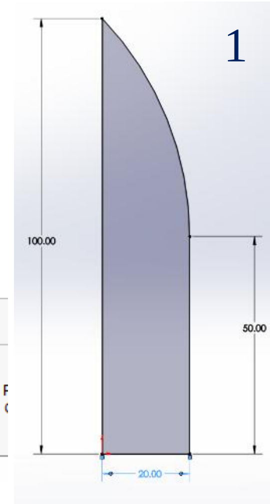




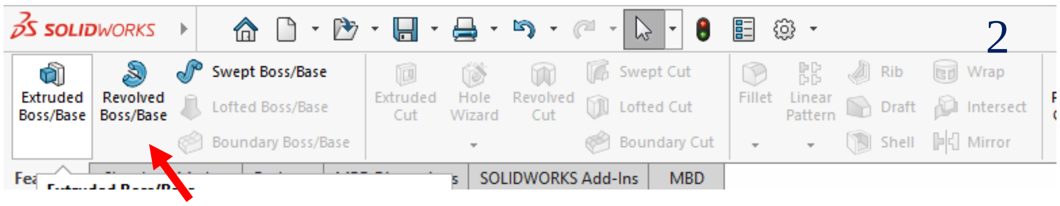


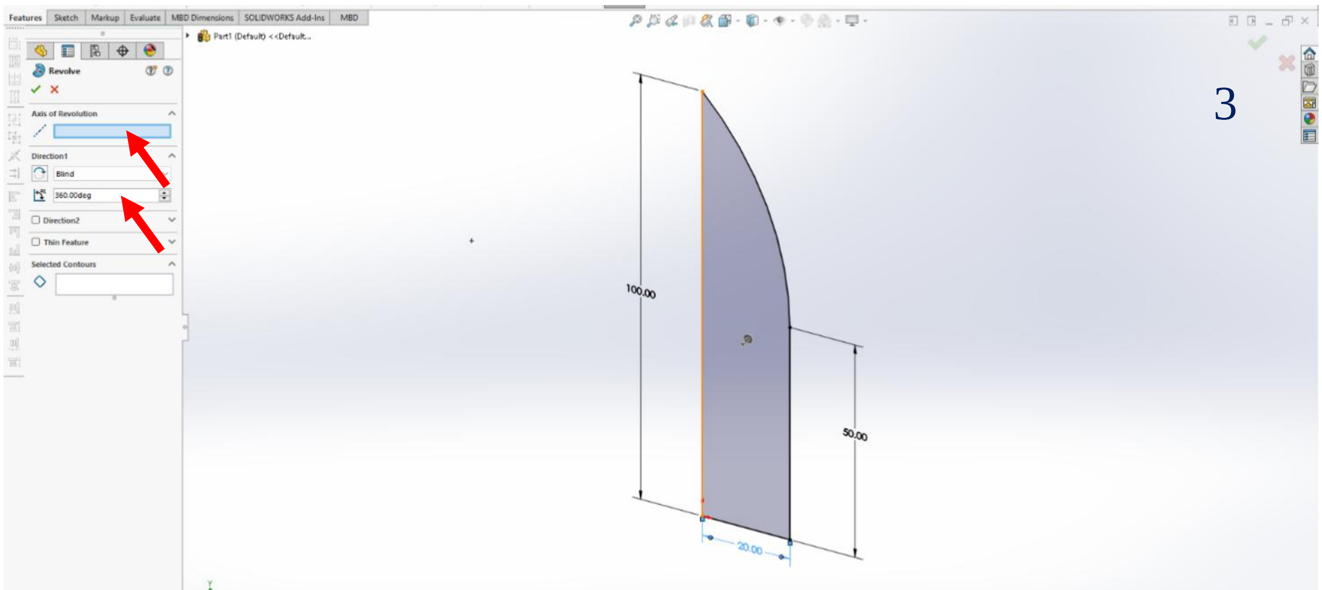


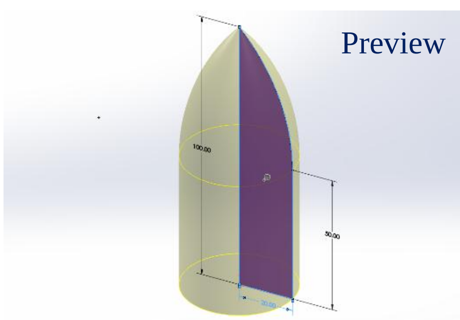
4.3.2 Revolved Boss & Revolved Cut:

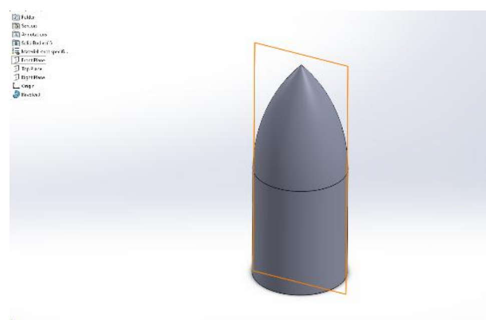


1. Draw a shape with one edge on which the revolution will be done.
2. Click on Features Tab → Revolved Base.
3. Select axis of revolution and give angle to be revolved. For a full rotation give 360°. Then click green tick.



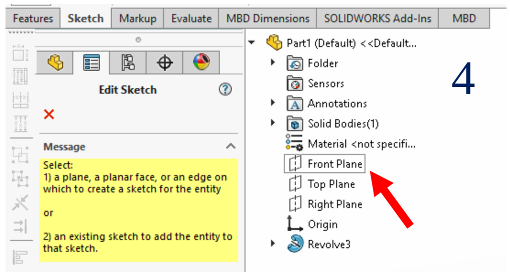




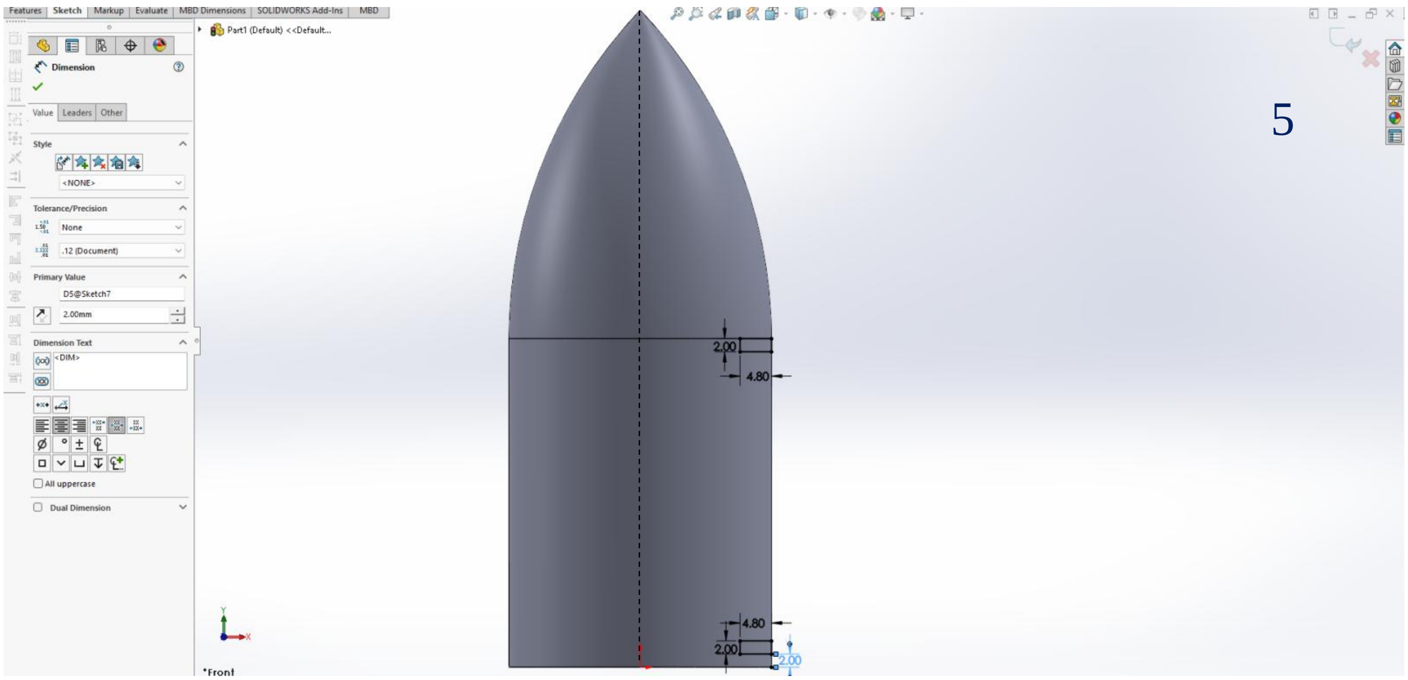


4. For revolved cut, select the same plane on which revolved boss was done. Click on the feature tree for this.
5. Draw the surface needs to be revolved cut. Also add a centerline for axis of revolution.
6. Click Features Tab → Revolved Cut.
7. Give Axis of revolution & angle of revolution → click the green tick.
8. Add color if you want (optional).

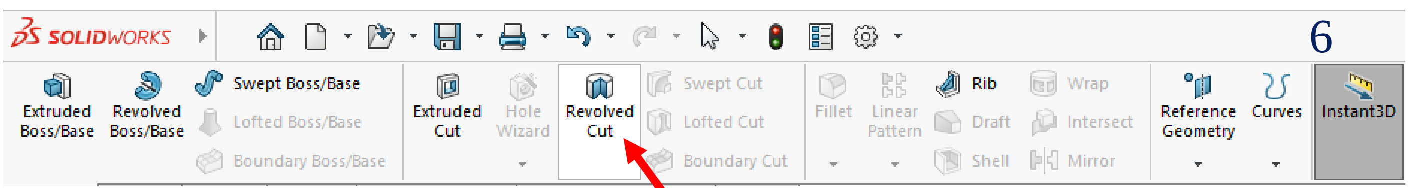
4


Features
Sketch
Markup
Evaluate
MBD Dimensions
SOLIDWORKS Add-Ins
MBD
Edit Sketch
Message
Select:
1) a plane, a planar face, or an edge on which to create a sketch for the entity
or
2) an existing sketch to add the entity to that sketch.
Part1 (Default) <<Default...
Folder
Sensors
Annotations
Solid Bodies(1)
Material <not specifi...
Front Plane
Top Plane
Right Plane
Origin
Revolve3

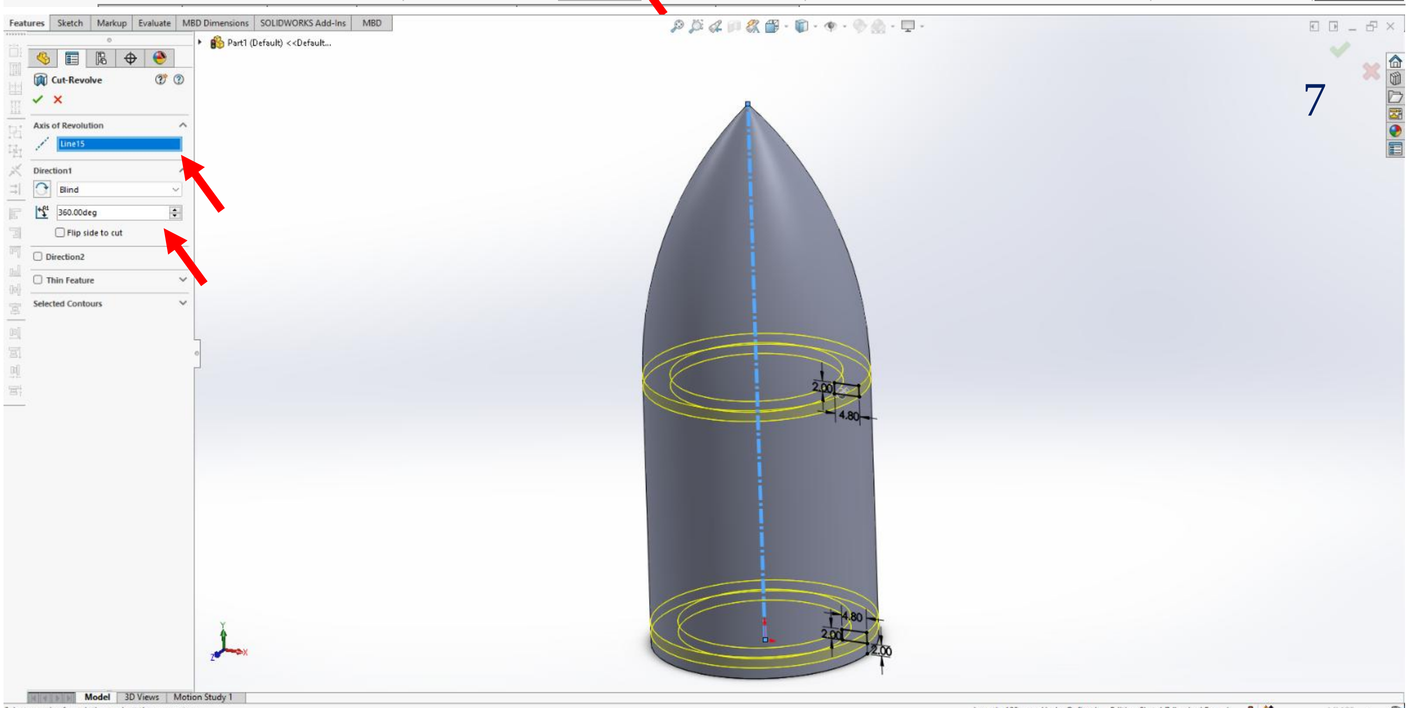
5

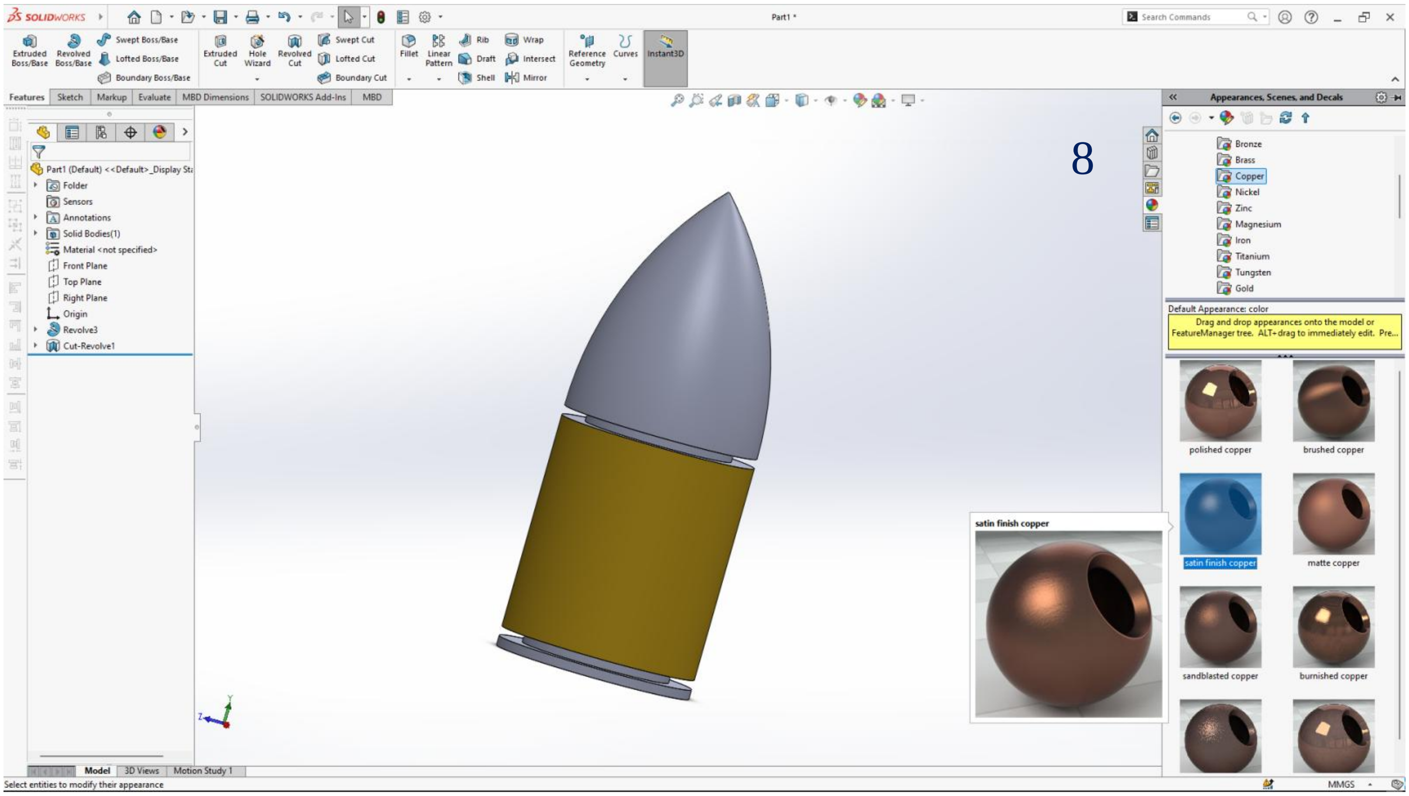

Dimension
Value
Leaders
Other
Style
Tolerance/Precision
None
.12 (Document)
Primary Value
D5@Sketch7
2.00mm
Dimension Text
All uppercase
Dual Dimension
2.00
4.80
*Front

6


SOLIDWORKS
Extruded Boss/Base
Revolved Boss/Base
Swept Boss/Base
Lofted Boss/Base
Boundary Boss/Base
Extruded Cut
Hole Wizard
Revolved Cut
Swept Cut
Lofted Cut
Boundary Cut
Fillet
Linear Pattern
Rib
Draft
Shell
Wrap
Intersect
Mirror
Reference Geometry
Curves
Instant3D

7


Cut-Revolve
Axis of Revolution
Line15
Direction1
Blind
360.00deg
Flip side to cut
Direction2
Thin Feature
Selected Contours
2.00
4.80
Model
3D Views
Motion Study 1
Select an axis of revolution and set the parameters.



4.3.3 *Some more Boss & Cut Types*

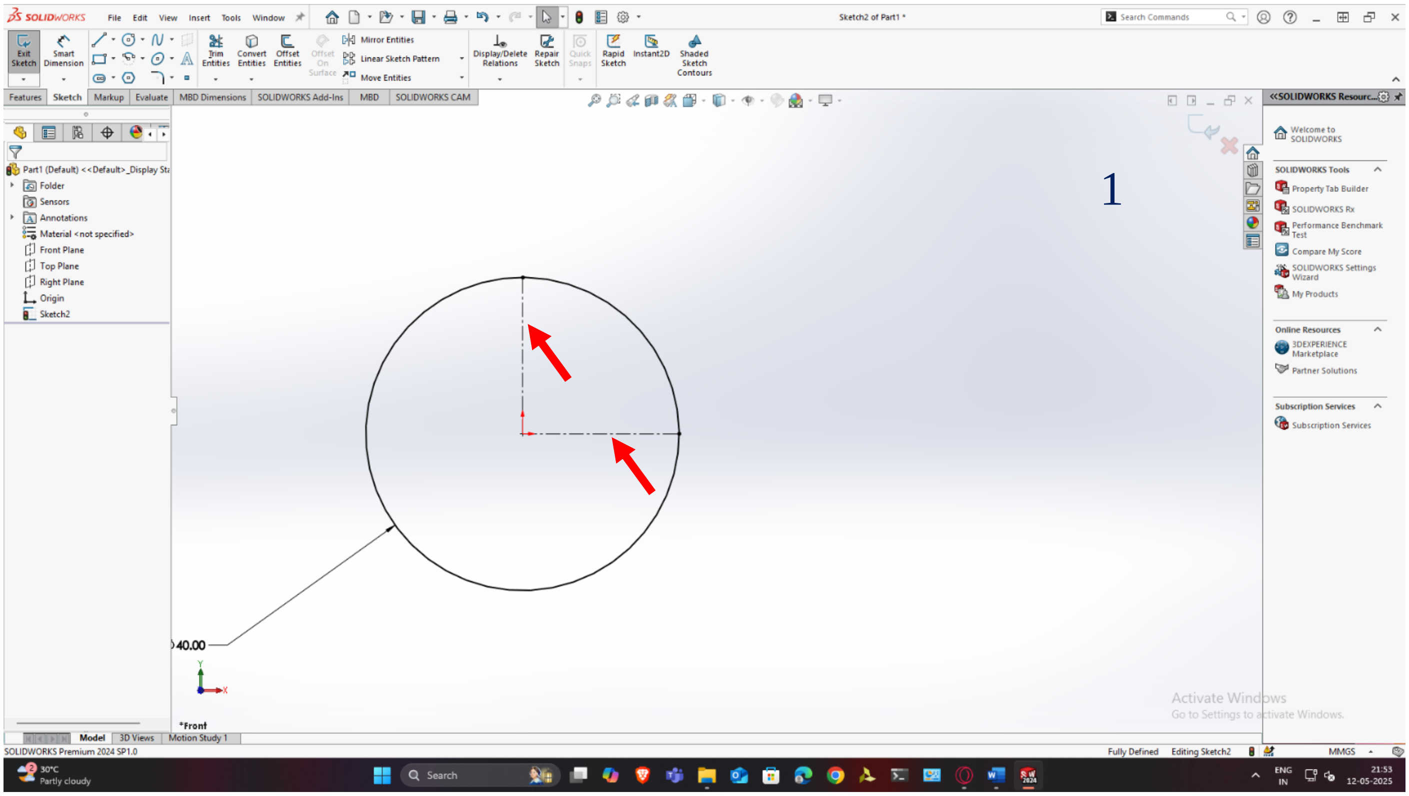
- There are a few more boss and cut types:
- Swept Boss / Cut – To boss or cut along a line or curve.
- Lofted Boss / Cut – To boss or cut between 2 different sketches.
- Boundary Boss / Cut – To boss or cut between multiple sketches.

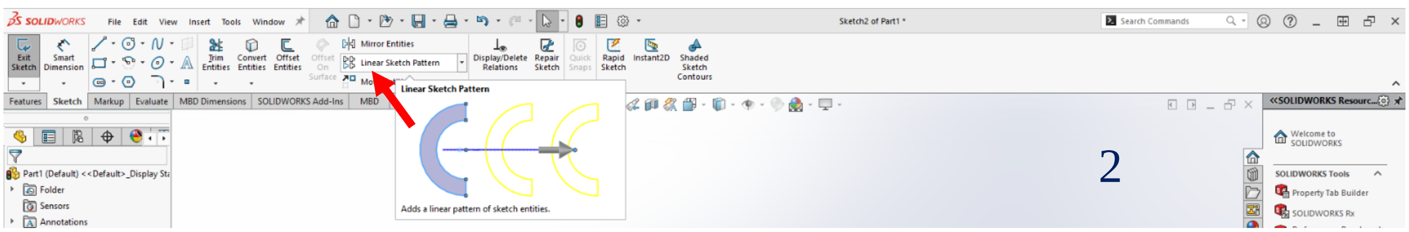
4.4 *Pattern & Mirror*

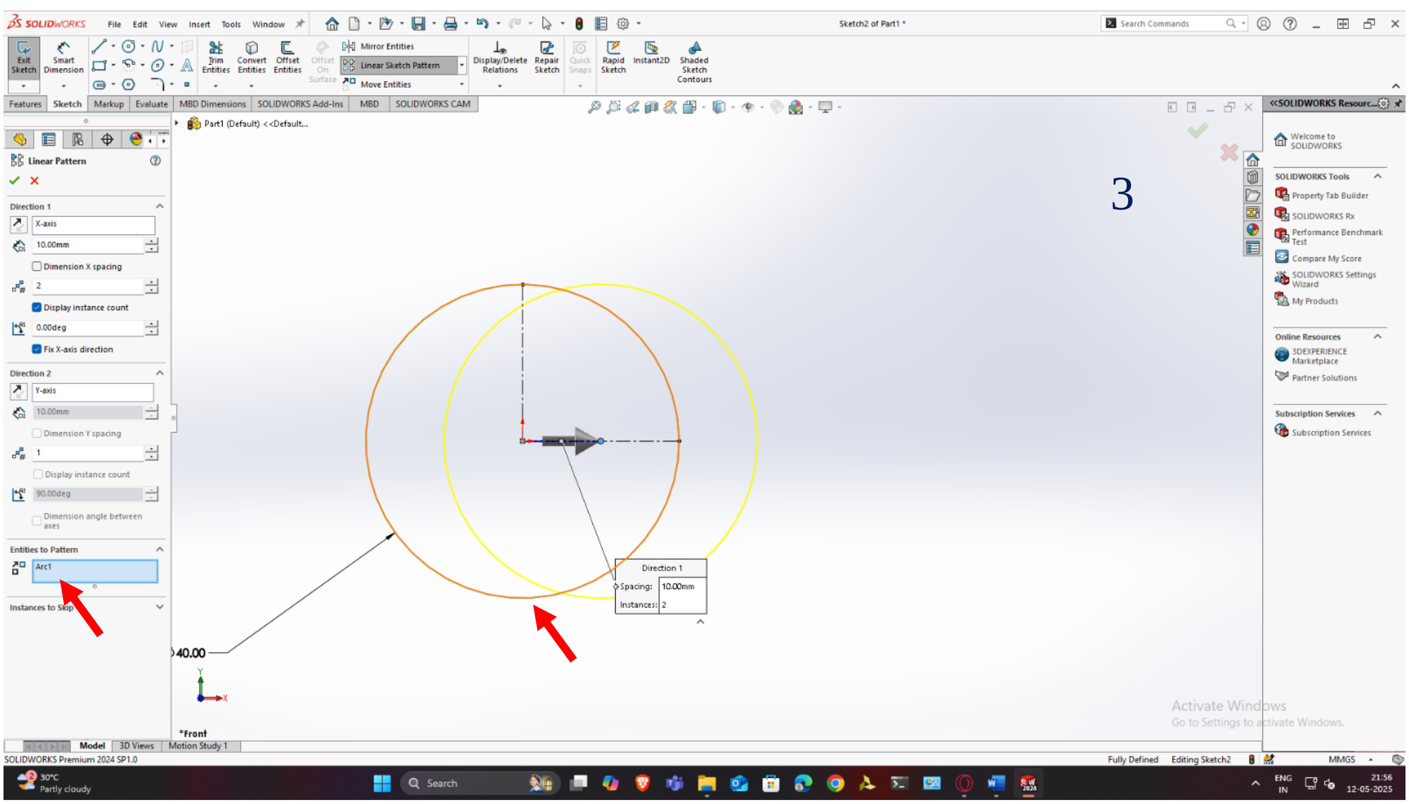
Pattern allows us to make multiple copies of a part or a feature. While mirror as suggest makes a mirror copy of a part. They are available in both sketch as well as in 3D. They also come with linear as well as circular pattern.

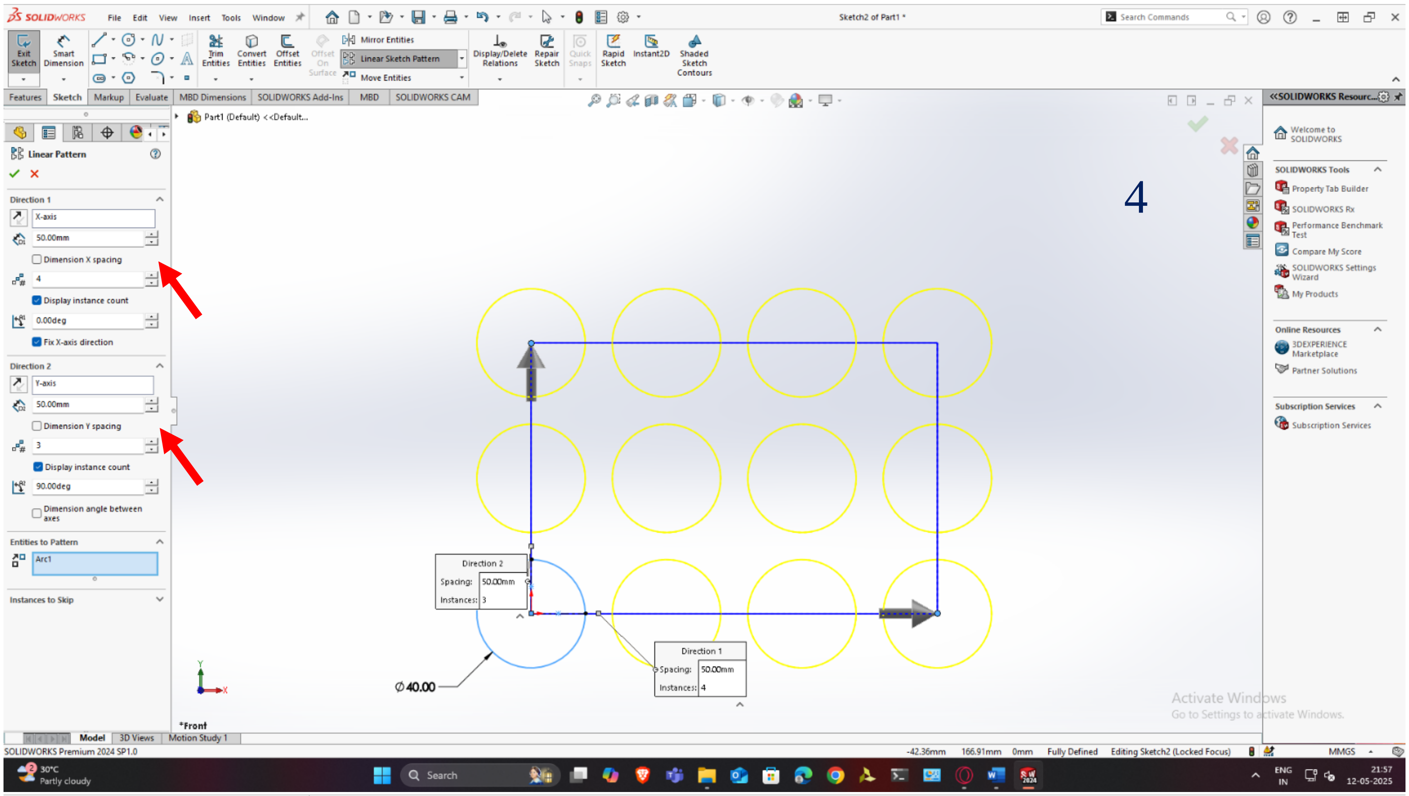
4.4.1 *Linear Sketch Pattern*

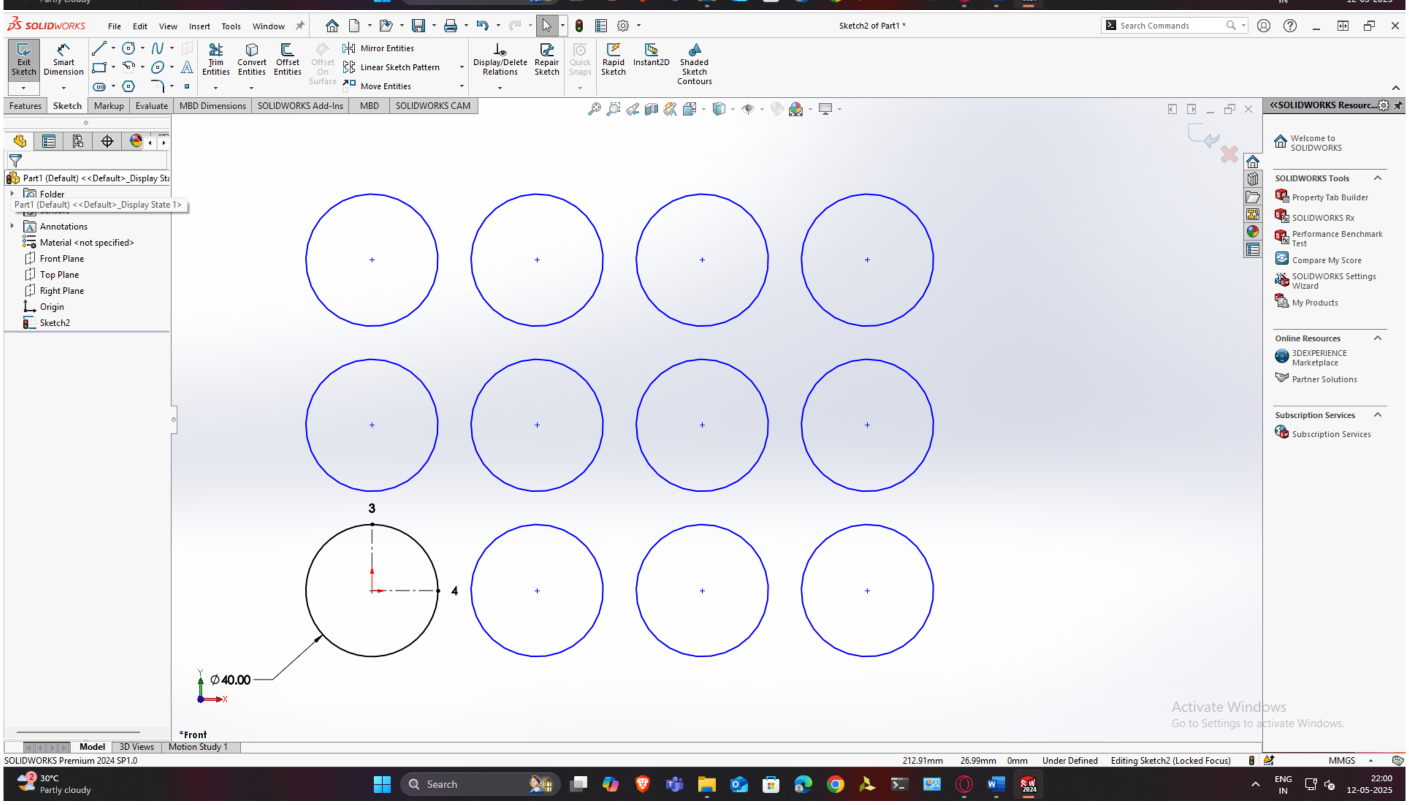
1. Draw the lines along the direction you want to make linear pattern.
2. Click Linear sketch pattern.
3. X-axis & Y-axis are by default set as direction of pattern, change if you want. Then select the entities to be patterned.
4. Then select the number of entities and spacing in each direction. Click the green tick after you have confirmed.


1
Sketch2 of Part1 *
Part1 (Default) <<Default>_Display St
Folder
Sensors
Annotations
Material <not specified>
Front Plane
Top Plane
Right Plane
Origin
Sketch2
40.00
*Front
SOLIDWORKS Premium 2024 SP1.0
Fully Defined
Editing Sketch2
MMGS


2
Linear Sketch Pattern
Adds a linear pattern of sketch entities.

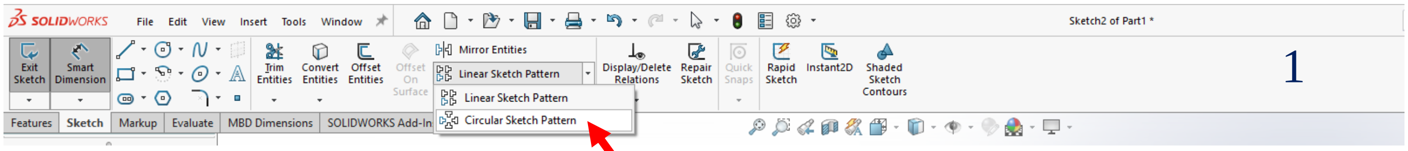

3
Linear Pattern
Direction 1
X-axis
10.00mm
Dimension X spacing
2
Display instance count
0.00deg
Fix X-axis direction
Direction 2
Y-axis
10.00mm
Dimension Y spacing
1
Display instance count
90.00deg
Dimension angle between axes
Entities to Pattern
Arc1
Instances to Skip
Direction 1
Spacing: 10.00mm
Instances: 2
40.00
*Front

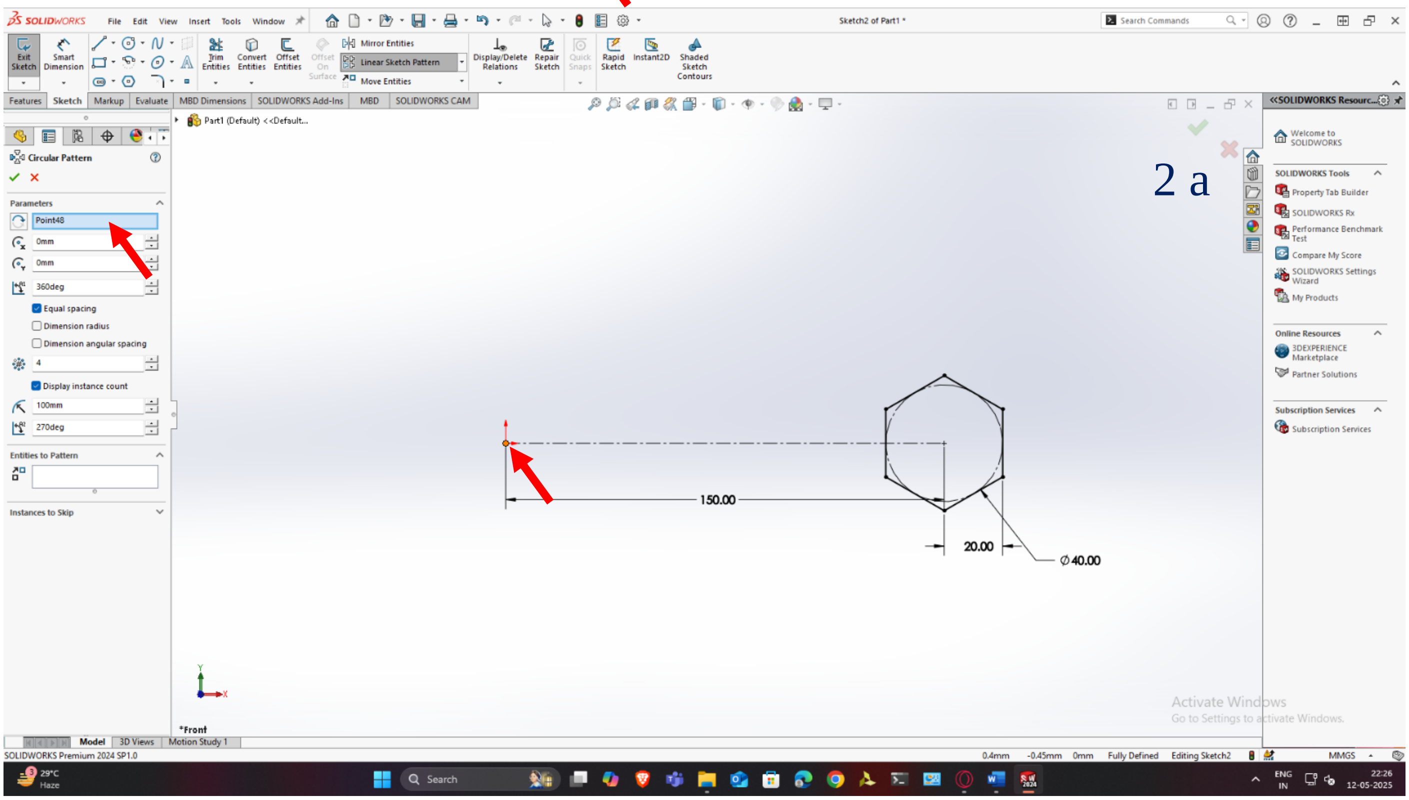


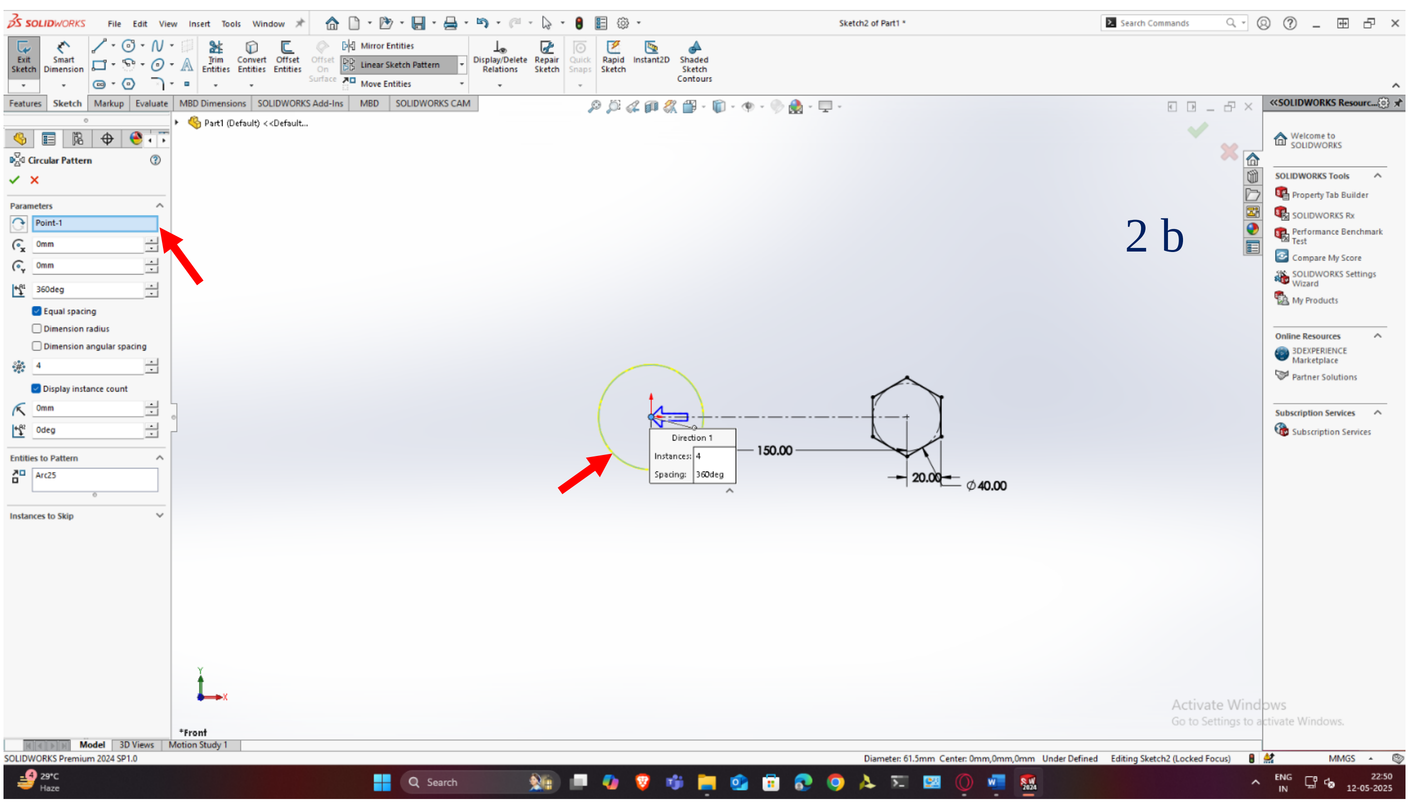


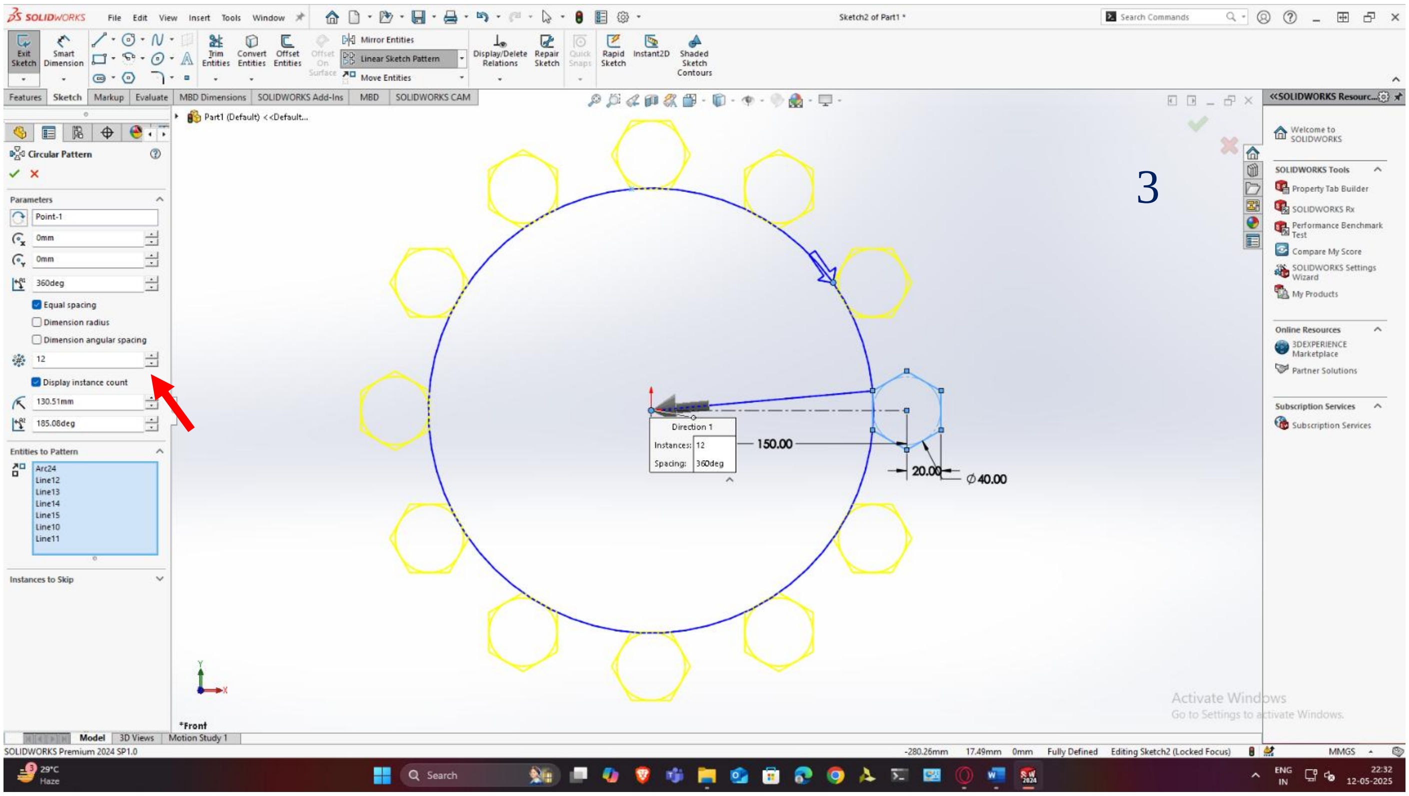
4.4.2 *Circular Sketch Pattern*

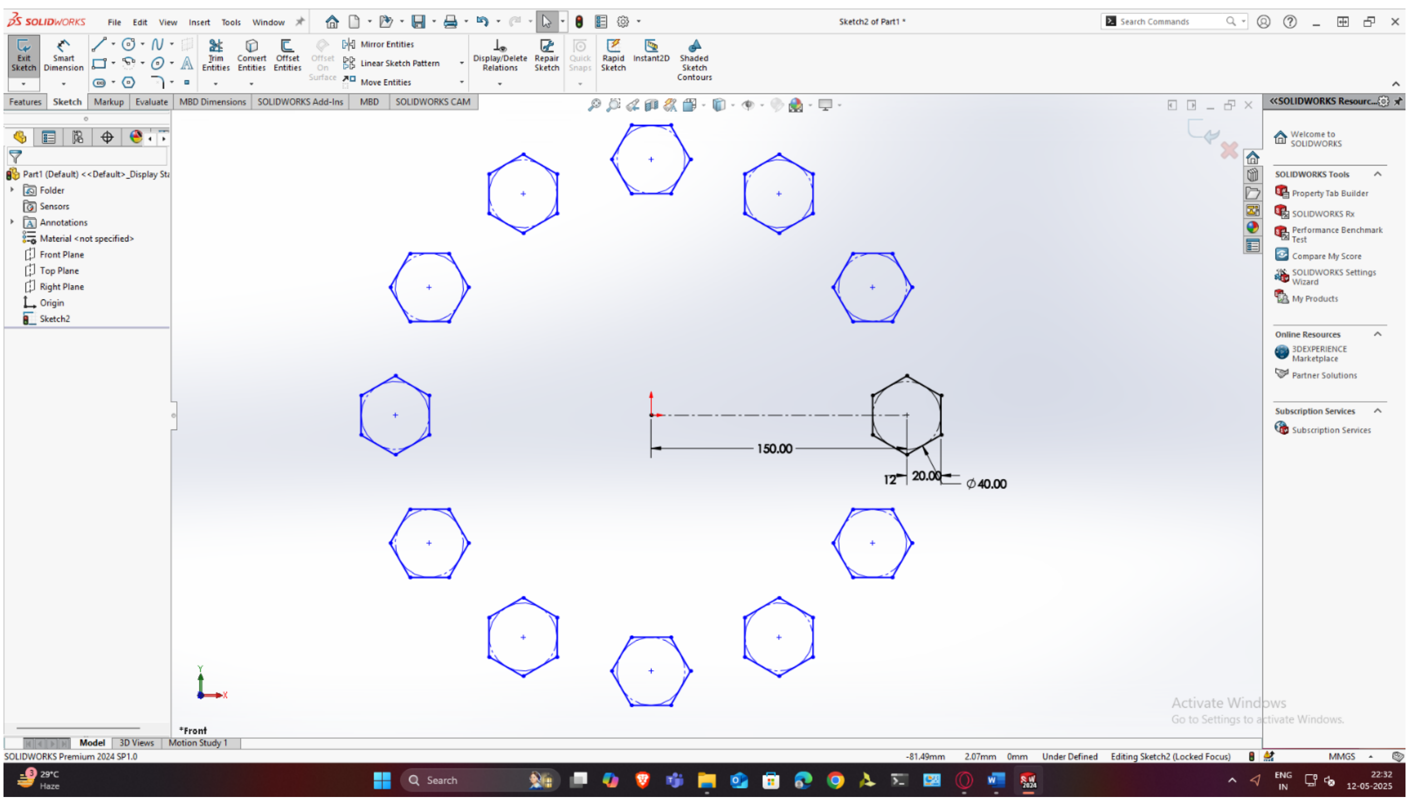
1. Click on circular sketch pattern on the down arrow of linear sketch pattern option.
2. Select a center point (a) or a circle (b) on parameters.
3. Select entities to pattern and number of copies. Then click green tick.


1
Mirror Entities
Linear Sketch Pattern
Circular Sketch Pattern


2 a
Circular Pattern
Parameters
150.00
20.00
Ø 40.00


2 b
Circular Pattern
Parameters
Direction 1
150.00
20.00
Ø 40.00

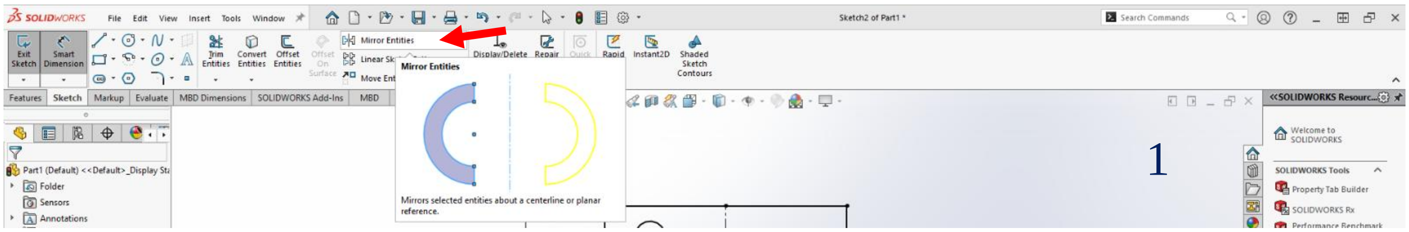


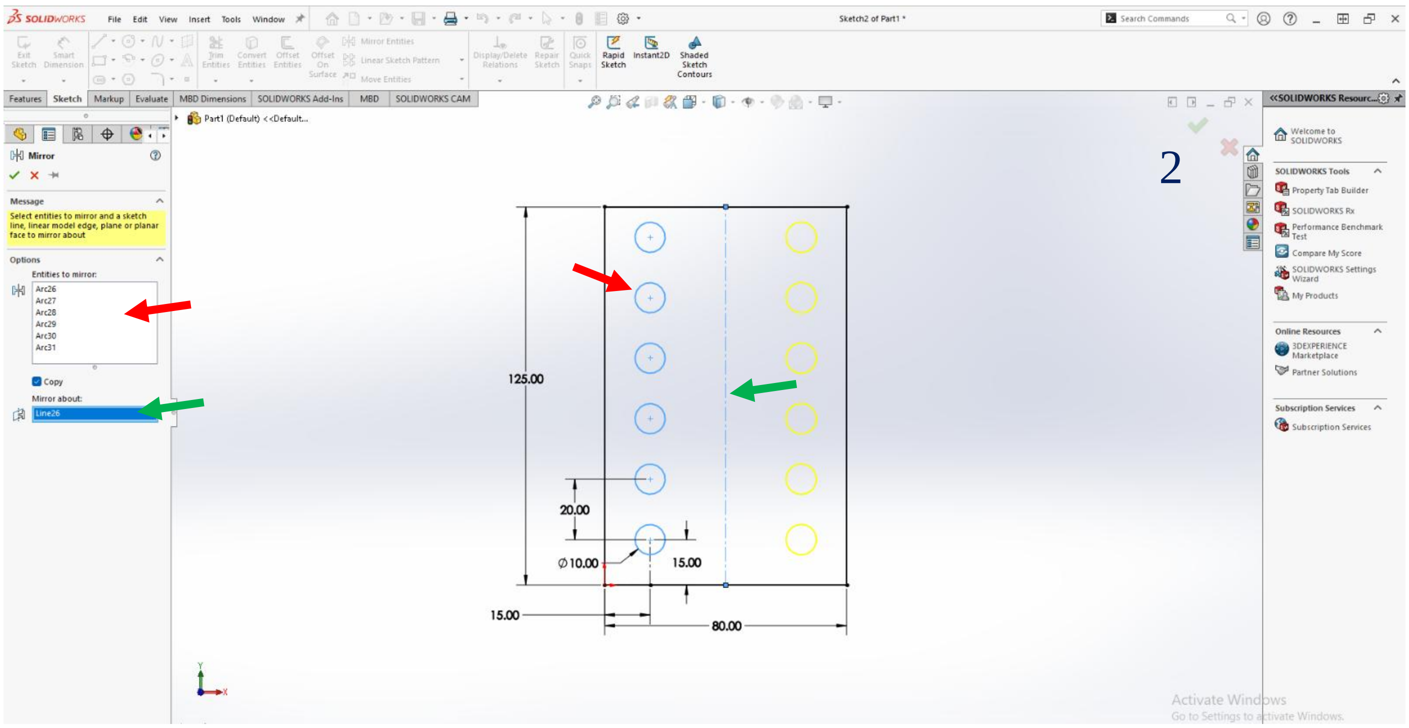


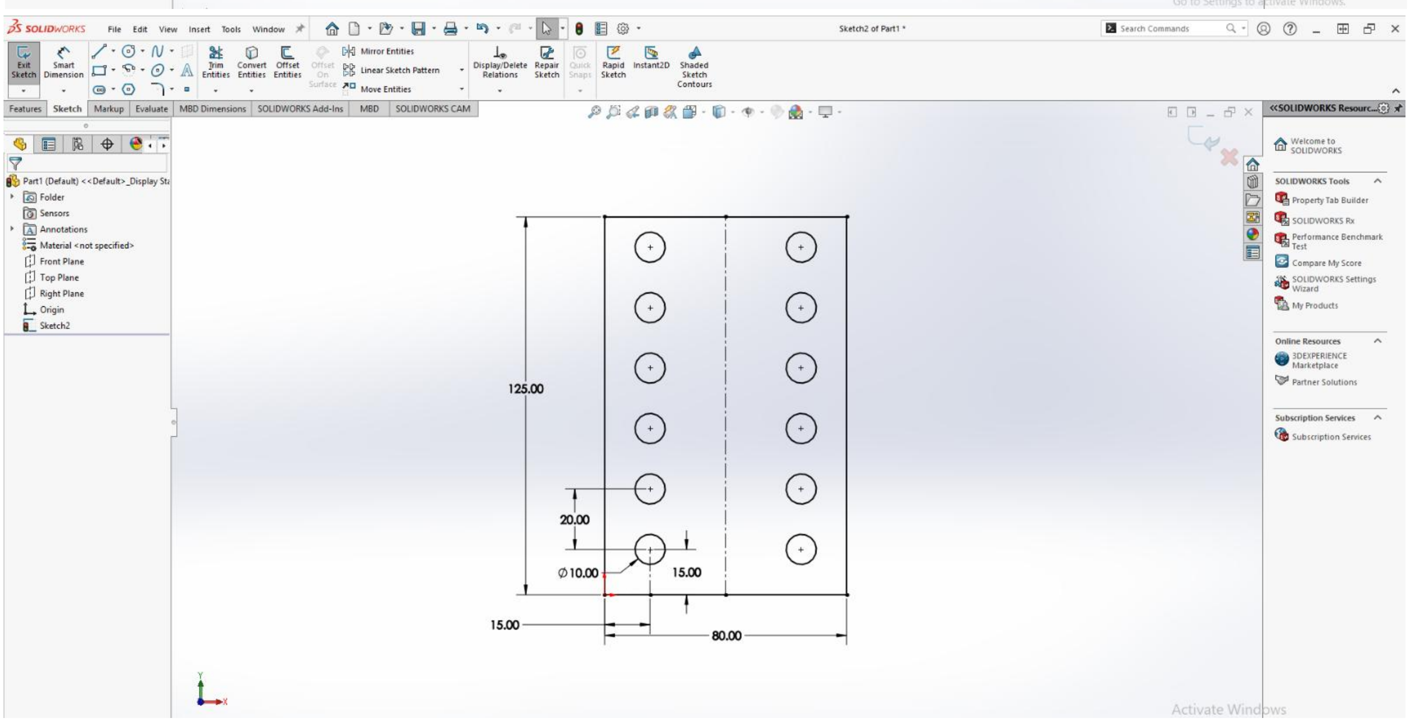
In 3d pattern, it’s pretty much the same. You can choose edges and arcs on the part itself as parameters.

4.4.3 Mirror Sketch

1. Click on Mirror Entities.
2. Click entities to mirror and mirror line on mirror about. Then click green tick.

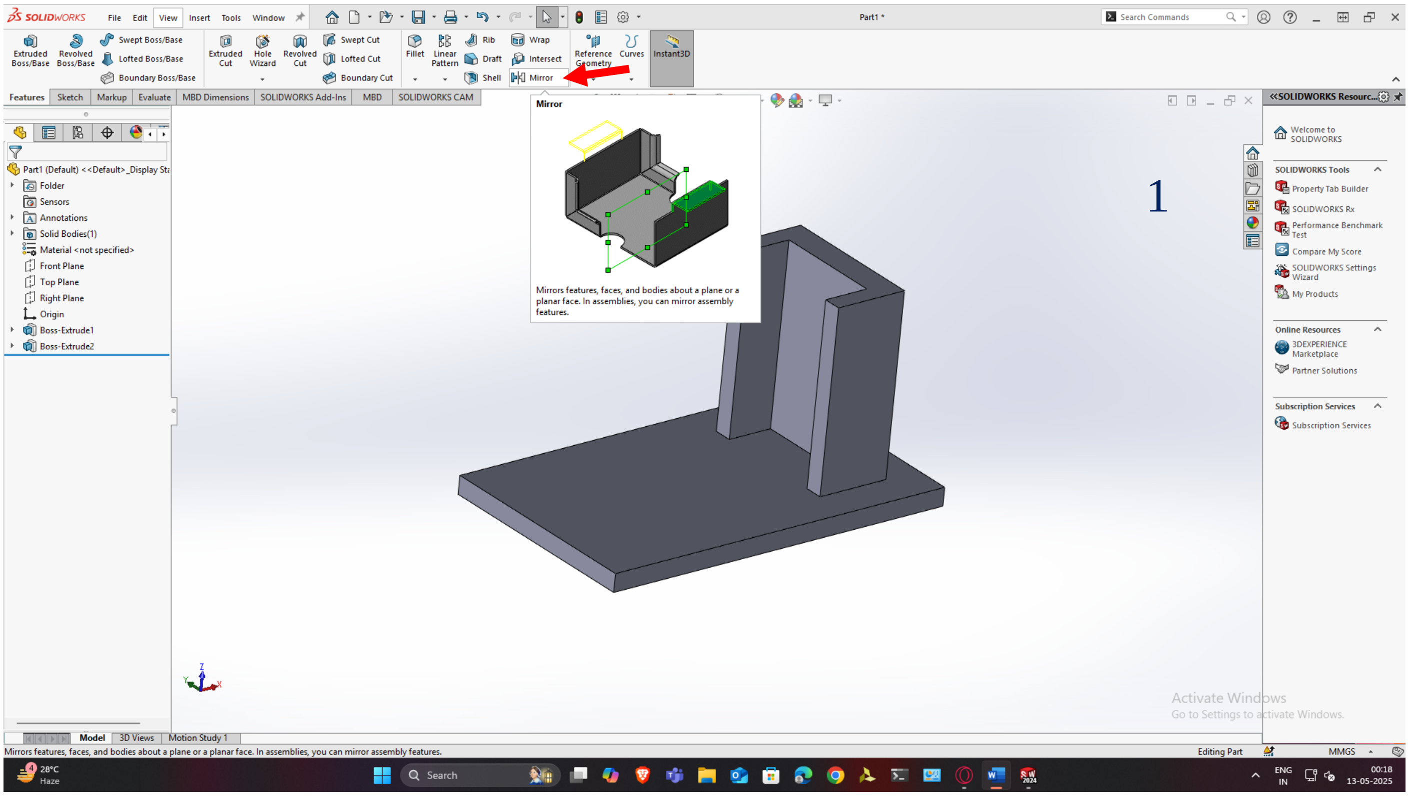


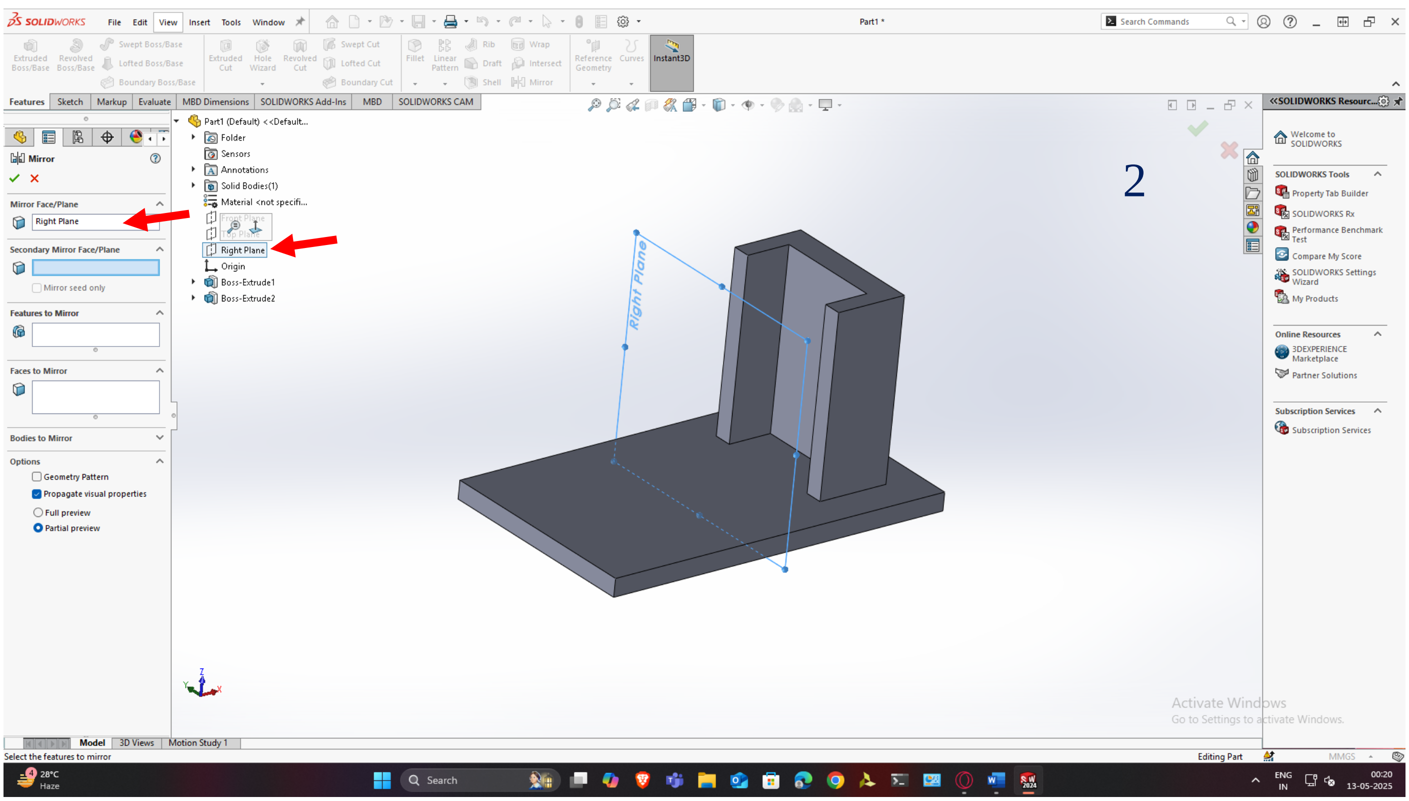


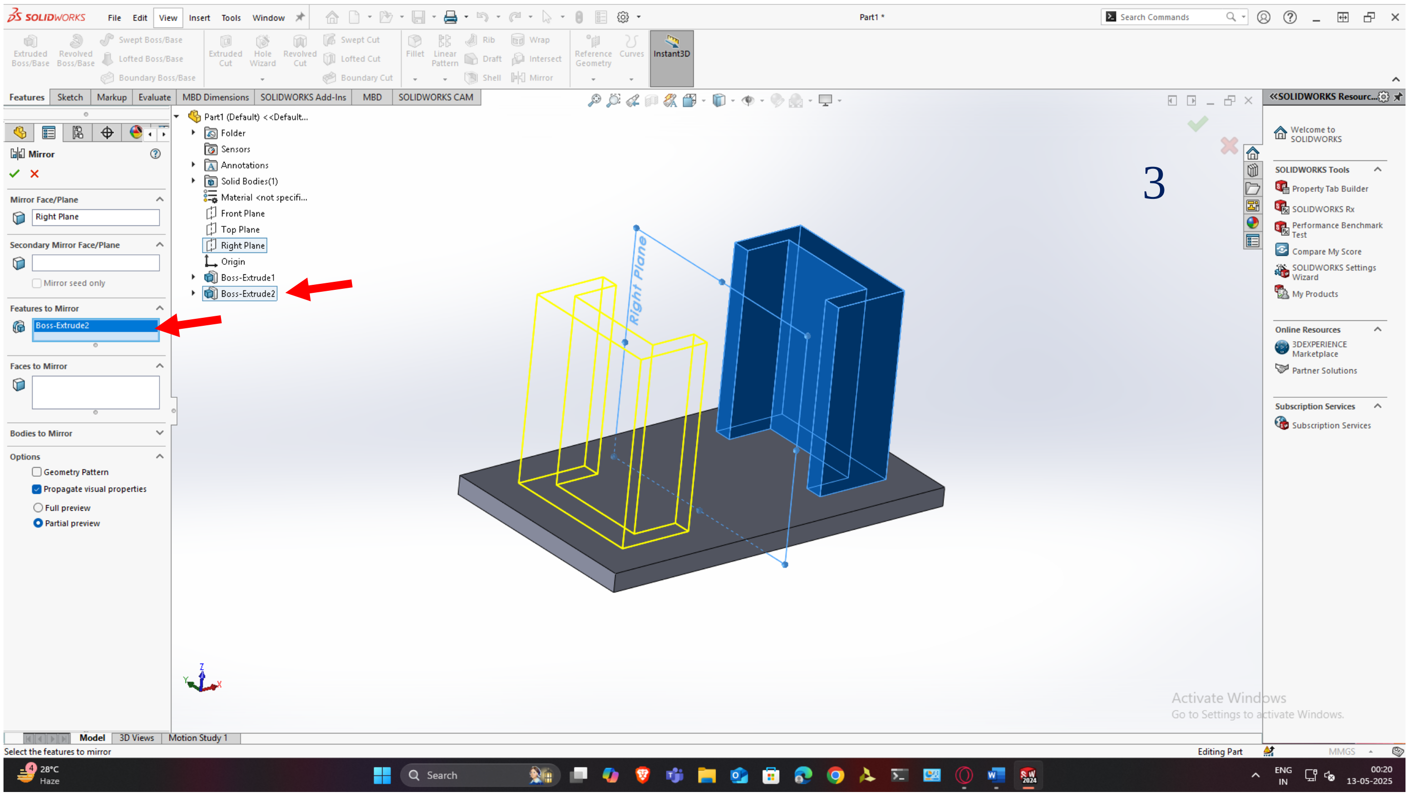


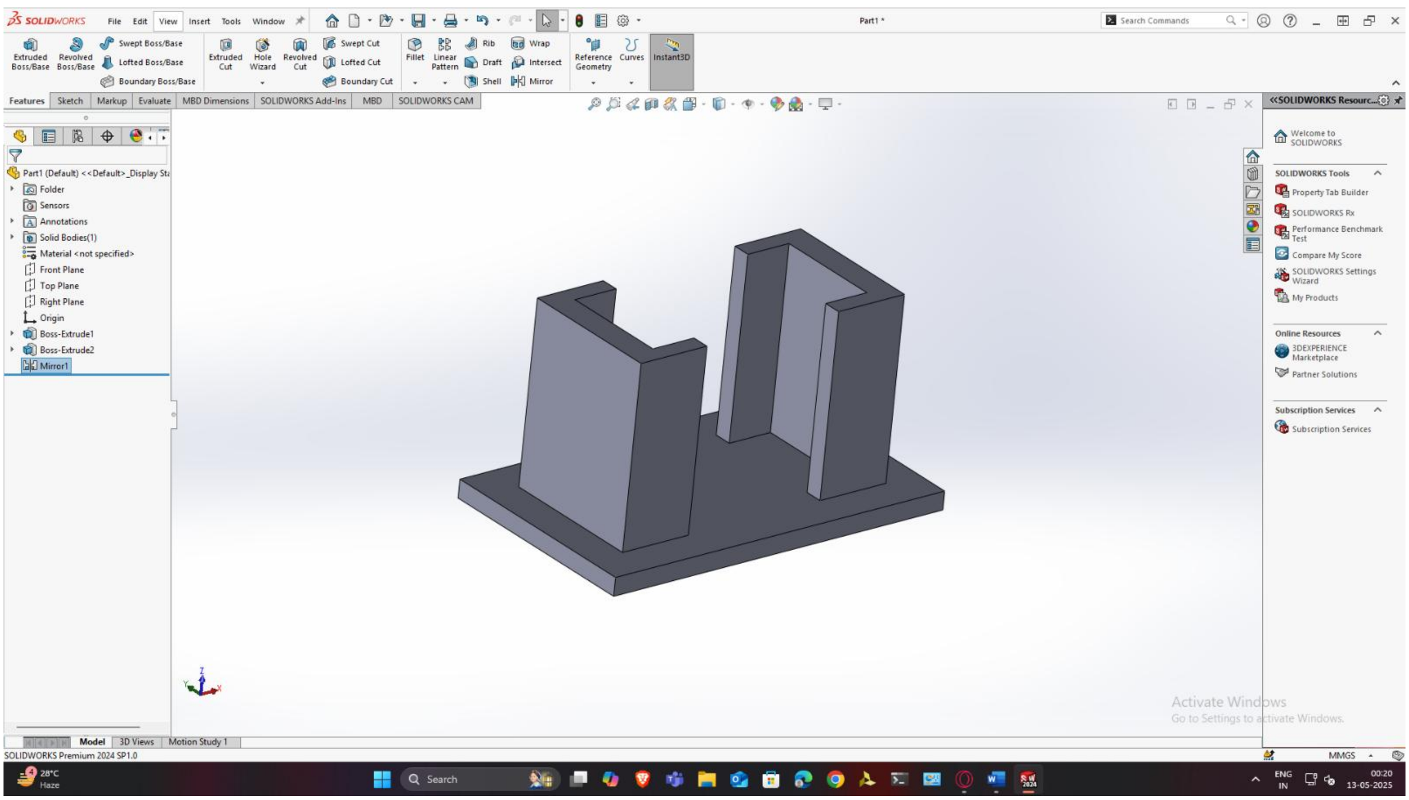
4.4.4 Mirror 3D

1. Click on mirror.
2. Select Mirror face / Plane. Select the mirror plane.
3. Select features to mirror. Then click green tick.





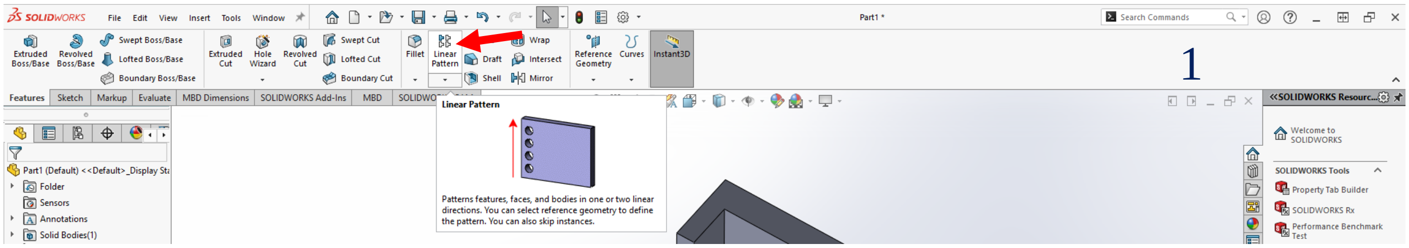


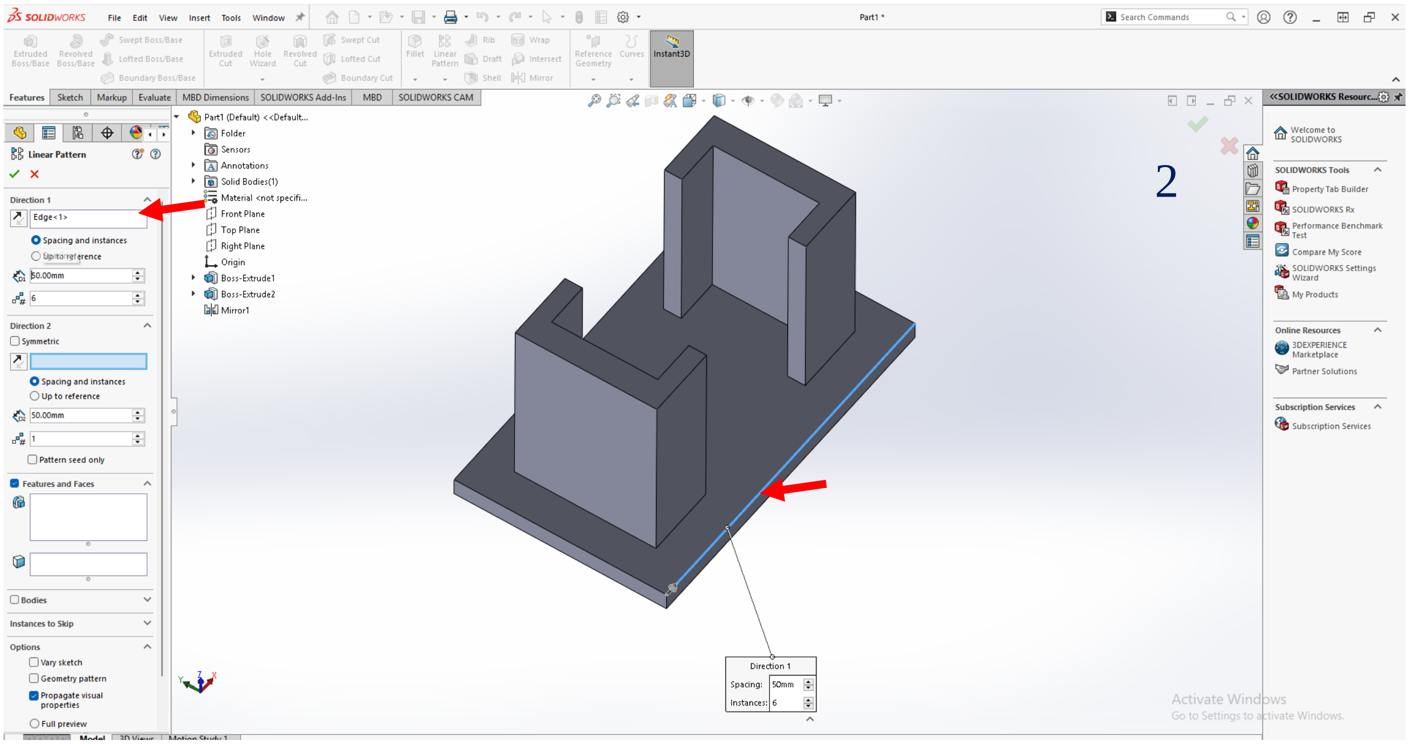


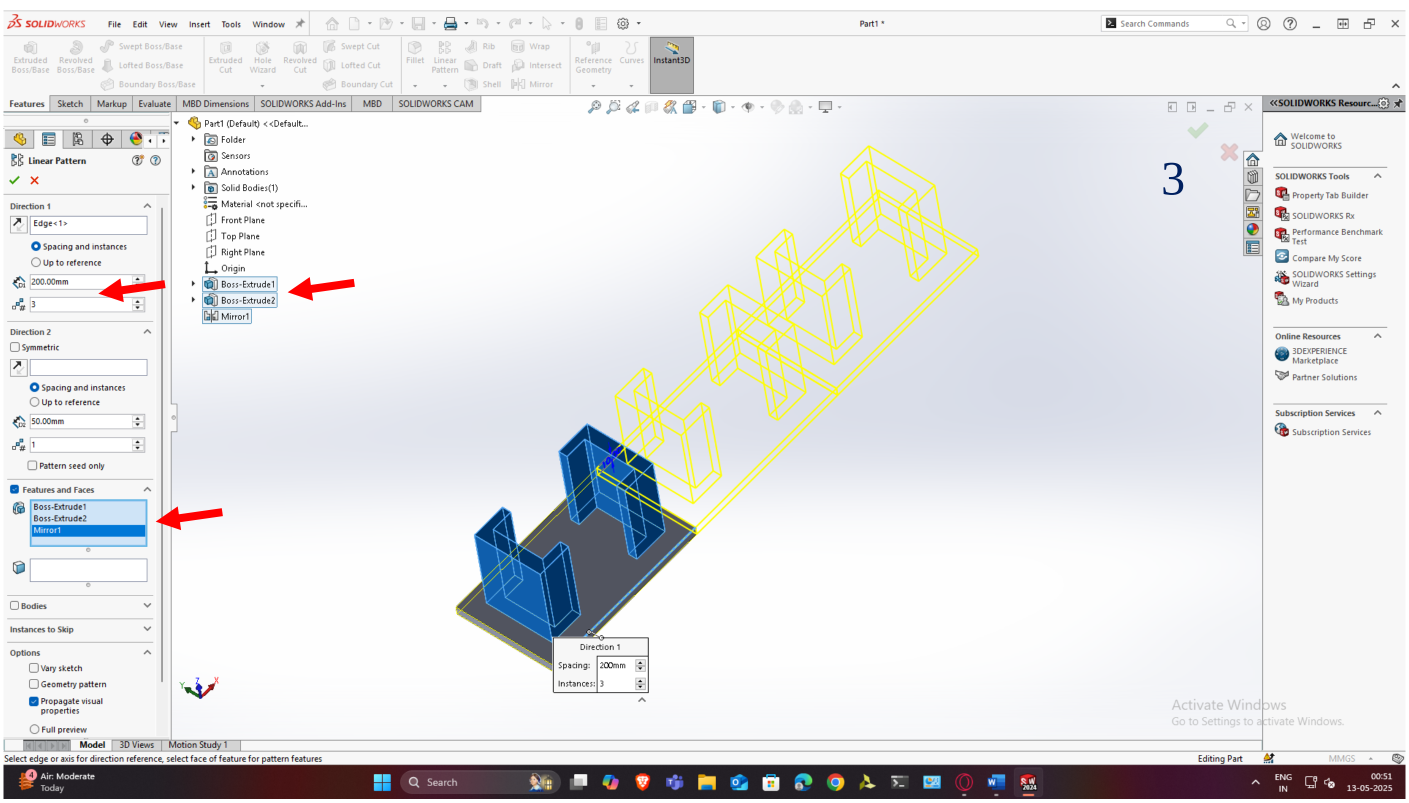
4.4.5 *Linear Pattern 3D*

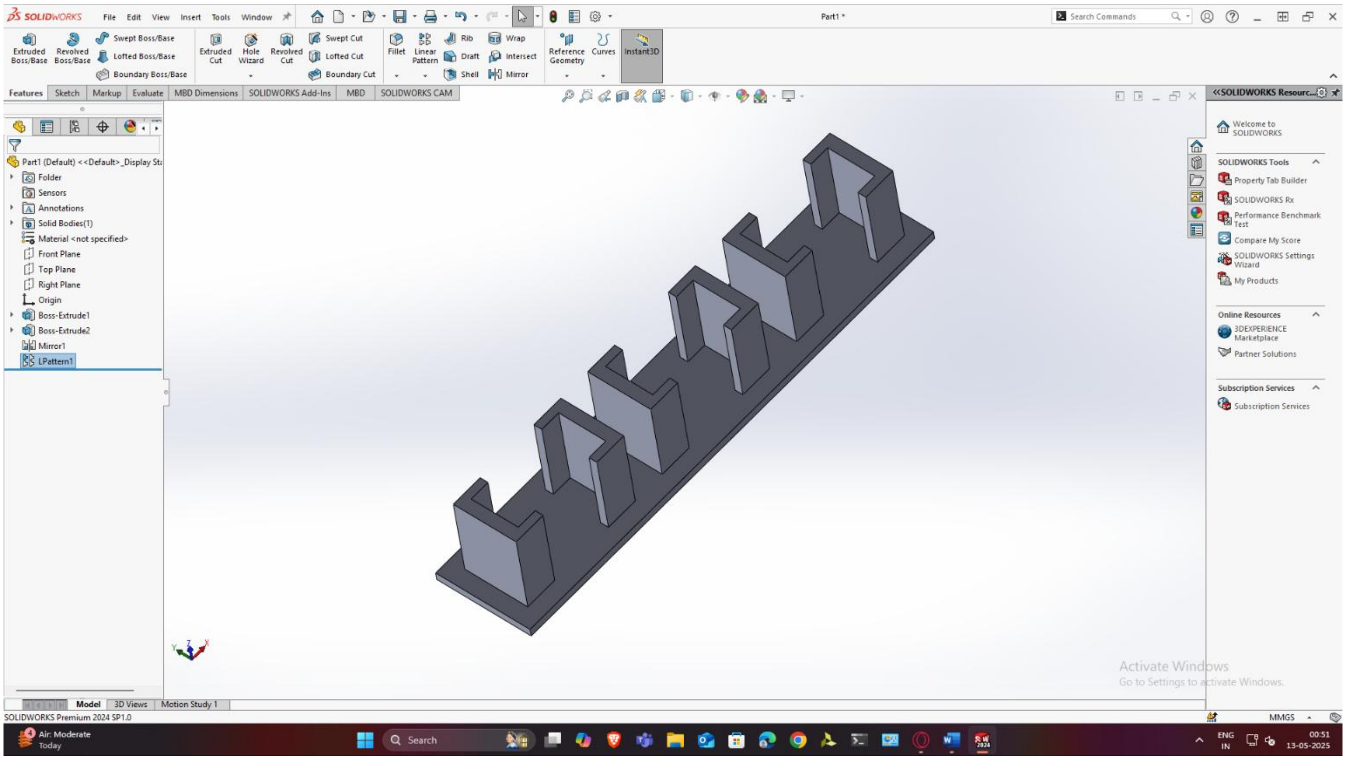
1. Click on Linear Sketch Pattern
2. Select the pattern direction

3. Select pattern features, instances and spacing. Then click green tick.



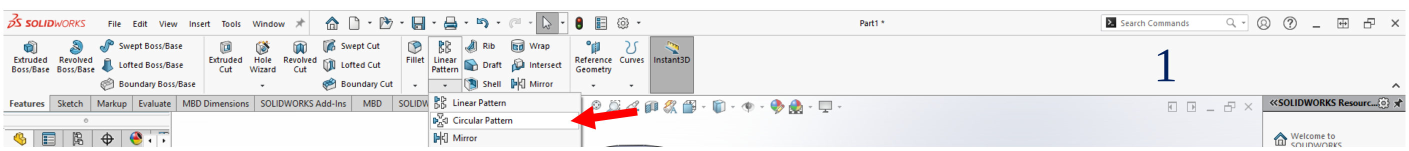


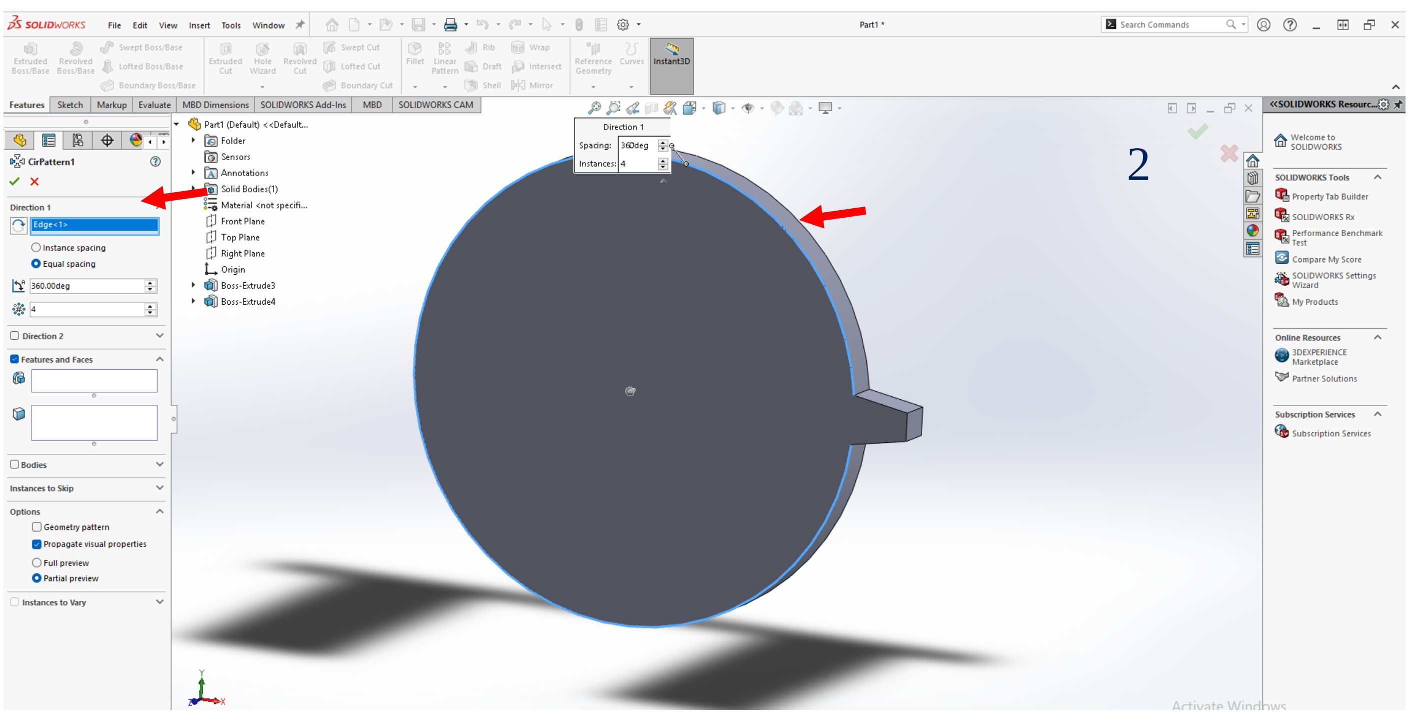


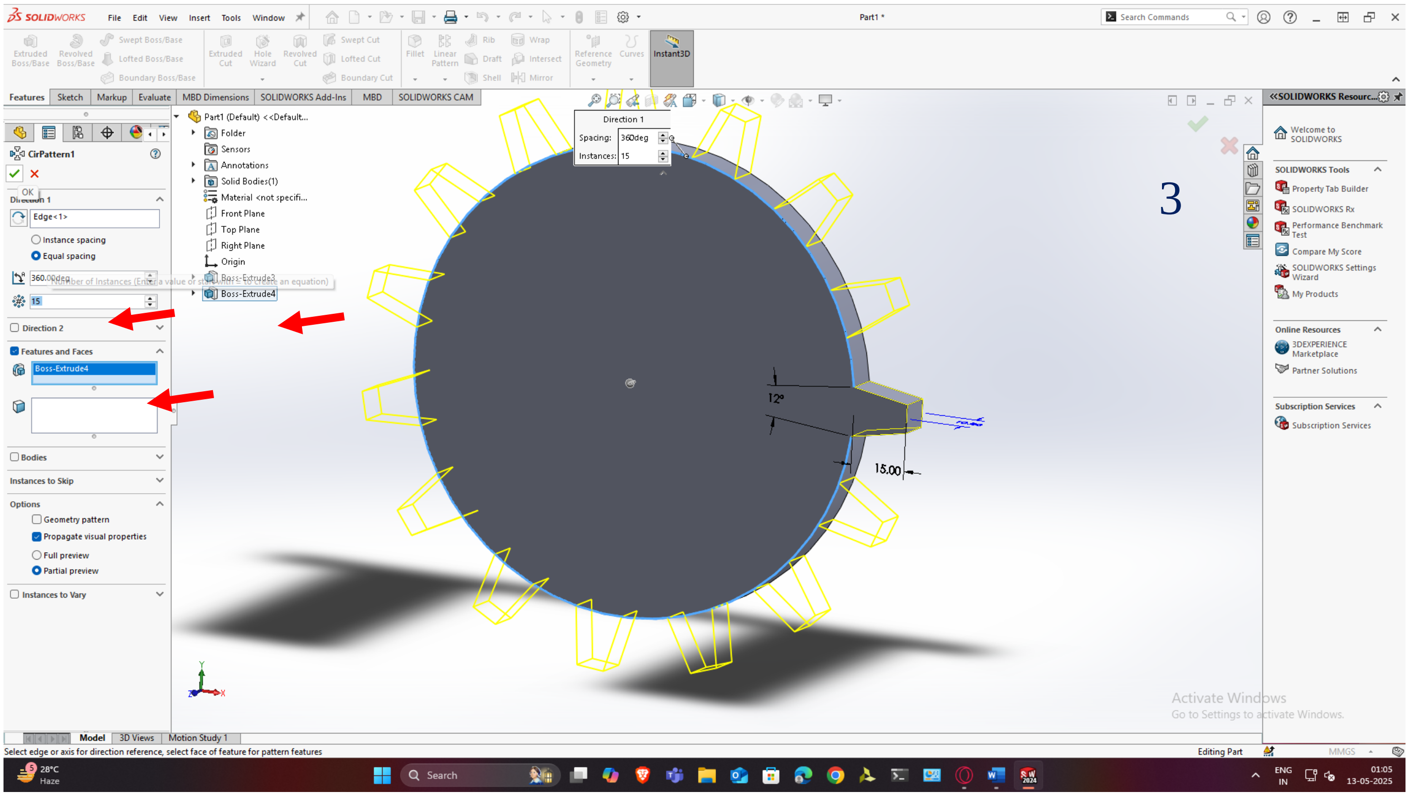


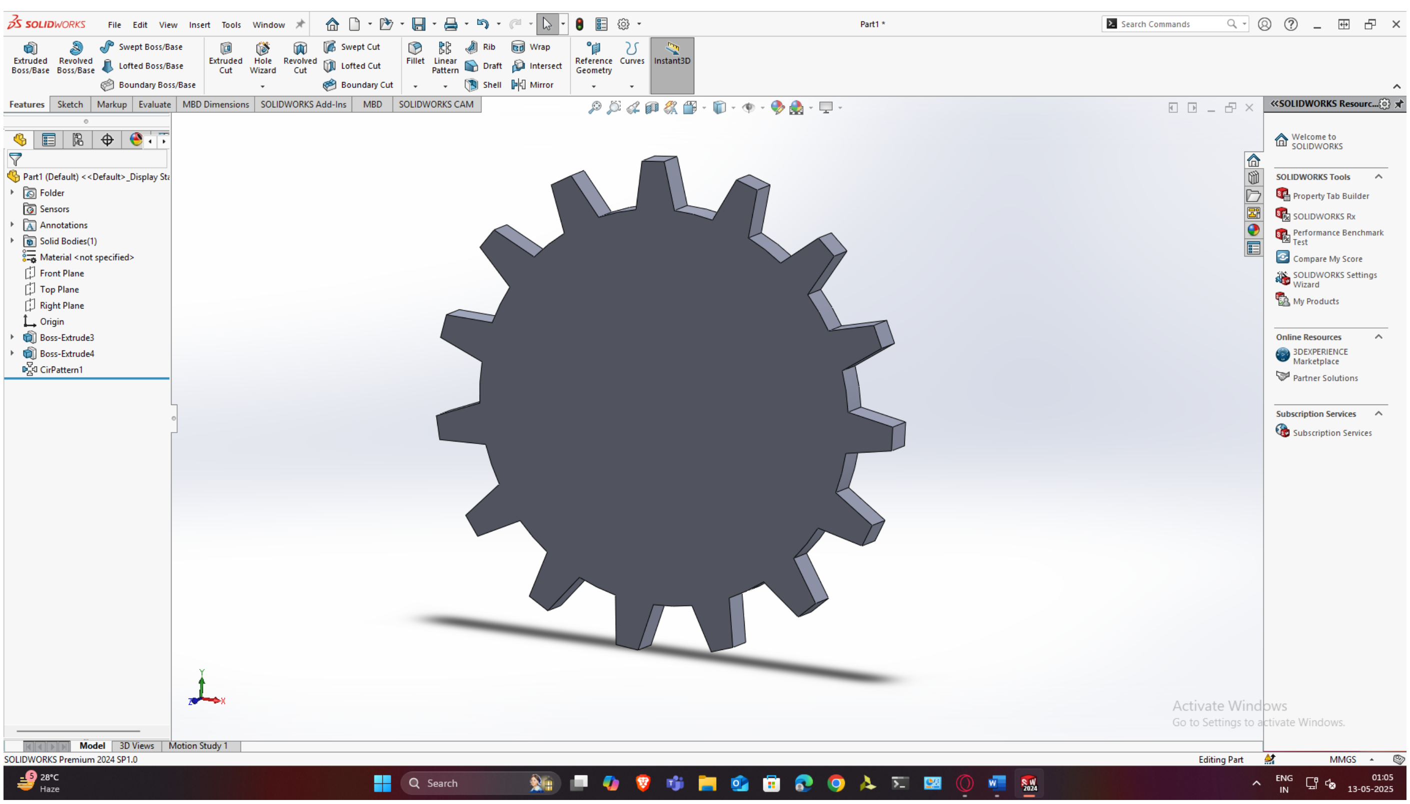
4.4.6 Circular Pattern 3D

1. Click on circular pattern from down arrow of linear pattern.
2. Select direction of pattern.
3. Select Features and instances. Click on green tick.





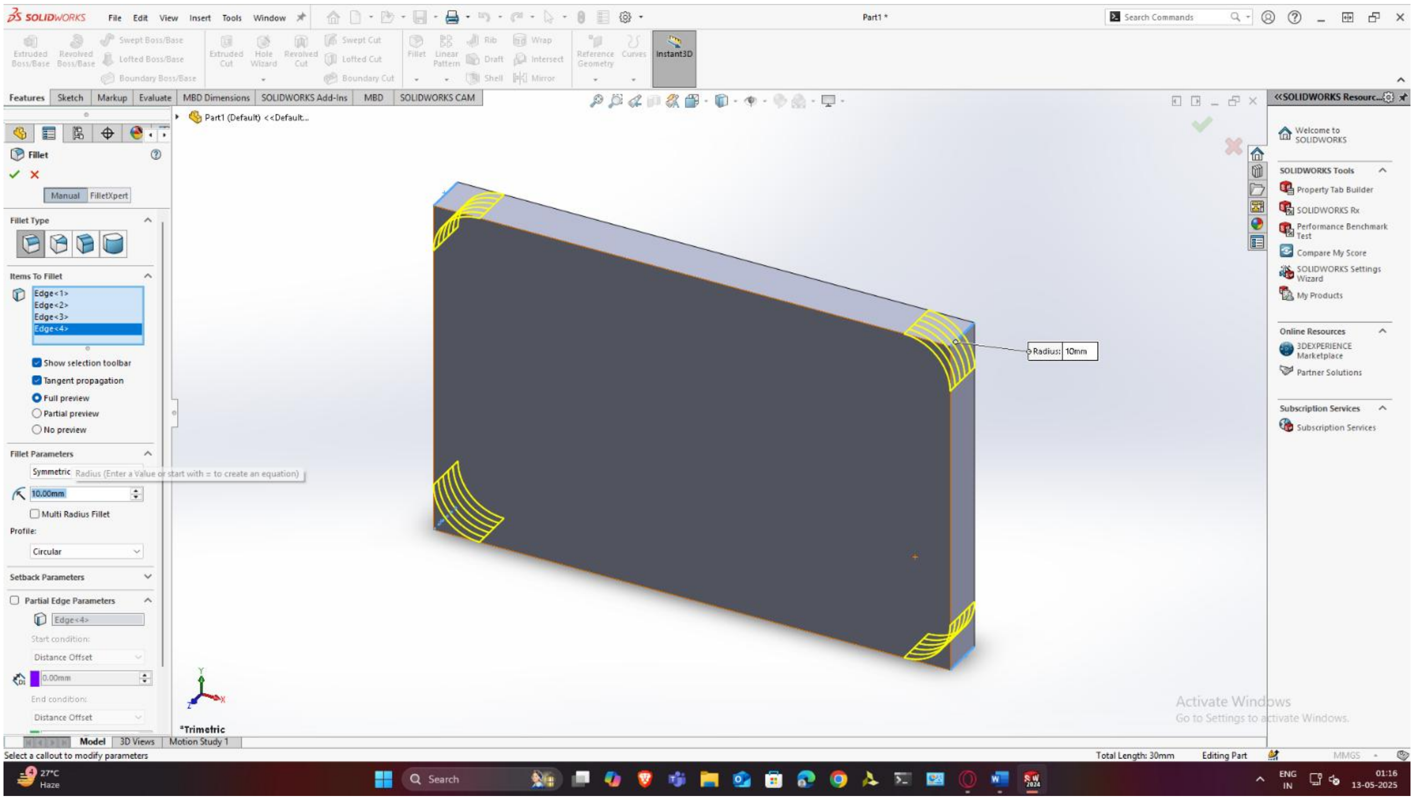

SOLIDWORKS
File Edit View Insert Tools Window
Part1 *
CirPattern1
Direction 1
Edge<1>
Instance spacing
Equal spacing
360.00deg
15
Direction 2
Features and Faces
Boss-Extrude4
Bodies
Instances to Skip
Options
Geometry pattern
Propagate visual properties
Full preview
Partial preview
Instances to Vary
Spacing: 360deg
Instances: 15
12°
15.00
3
Select edge or axis for direction reference, select face of feature for pattern features

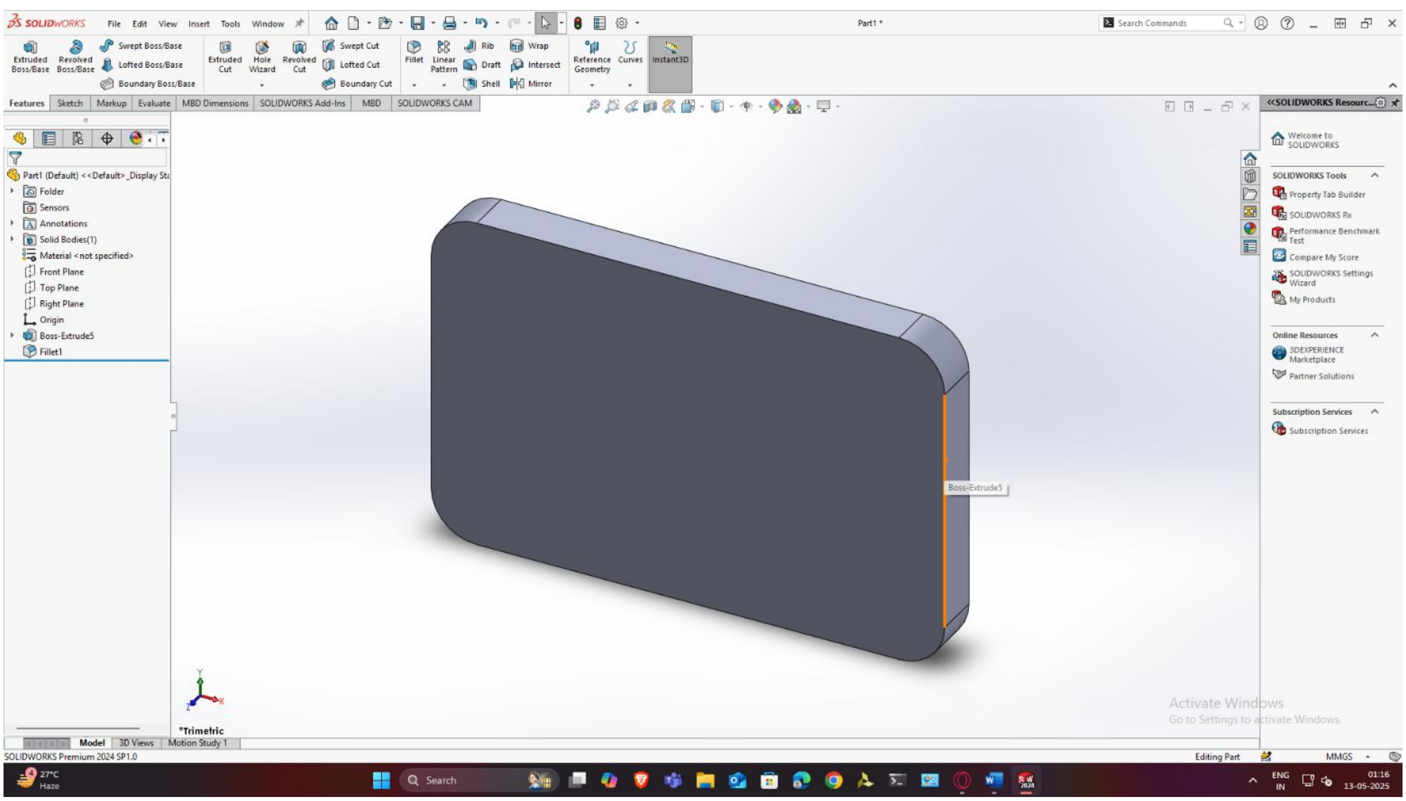

SOLIDWORKS
File Edit View Insert Tools Window
Part1 *
Part1 (Default) <<Default>_Display St
Folder
Sensors
Annotations
Solid Bodies(1)
Material <not specified>
Front Plane
Top Plane
Right Plane
Origin
Boss-Extrude3
Boss-Extrude4
CirPattern1
SOLIDWORKS Premium 2024 SP1.0

4.5 Some More Features

4.5.1 Fillet

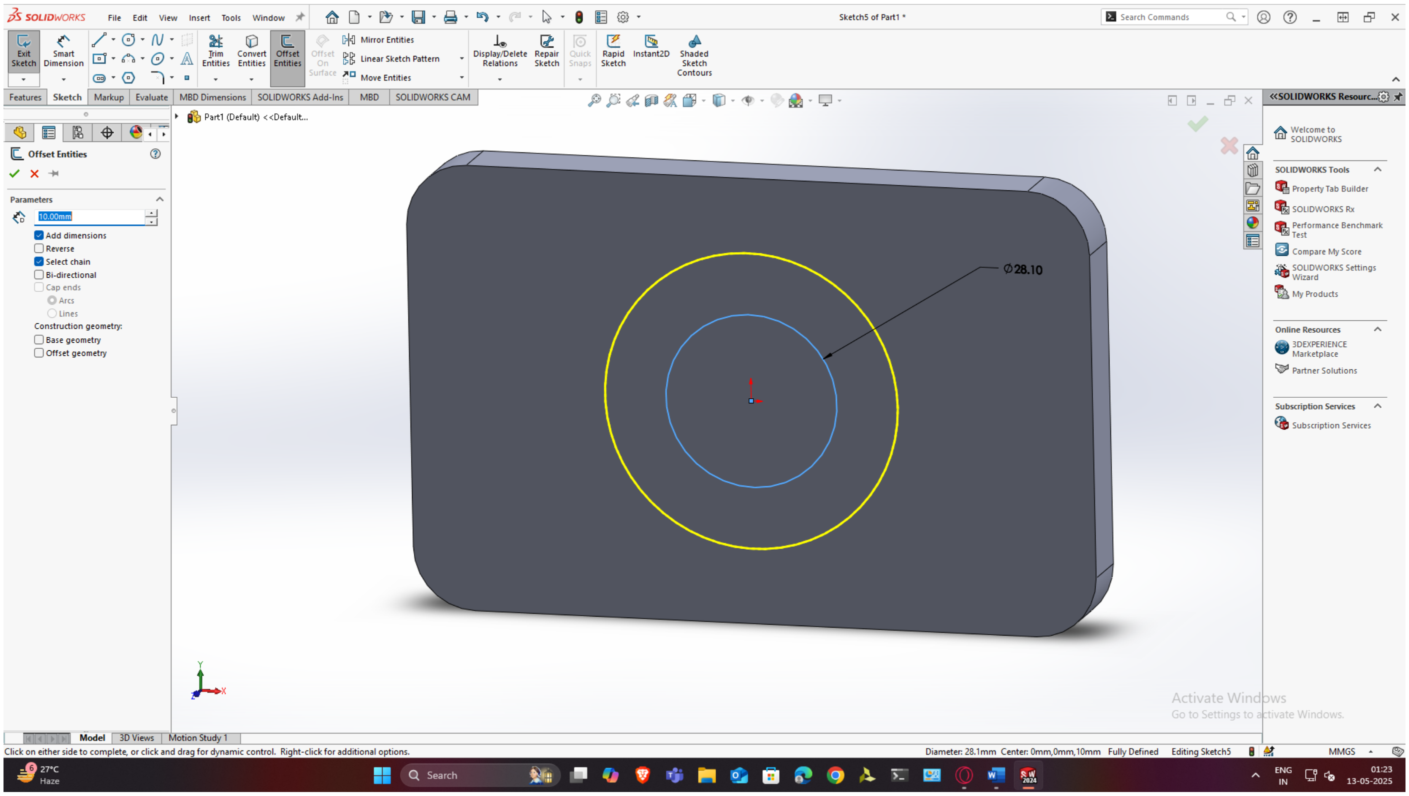
It's used to add fillet to the edges.

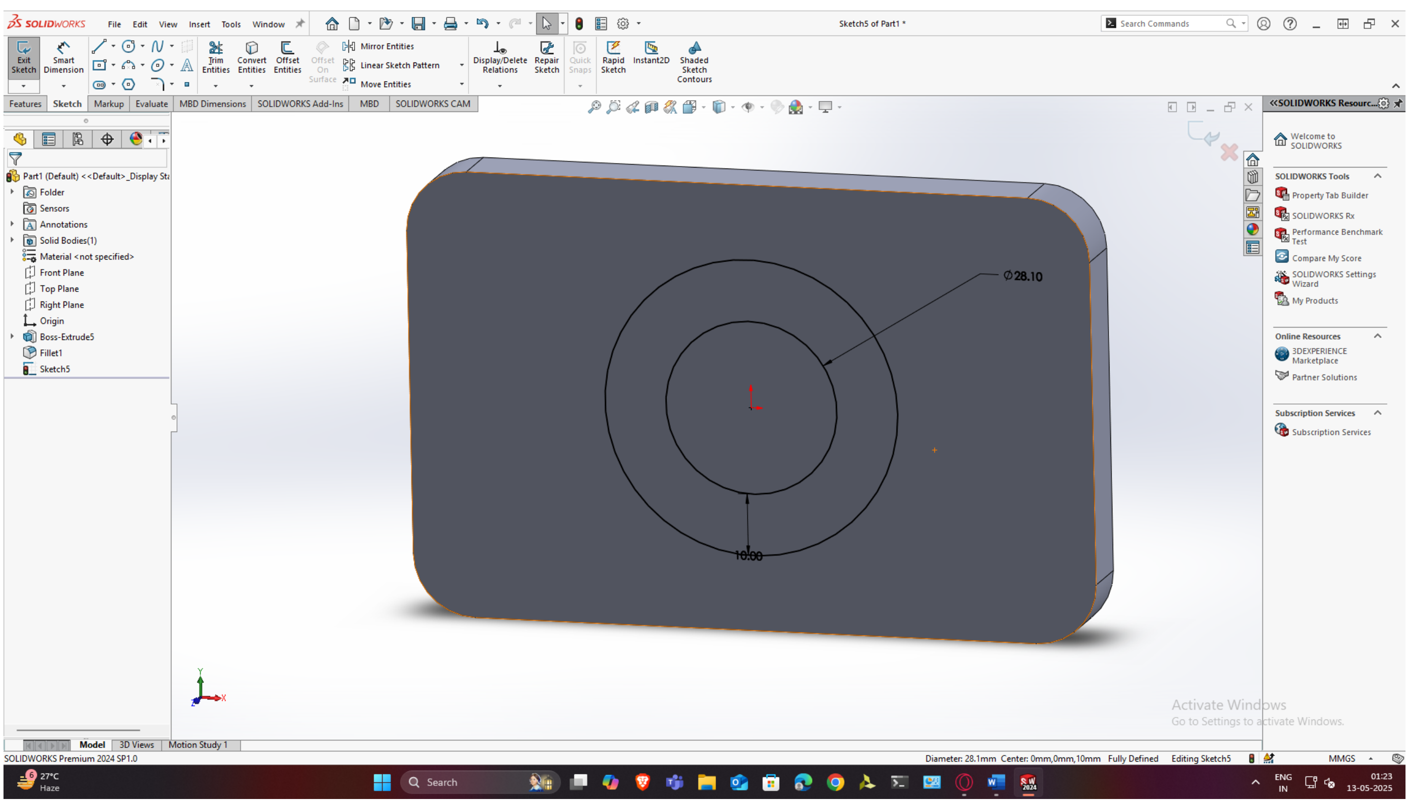




4.5.2 *Offset*

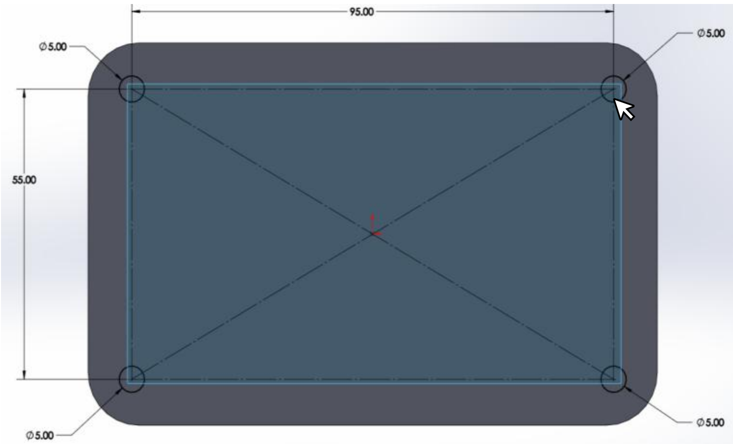
This option is available in sketch. It’s used to add an offset to the sketch.

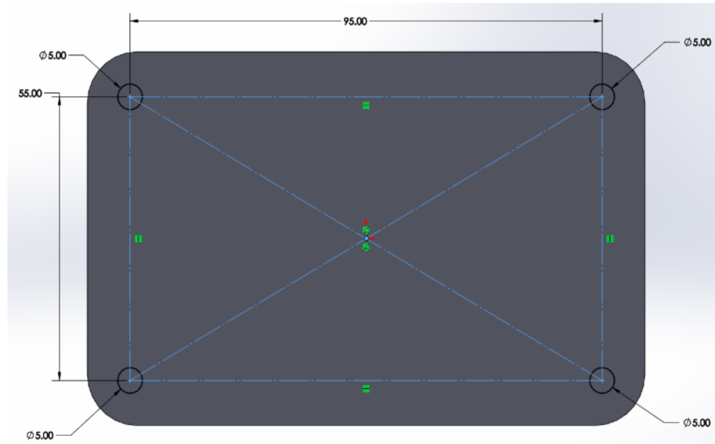




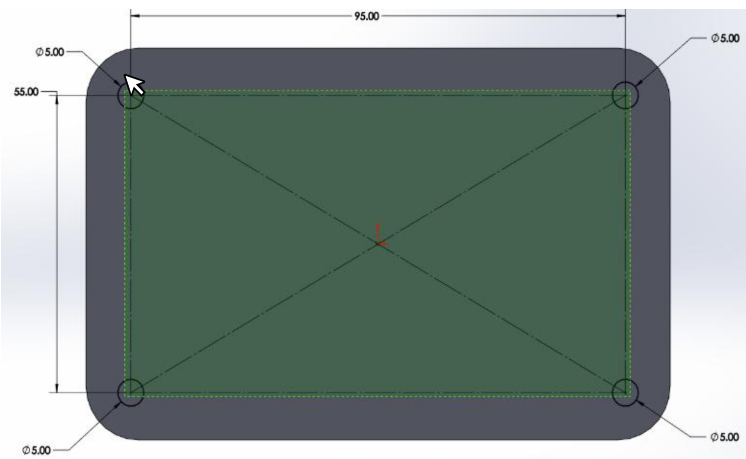
4.5.3 Green Select & Blue Select

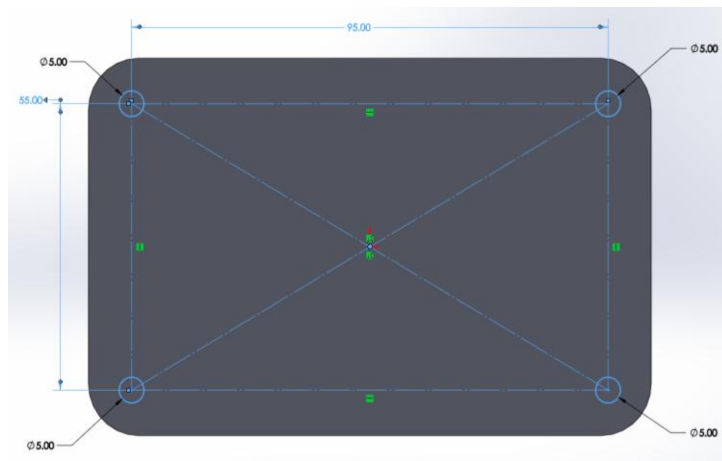
Blue select arrives when you drag the cursor from left to right. It selects everything that's enclosed in the blue contour.





Green select arises when you select from right to left. It selects everything that the contour touches.





4.5.4 SolidWorks Drawing

In this window, you can make engineering drawings directly from your part.

4.5.5 SolidWorks Assembly

In this window you can join multiple parts with one another to form a complex machine.

4.5.6 SolidWorks Simulation

In this feature we can do static structural study, flow simulation and many more.

4.5.7 Evaluate

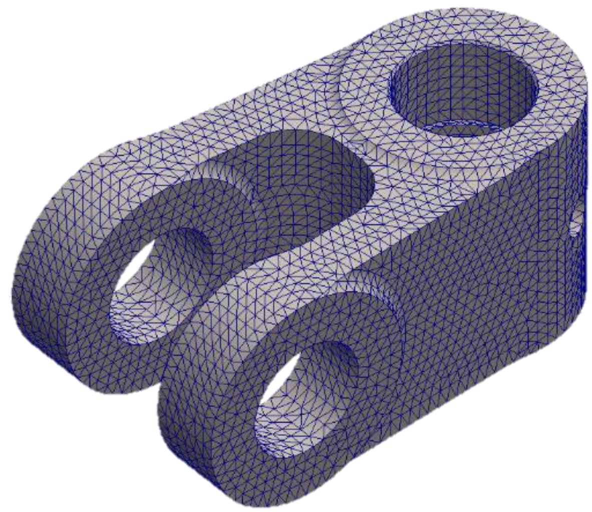
With this feature you can measure the distances after the model is formed for verification. It also has mass properties, interference detection and many more.

That's pretty much everything how to design a model in SolidWorks. There are many more things to know but mentioning them wouldn't finish. So, we should wrap it up here and move to FEA.

The End

Chapter 5

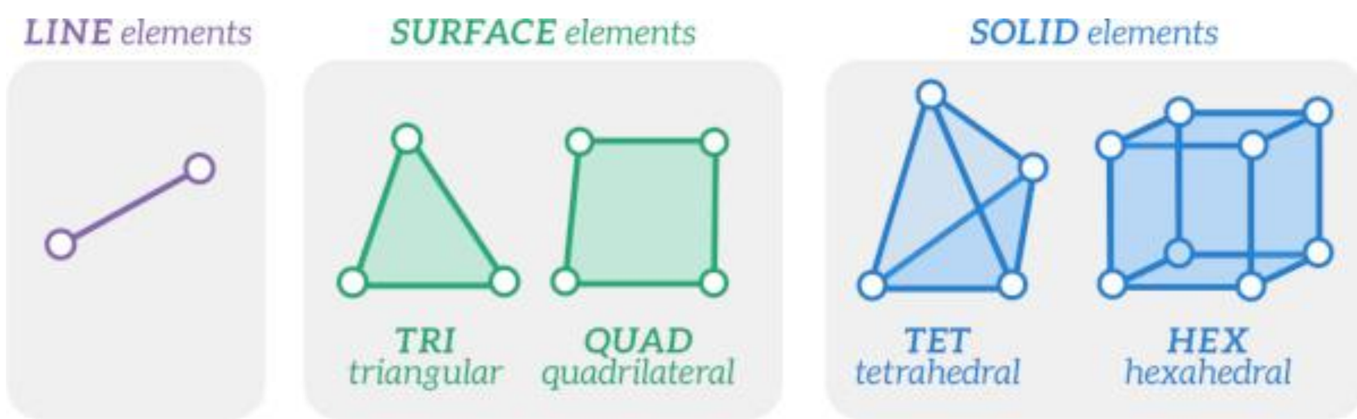
Finite Element Analysis



The Finite Element Analysis (FEA) is a powerful computational technique used to approximate the behavior of physical systems under various conditions. It is widely applied in the field of engineering, physics, and mathematics for visualization of structural rigidity, thermal distribution, fluid flow, and electric & magnetic field.

5.1 FEA Technique

The physical system or domain is divided into finite number of smaller & simpler elements (triangles, tetrahedrons), these elements are connected at points called nodes. Collection of elements and nodes form the mesh. Finer mesh yield more accurate result but takes time to render. Depending on the problem different types of elements are choose like 1D element for beams and rods, 2D elements for plates and shells, 3D elements for 3D objects. This process is called discretization.

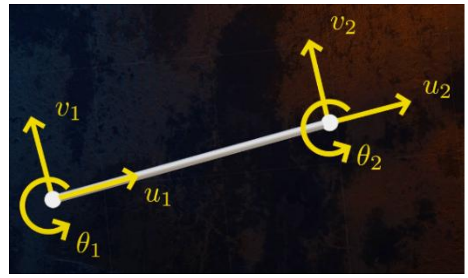


Physical laws & PDEs like (S-N curve, equilibrium, Maxwell's equations, Heat flow equation, Navier-Stokes equation) are used to calculate the stress-strain, temperature distribution, EM fields & fluid flow etc. in the system, but they become difficult when dealing with bodies with very complex geometry. By desacralizing the body into smaller simpler elements, it becomes easier to solve in those elements.

Field Variables: The goal is to calculate the stresses, strain, displacement, temperature, field strength etc. in a body. These unknowns are known as field variables.

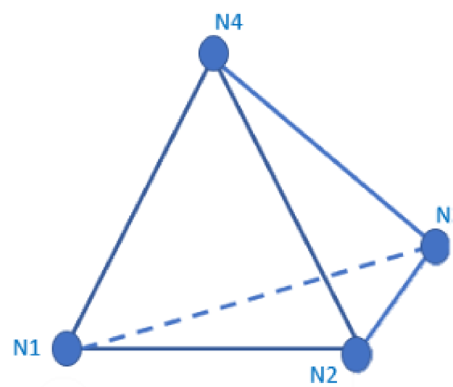
Vector of Nodes: To approximate the field variable in an element, Vector of Nodes is used. It is represented as a vector {u}. for example, for a displacement problem in 2D plane for a 1D line element, each node can move in 2 dimensions and rotate along one axis, the vector of nodes will be:

$$\{u\} = \begin{Bmatrix} u_1 \\ v_1 \\ \theta_1 \\ u_2 \\ v_2 \\ \theta_2 \end{Bmatrix}$$



The vector of nodes contains all the displacements and rotations called degrees of freedom. In 3D Meshes, there are total 3 translational degrees of freedom, but no rotational degrees of freedom as the rotation of element goes by translation of the node. For example, the vector of node for hexahedral element:

$$\{u\} = \begin{Bmatrix} u_1 \\ v_1 \\ w_1 \\ u_2 \\ v_2 \\ w_2 \\ u_3 \\ v_3 \\ w_3 \\ u_4 \\ v_4 \\ w_4 \end{Bmatrix}$$



Stiffness Matrix:

By multiplying the vector of unknowns with stiffness matrix, we get displacement value for each node. This matrix contains elements analogous to spring constant, thus multiplying with displacement vectors we get force and moment, describing how the nodes will move. It is a square matrix, resulting in a transformation equation.

$$\begin{Bmatrix} f_{x1} \\ f_{y1} \\ m_1 \\ f_{x2} \\ f_{y2} \\ m_2 \end{Bmatrix} = \begin{bmatrix} k_{11} & k_{12} & k_{13} & k_{14} & k_{15} & k_{16} \\ k_{21} & k_{22} & k_{23} & k_{24} & k_{25} & k_{26} \\ k_{31} & k_{32} & k_{33} & k_{34} & k_{35} & k_{36} \\ k_{41} & k_{42} & k_{43} & k_{44} & k_{45} & k_{46} \\ k_{51} & k_{52} & k_{53} & k_{54} & k_{55} & k_{56} \\ k_{61} & k_{62} & k_{63} & k_{64} & k_{65} & k_{66} \end{bmatrix} \begin{Bmatrix} u_1 \\ v_1 \\ \theta_1 \\ u_2 \\ v_2 \\ \theta_2 \end{Bmatrix}$$

$$\{f\} = [k]\{u\}$$

Force Matrix:

By multiplying the stiffness matrix with vector of unknowns, by Hooke's law it gives the force matrix. It represents the forces & moments acted on each node on each degree of freedom.

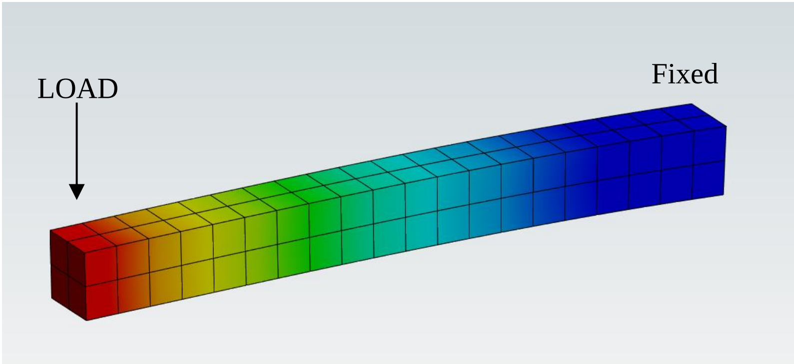
Global Stiffness Matrix:

Now defining the stiffness matrix globally, it shows the general equation for the whole body represented in mesh. As the force matrix is defined by user, we can find individual displacement by inverting the matrix and multiplying with force matrix.

$$\{F\} = [K]\{U\}$$

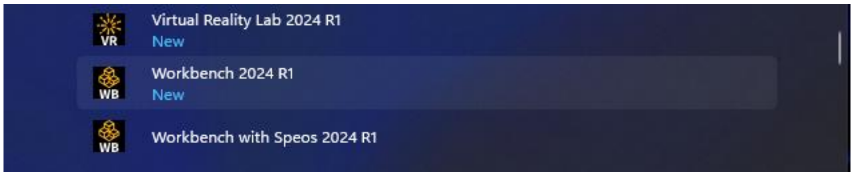
$$\therefore \{U\} = [K]^{-1}\{F\}$$

This example is for static structural analysis for displacement, for {U} it is global displacement. To find any other Field variable, the process goes similar.



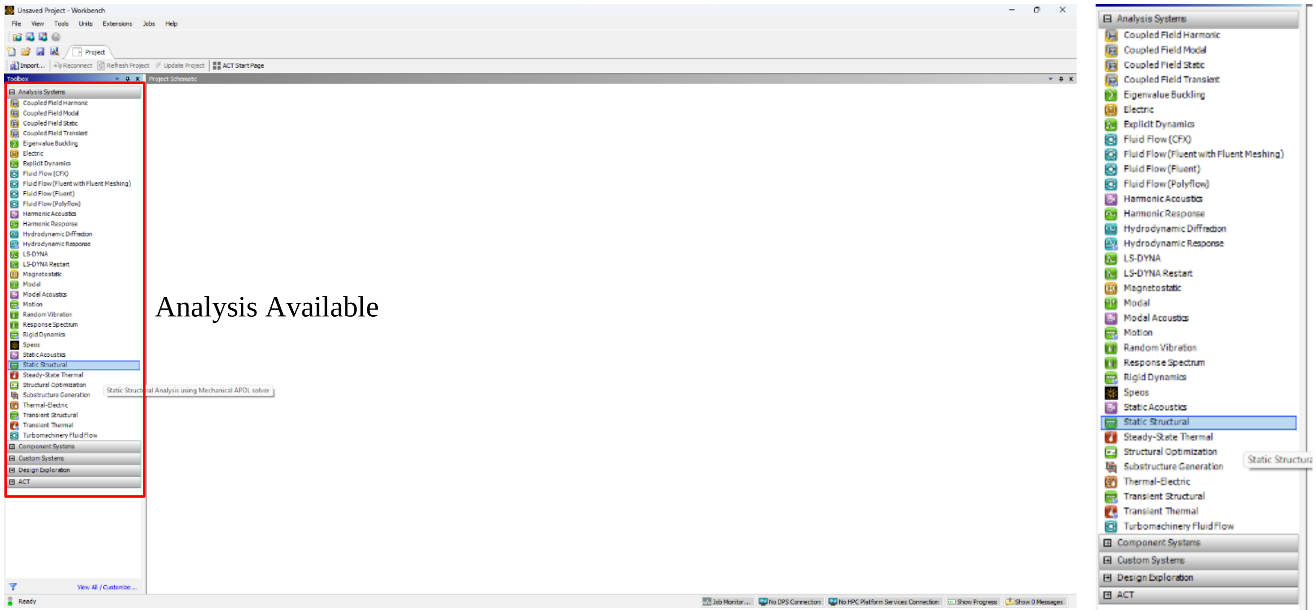
We do not need to go deeply through the method of it, there are software available for do the job. In SolidWorks you will find Simulation Manager where you can do static analysis, but I prefer Ansys as it is a lot more than only static structural like flow simulation, electric-magnetic fields and lot more. As an example, I will tell you how to make a static structural analysis of this cantilever beam using Ansys.

5.2 *Introduction To Ansys*



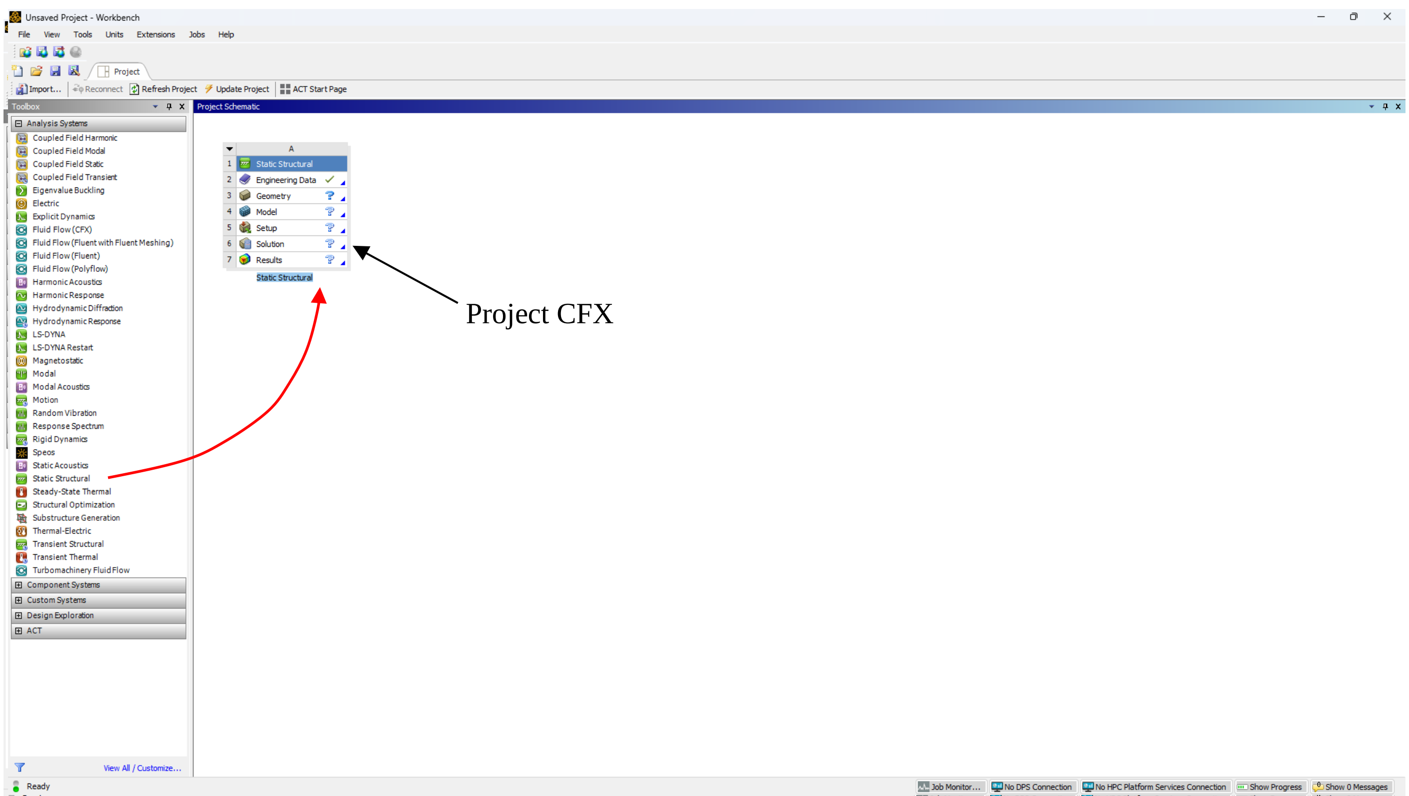
The dimensions and forces go as shown in the diagram. To start with click on "Ansys Workbench" from all the Ansys Software.

After that window will appear like shown. You will find a lot of simulation things on the left side. We are going to do Static Structural analysis which includes stress, deformation etc. So, click on drag it to the workspace. The following window will appear there. We must go through each of the steps:



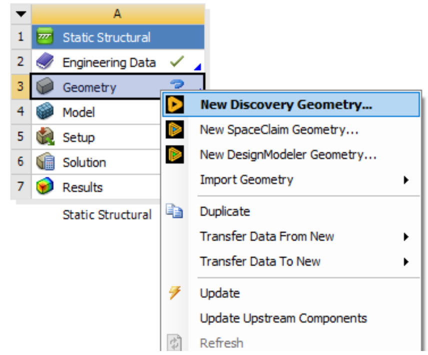
5.3 *Static Structural Study*

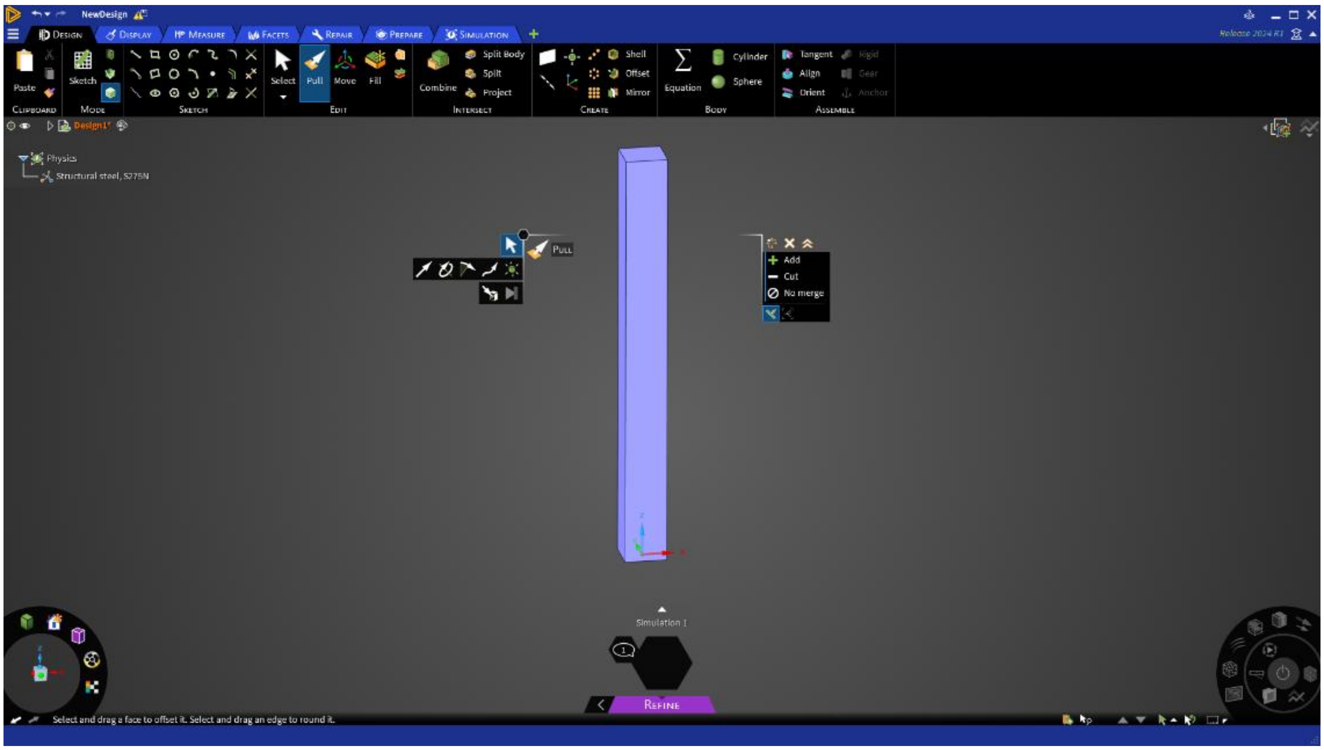
Engineering data → Geometry → Model. After finishing model all others automatically get done.



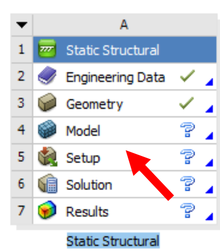
In engineering data, you select the material to be used. By default, it's selected Structural Steel. You change if you need by clicking on Engineering Data. To add other material, you can click on the space shown, then you can close or switch tab back to project.

After defining material, we need to define geometry, if you click on geometry, you will be directed to Ansys Discovery, a CAD software by Ansys. The interface is very modern, but you need a good CPU and Graphics Card for the smooth run. If you right click you can import geometry from other CAD software, to do it you need to import an “IGS” file of your model and rebuild it in Ansys, else you can always create a new model in Ansys Discovery.

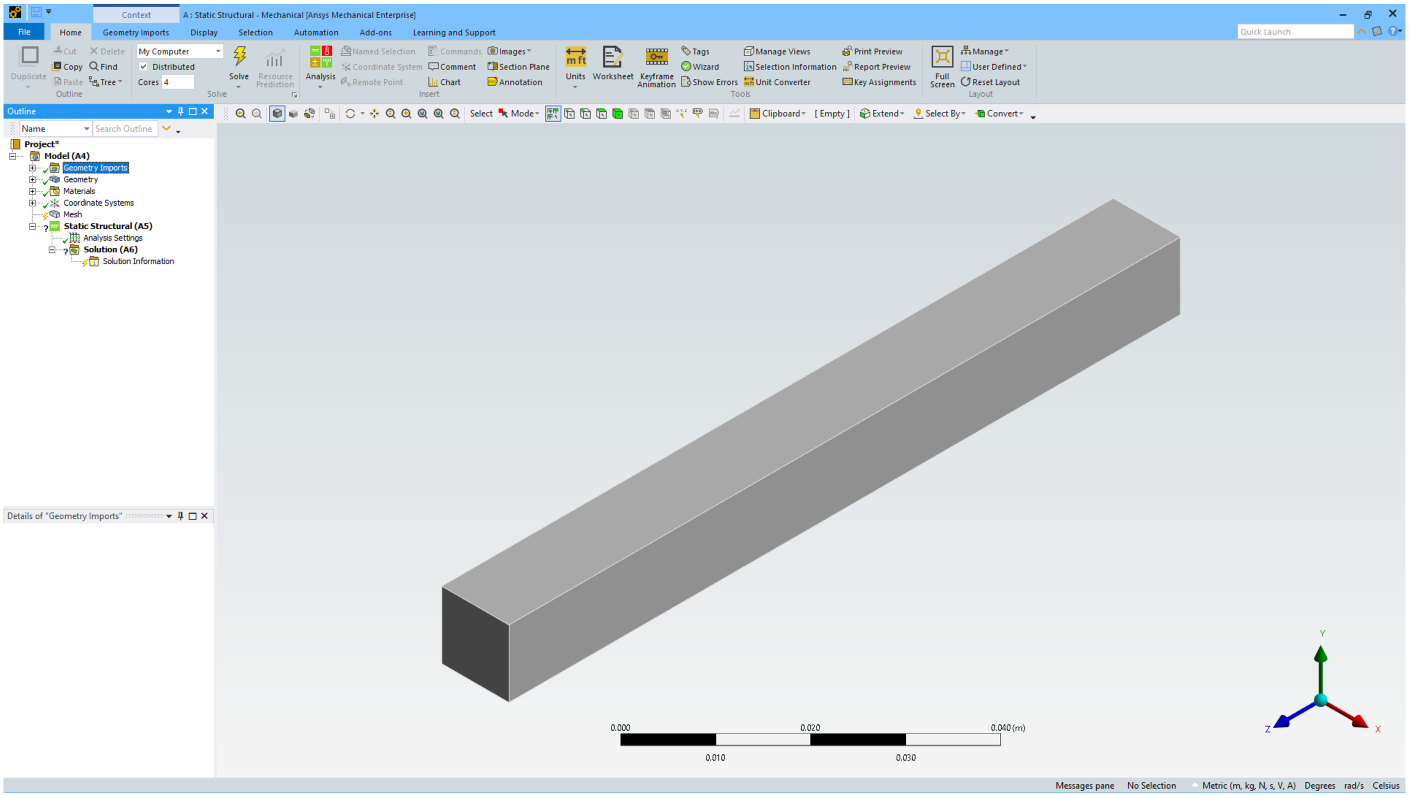


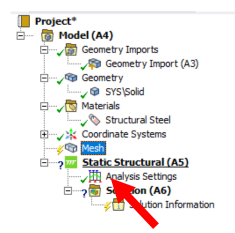


Create a bar in Discovery as shown in the diagram. It’s pretty much like SolidWorks. If you want, you can use SpaceClaim or DesignModeler instead of Discovery as well. After creating the bar, you can close Discovery or go back to Workbench, but keeping Discovery open helps if you want to update your model.

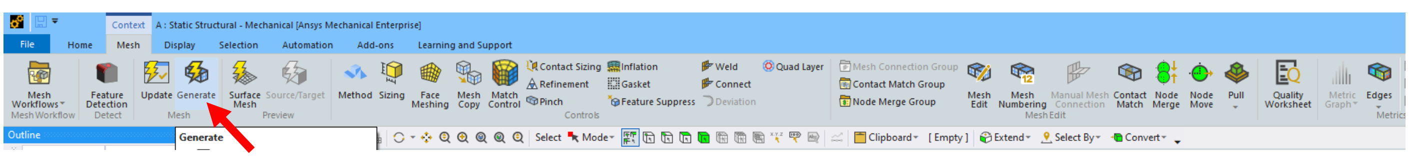


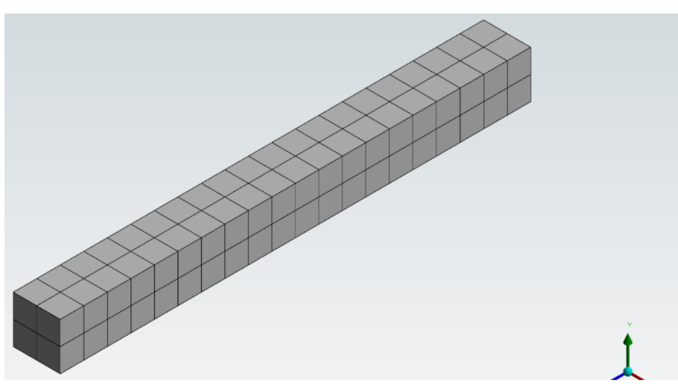
After that click on Model from Project CFX, it will open “Ansys Mechanical.” Here we create the mesh, assign the weights, and run simulation.





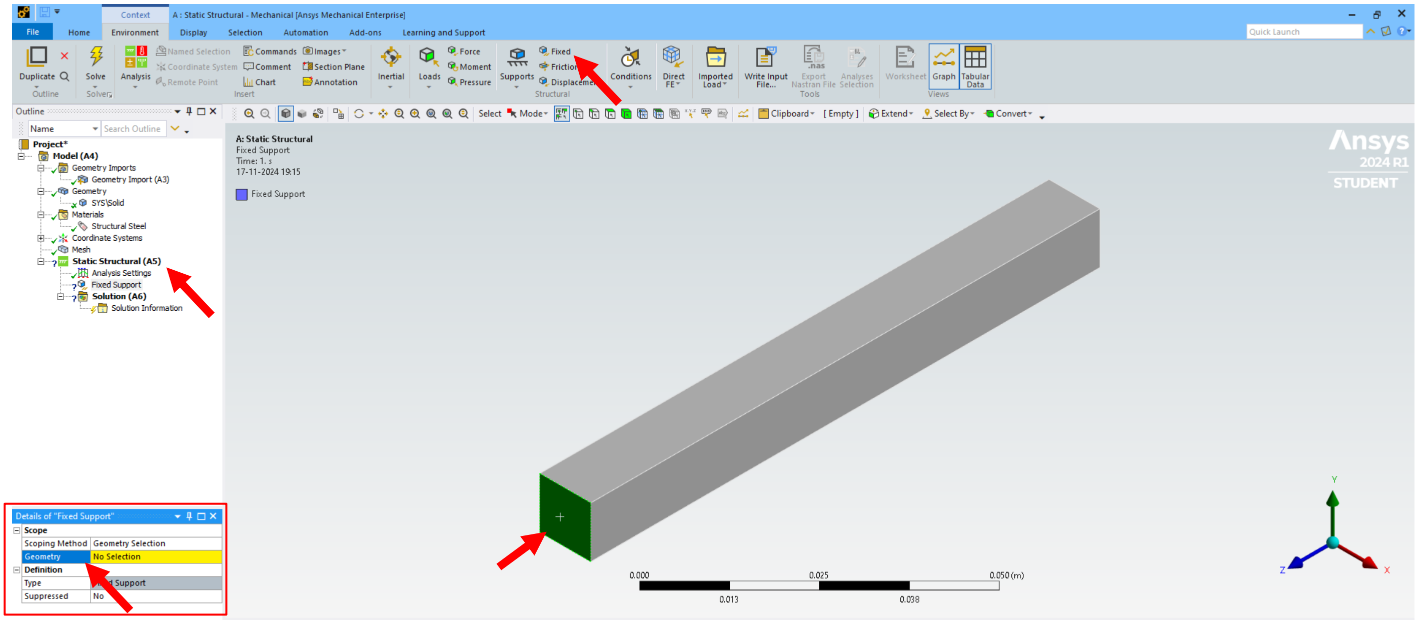
So, at first, we need to check Geometry Imports, Geometry, Materials, Co-ordinate system are all good. Then we need to generate the Mesh of the object. For this click on Mesh from project manager, and then Mesh Tab from Menu bar → Generate Mesh. Now the Mesh for FEA will be created in the model.



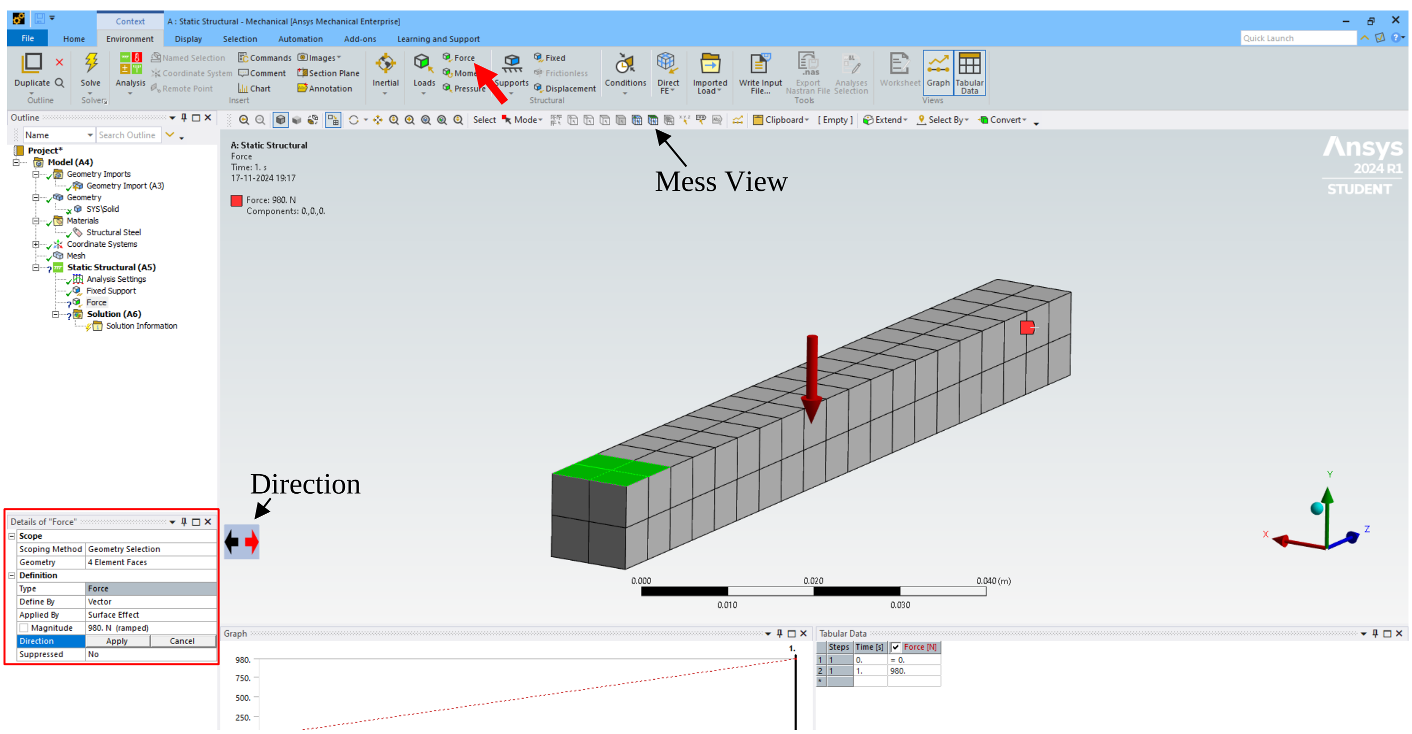


In this small meshes, the computer will calculate each strain, stress and other values and will also run a simulation. Next step is to select fixed faces and apply the load. Let's first apply the fixed surface, to do this first click on static structural from project manager, then go to Environment Tab

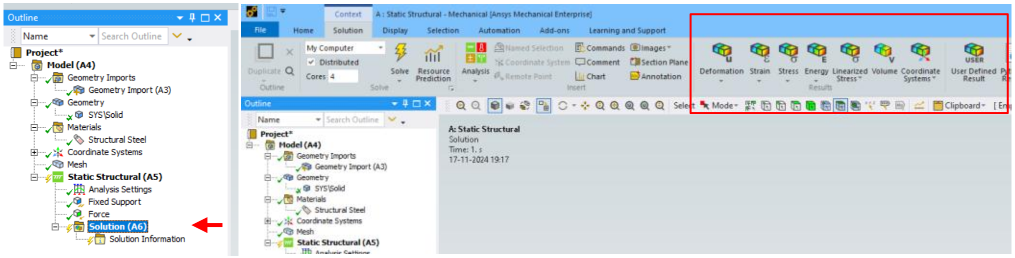
→ Fixed. Then click on geometry, select one side face and then apply which will appear on details box. (*In Ansys yellow box means this needs to be filled)

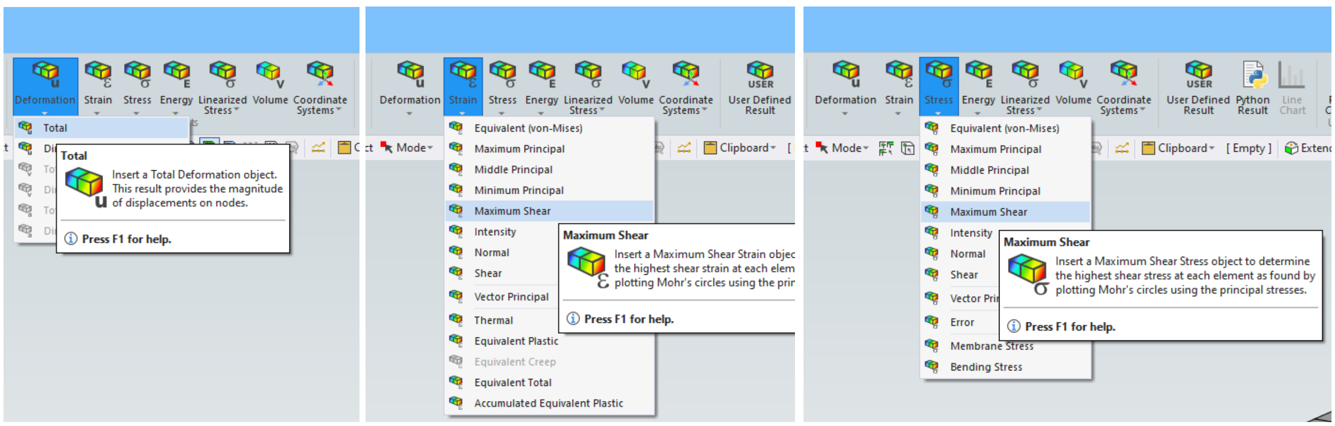


Now the selected face will act as a fixed support. There are also many more options for support like, bearing, roller etc. Now it's time to apply LOAD. For that first click on the button shown to view the Mesh. Likewise, select Force from Environment Tab, then in Details box, select the shown 4 faces → apply Magnitude (100 kg = 980N) → set Direction → click Apply. As the load is to be applied on the other side of fixed support, you can rotate the body by using middle mouse button.

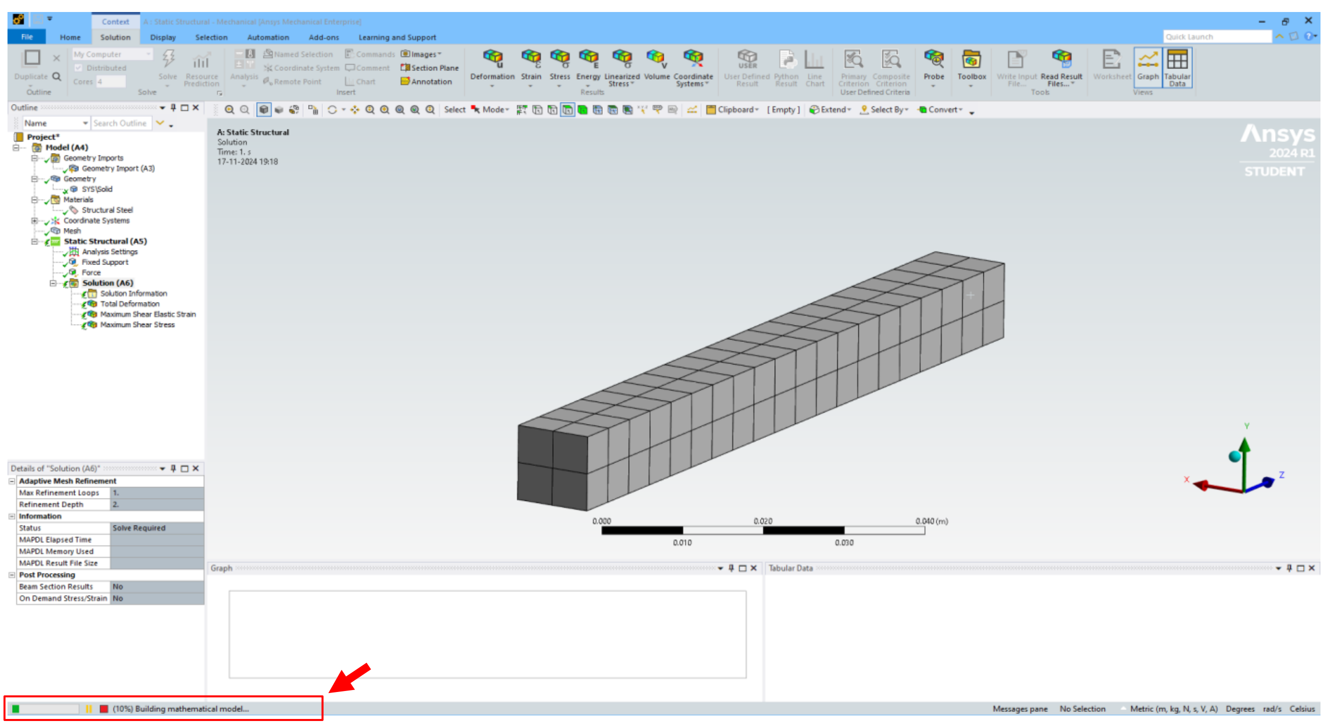


Then we wave to specify the result we need. First click on solution on Project Manager and click on Solution Tab. There you will find all type of results. Everything you will choose will be added to your project manager. I will go with Total Deformation, Maximum Shear Stress & Maximum Shear Strain.

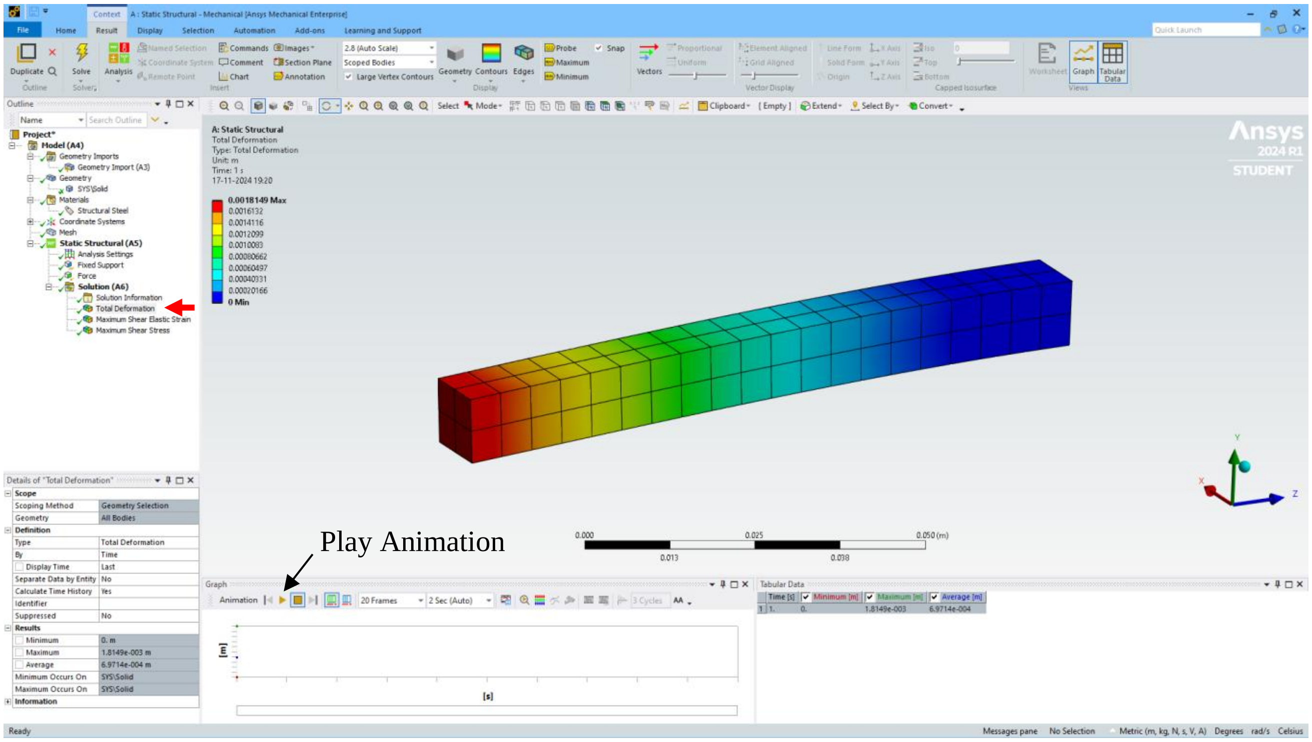




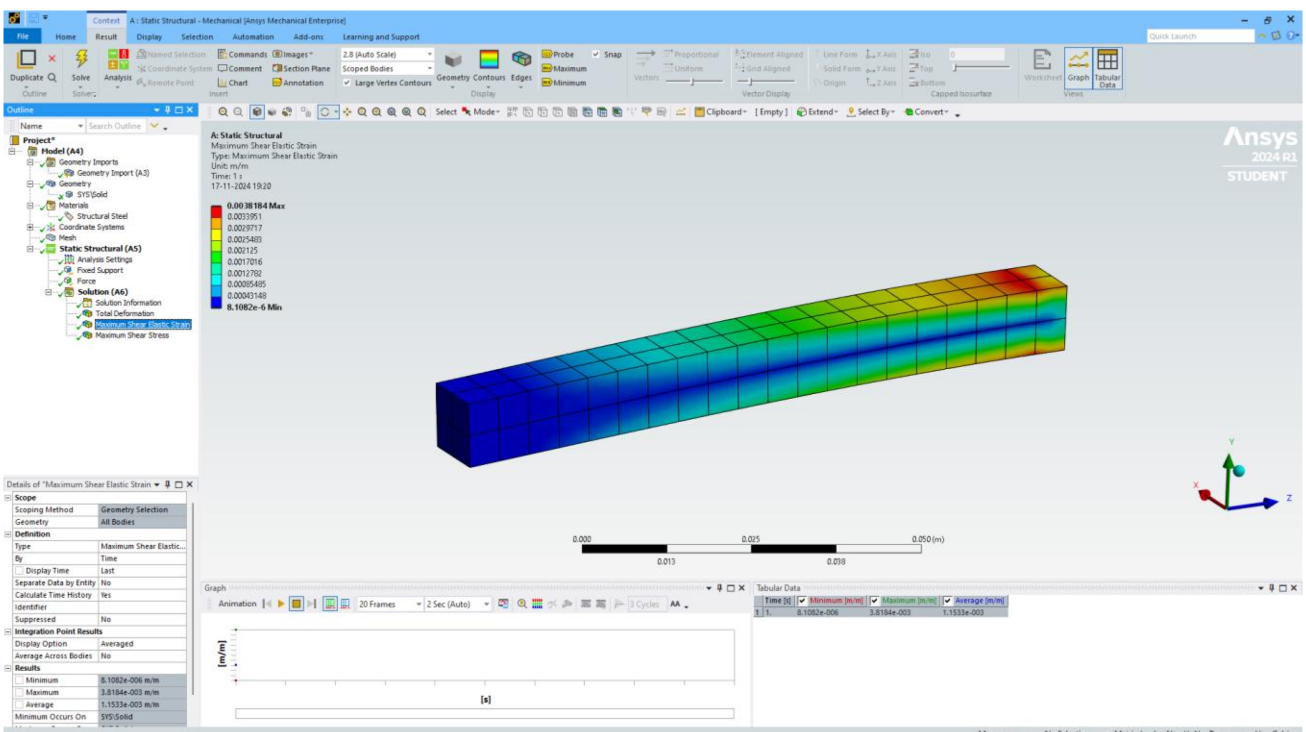
Then hit the solve button. There will be a loading bar at the message bar, when it will be completed, you will get the respective results by clicking on the result from the project manager.



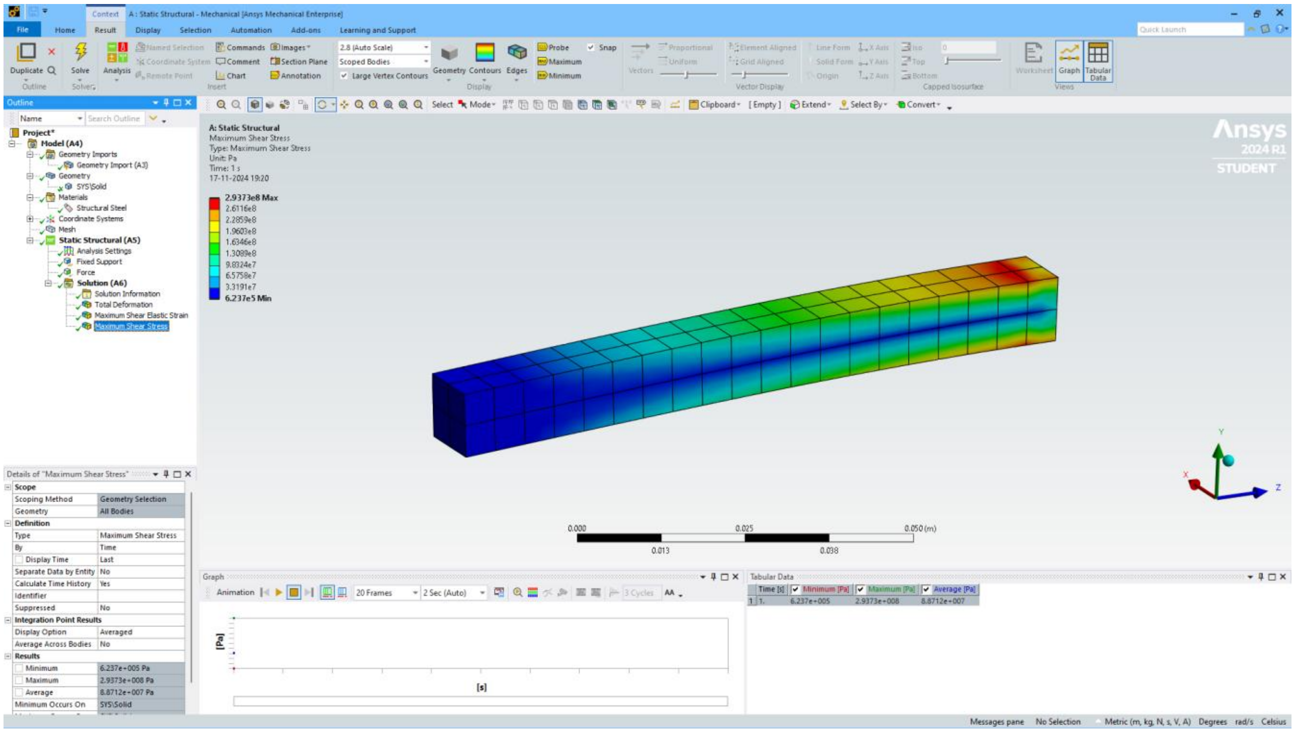
This is the Total Deformation. You can change the colors gradient (smooth/sharp, Mesh/no Mesh by clicking on the button. You can also play the animation by clicking the Play button.



This one's Maximum Shear Strain.



This one's Maximum Shear Stress. As the stress goes above the shear



Fatigue Tool

The fatigue tool is very important in FEA. It is used to simulate on what load the structure will break. In Ansys it's pretty much like use. Primarily we check 2 most important parameters: Life and Safety factor.

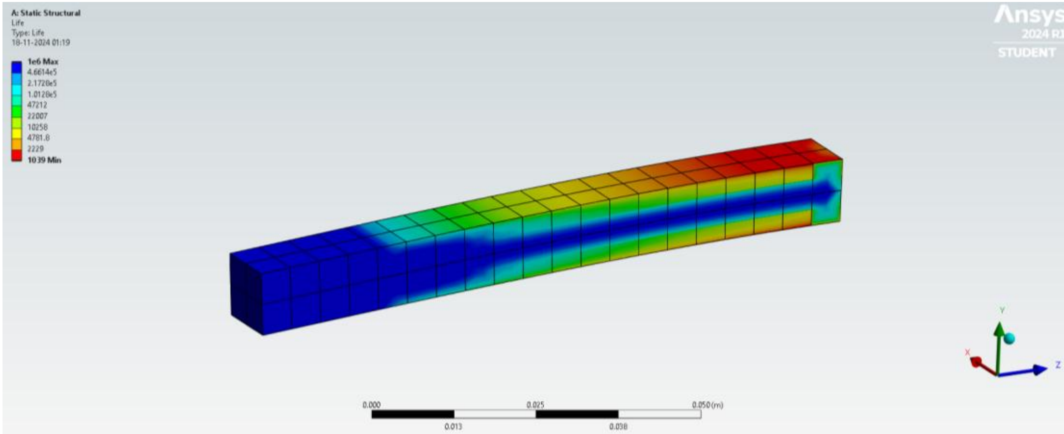
Life: It's assumed that the load on the structure is applied in sinusoidal manner and after how many cycles of that load wave the structure will break. Just like when you break a metal wire by bending it 5-6 times, its Life cycle is 6.

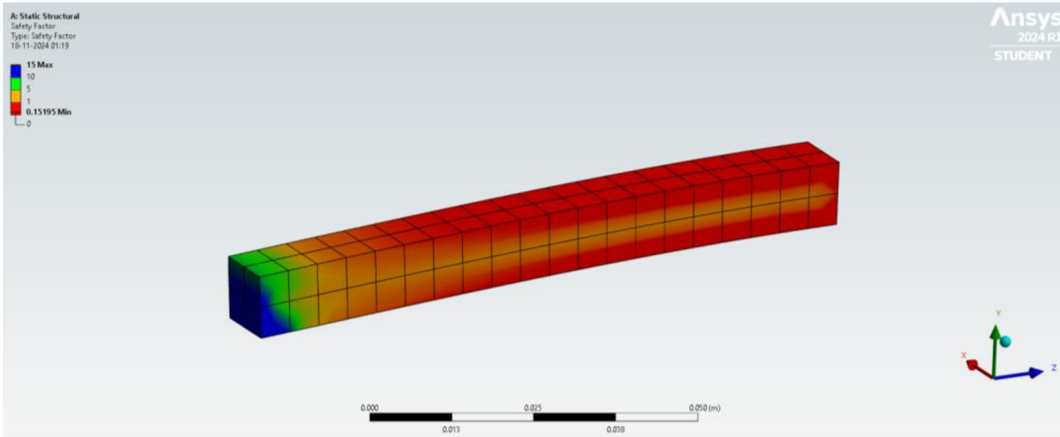
Safety Factor: It's the ratio of maximum allowed strength (yield strength) of the material to the load applied at that point. It refers if the design is safe or not. It's also written as FoS (Factor of Safety)

$$FoS = \frac{maximum\ allowed\ strength}{Applied\ Load}$$

- If the safety factor is 1, the structure will fail immediately with application of load.
- If the cycle is 1, the structure will break immediately on application of the load.

On the above 2 conclusions let us see how the simulation runs for our 10cm steel bar.





The results shows that the safety factor is low in lower than 1 in red regions, that means after application of load, the structure will bend at those regions. The minimum life is 1039, that means the bar will break after 1039 times the load is applied continuously. Here is a table for equipment and safety factor used:

Equipment	FoS	Equipment	FoS
Aircraft Components	1.5 – 2.5	Bolts	8.5
Engine Components	6 – 8	Heavy Duty Shafts	10 – 12
Hooks	8 – 9	Structural Steel Works (buildings)	4 – 6
Turbine Components (rotating)	2 – 3	Structural Steel Works (bridges)	5 – 7
Turbine Components (static)	6 – 8	Wire ropes	8 – 9
Springs, Large Heavy Duty	4.5	Pressure Chambers	3.5 – 6

The End

Chapter 6

The Blueprint

In this chapter we will see how to design our Radio telescope using CAD model and also test its structural integrity using FEA. It covers the common process of starting with a design → test design → assembly, so let's start.

6.1 Getting Started with Parabolic Dish

In this chapter we are going to see how the parameters to be set such that the radio telescope works well. In general, it is done in every machine before production. As we don't have any idea about mass, strength, Inertia, we are going to use Computer Aided Design (CAD) tools to determine it. Also, the CAD software offers Finite Element Analysis (FEA) that can determine rigidity, strength, load capacity etc.

6.1.1 Sketching The Dish

Radio telescopes use a parabolic reflector. The general equation of parabola:

$$y = ax^2$$

$$\therefore \frac{dy}{dx} = 2ax$$

The parabola is parameterized by the constant a. In my telescope I want a property that at the end i.e.

at x = 2m, I want its angle to be 30°. thus putting

$$\frac{dy}{dx} = \tan 30° = 2a.2$$

$$\therefore a = \frac{\tan 30°}{4} = \frac{0.57735}{4} = 0.14434$$

x	0	0.615	1.26	2
y	0	0.054	0.229	0.577
θ	0	10°	20°	30°
m	0	0.17	0.36	0.577

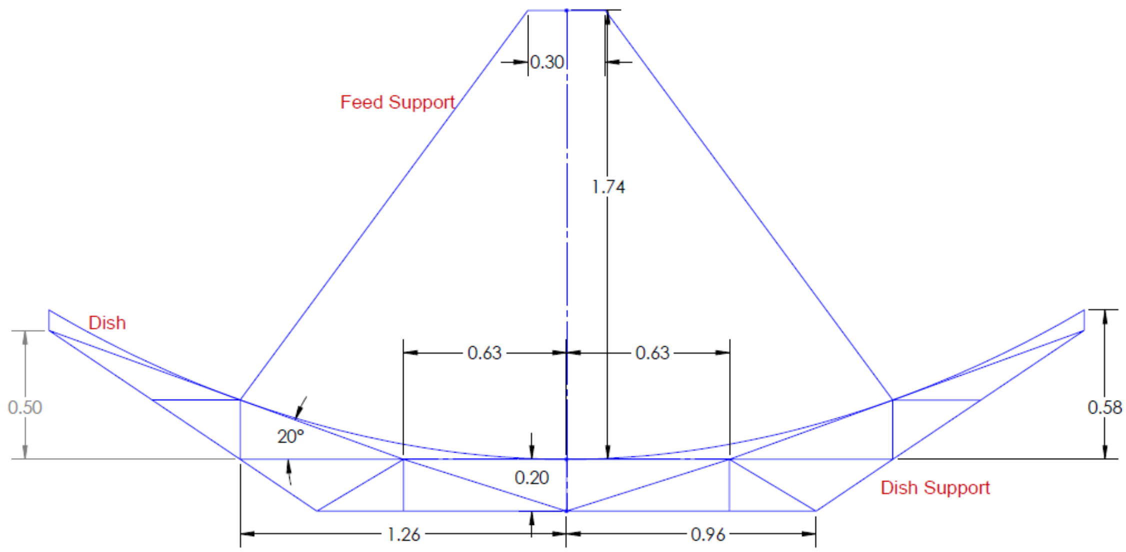
Thus, in accord to this parameter, we got the properties of the parabola:

From the equation of parabola, we got the formula for focus:

$$f = \frac{1}{4a}$$

$$\therefore f = \frac{1}{0.57735} = 1.732$$

Thus using “SolidWorks Drawing”, the sketch was made:



The f/D ratio comes out to be:

$$\frac{f}{D} = \frac{1.732}{4} = 0.433$$

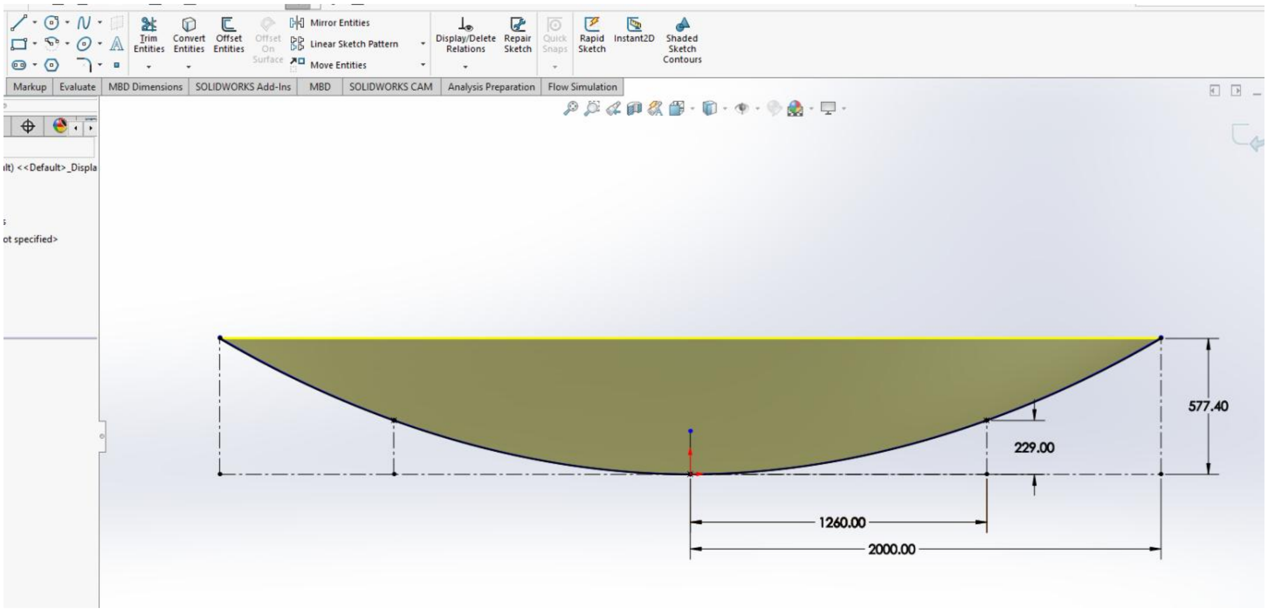
∴ It is in the good range of radio dishes (0.25 - 0.5). f/D radio of GMRT = 0.412, IIRI = 0.4

6.1.2 CAD Model

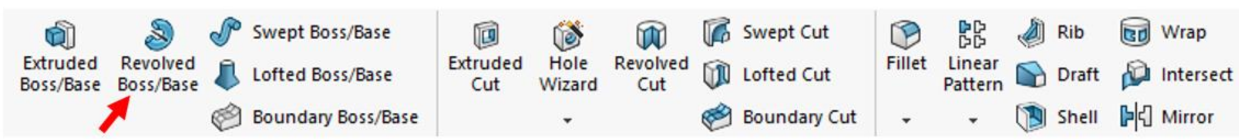
Now we need to make the CAD model as we have the geometry, after that the software will show the mass, moment of inertia and other properties as well. The detailed steps are shown.

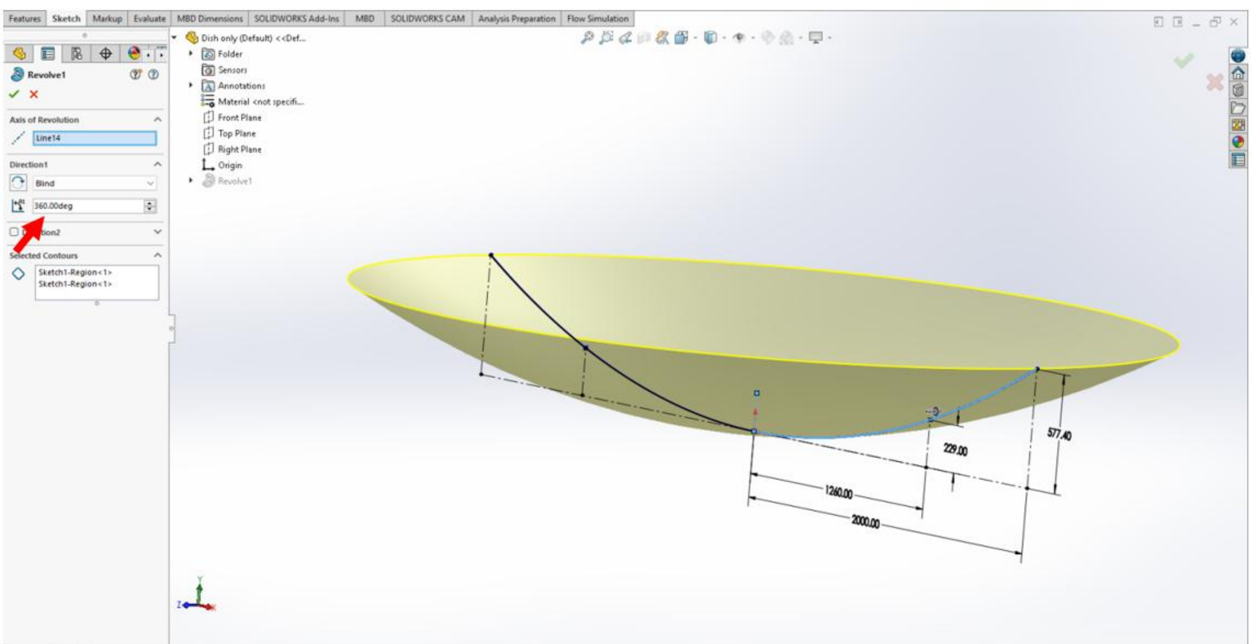
Go to the sketch tab and select front plane.

Now it’s time to draw the cross section of the parabola. Draw a straight horizontal line with marked x-coordinates. Then there add the vertical lines of y co-ordinate at each x-value. Then join the points using spline tool from drawing tab. By giving one more 1mm extra towards ach vertical line, we are making the dish 1mm thick.

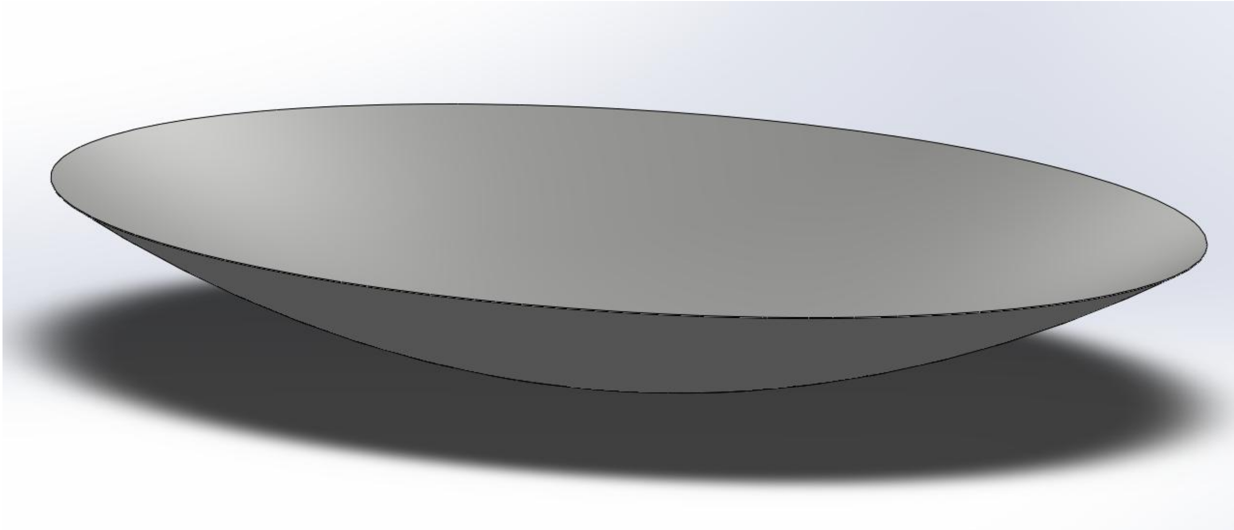


Now do a revolved base from the surface with 360º revolution.

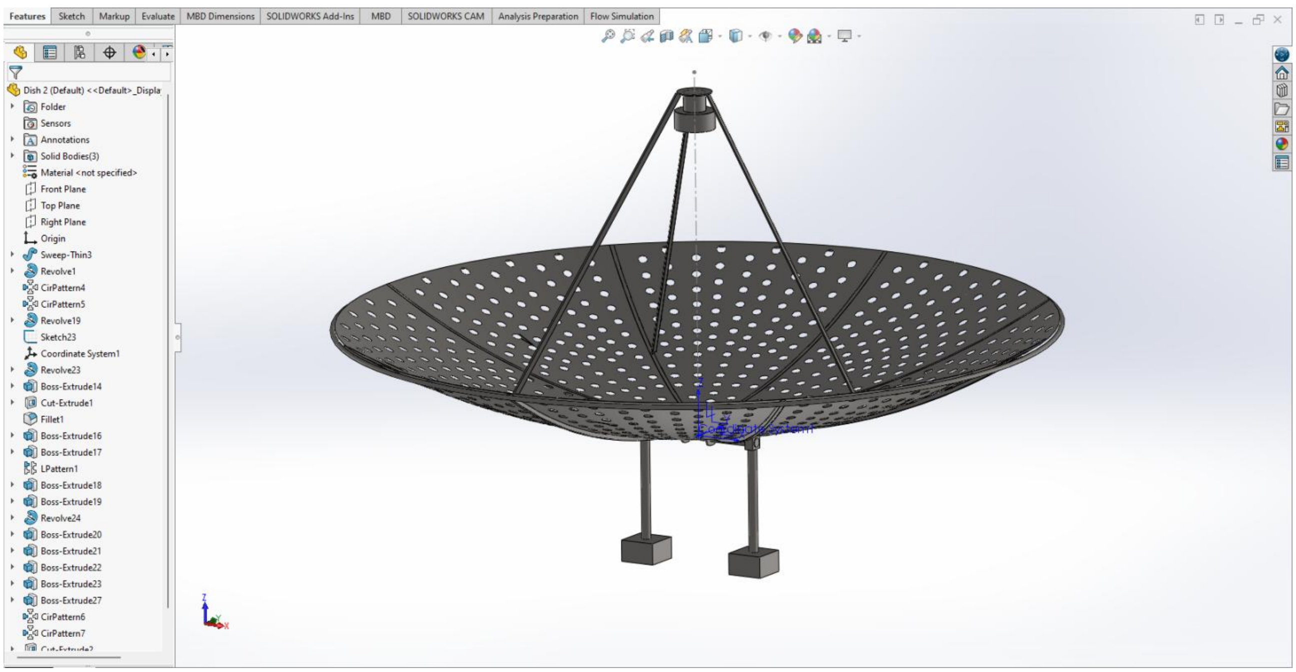




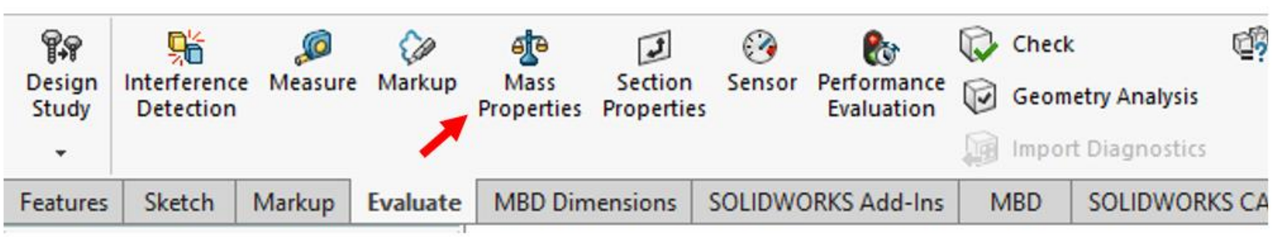
Thus, now you will have your 3D parabolic dish. From that you can calculate the mass and moment of inertia by using the mass properties from evaluate tab.



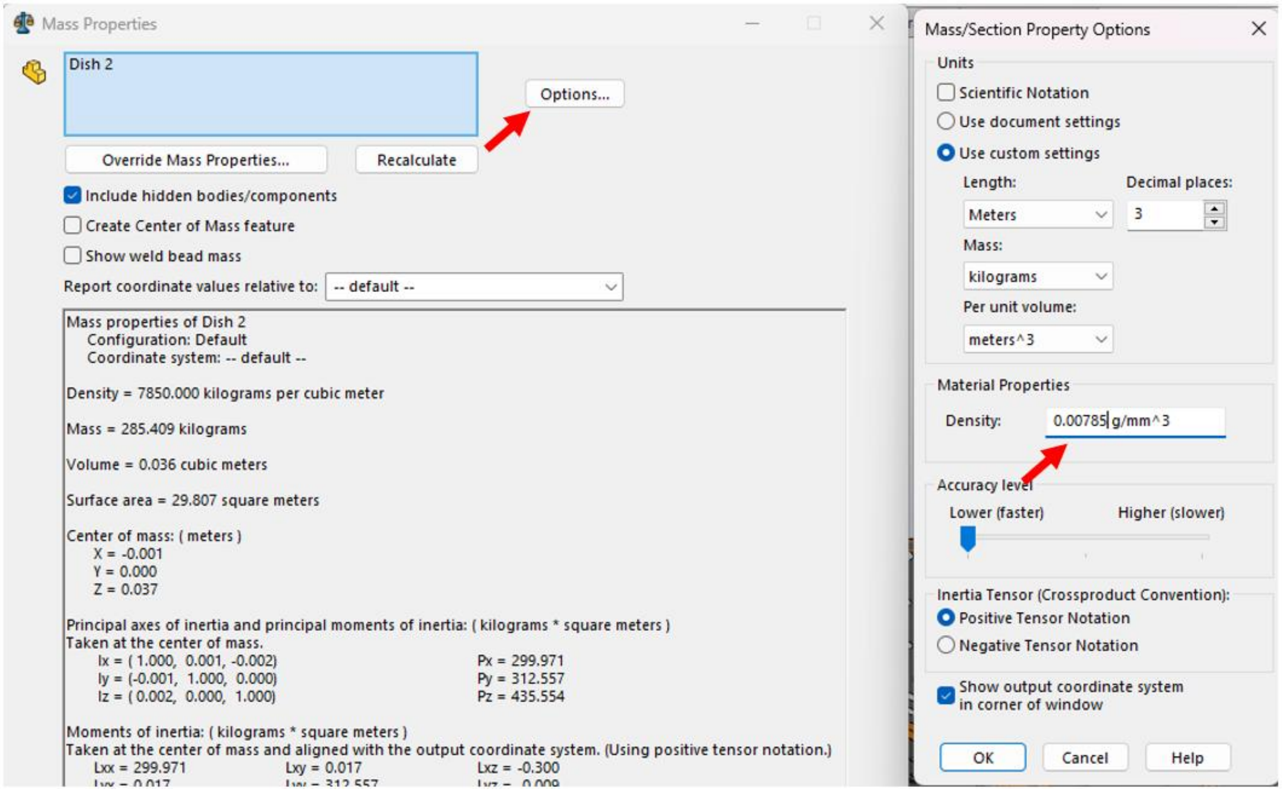
This is the dish we need to make. With some little more effort, we added the feed support, dish support and counterweight, and the design is shown below.



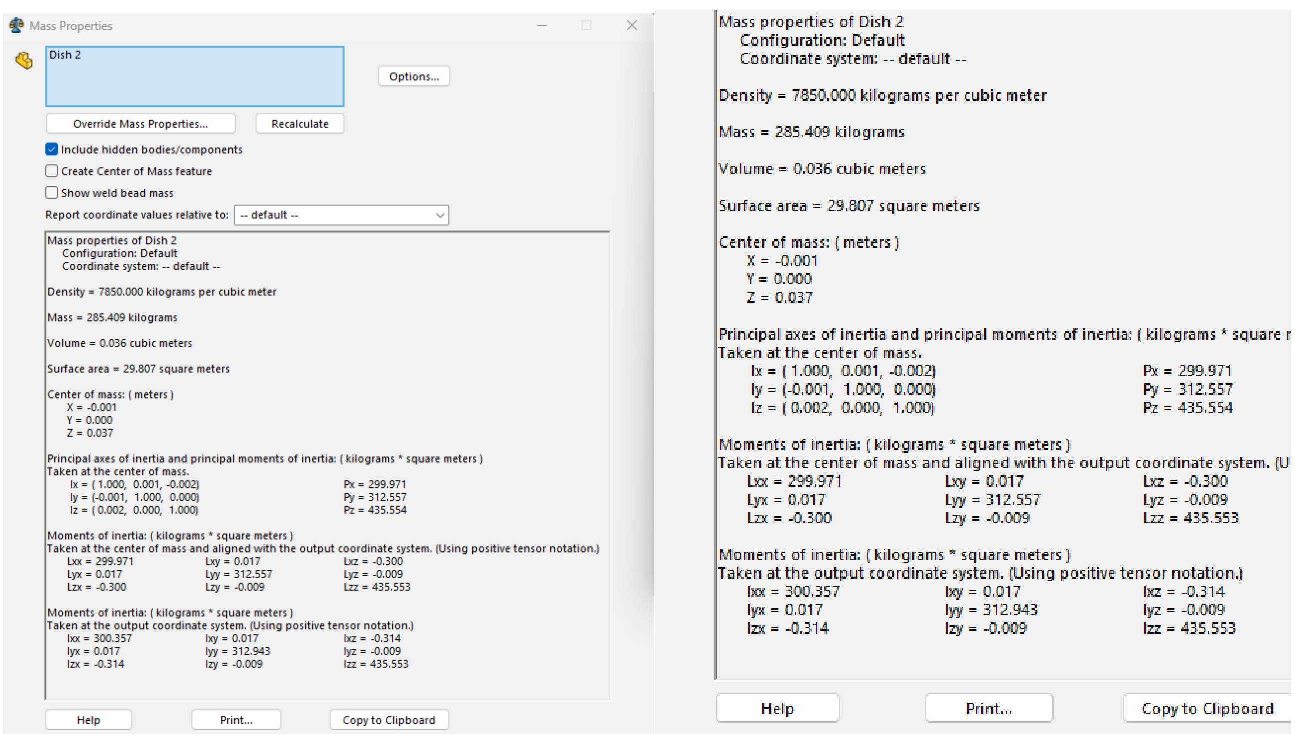
Now to calculate the mass properties go to “evaluate” tab → mass properties.



Initially it will show the window with some mass and moment of inertia, but the values will not be right. We need to provide the density of the material we are using. Click on options on the new window.



As we are using structural steel, the density of aluminium is 7.85 g/cc. To convert it into g/mm3, divide it by 1000, thus 7.85/1000 = 0.00785 g/mm^3. Now you should be getting the correct answer.



6.1.3 Resolution & Mechanical Properties

As we have calculated mass & moment of inertia of the radio dish. Now we can calculate the torque required. The torque will vary depending on the angular position, friction surface and wind conditions. But we do not need to calculate the torque required as a function of position, as the motor we are going to use (servo motor) will adjust the torque accordingly. We just need to verify that the torque we are providing is way more than the minimum torque requirement of the dish, including frictional, gravity & wind conditions.

Apart from mechanical properties we also have some radiative properties like resolution, bandwidth of it which depends on the size and the wavelength of incoming beam. Let us go through them one by one.

For a parabolic reflector, the resolution is given by:

$$\Delta\theta = 1.02\frac{\lambda}{D}$$

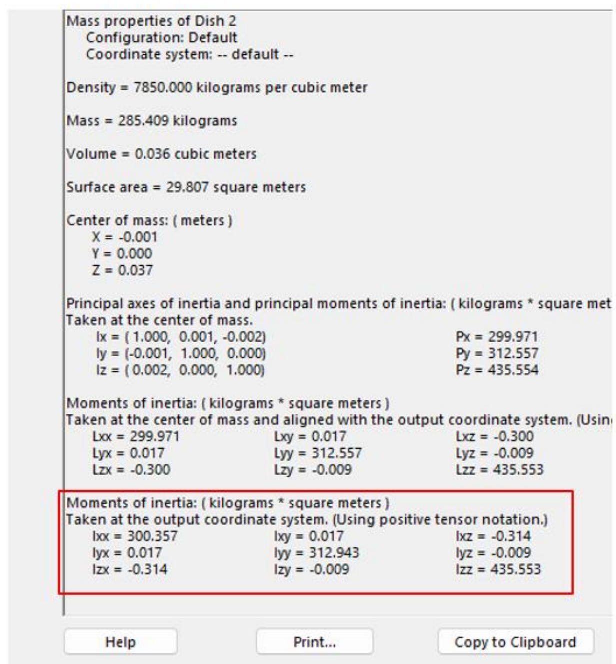
For our 4m dish, it turns out to be:

$$\Delta\theta = 1.02 \times \frac{0.21}{4} = 0.05355\, rad = 3.068°$$

Therefore, when tracking the maximum amount of rotation in single move will be 3.068°. Now also there is sky velocity, which is 15 arcsec/sec. In degrees per min, it will be roughly 0.005°/sec. Adding up the maximum angular velocity will be 3.073°/s. Rounding up to 3.1°/s lets proceed. Let us make a hit and trial guess, say the update time is 0.1s from one pixel to another, if it does not meet the requirements we'll modify it.

$$\omega = 3.1°\, s^{-1} = 0.054\ rad/s$$

$$t = 0.5\, s \therefore \alpha = 0.108\, rad/s^2$$


Mass properties of Dish 2
Configuration: Default
Coordinate system: -- default --

Density = 7850.000 kilograms per cubic meter

Mass = 285.409 kilograms

Volume = 0.036 cubic meters

Surface area = 29.807 square meters

Center of mass: (meters)
X = -0.001
Y = 0.000
Z = 0.037

Principal axes of inertia and principal moments of inertia: (kilograms * square met
Taken at the center of mass.

Ix = (1.000, 0.001, -0.002)	Px = 299.971
Iy = (-0.001, 1.000, 0.000)	Py = 312.557
Iz = (0.002, 0.000, 1.000)	Pz = 435.554

Moments of inertia: (kilograms * square meters)
Taken at the center of mass and aligned with the output coordinate system. (Usin

Lxx = 299.971	Lxy = 0.017	Lxz = -0.300
Lyx = 0.017	Lyy = 312.557	Lyz = -0.009
Lzx = -0.300	Lzy = -0.009	Lzz = 435.553

Moments of inertia: (kilograms * square meters)
Taken at the output coordinate system. (Using positive tensor notation.)

Ixx = 300.357	Ixy = 0.017	Ixz = -0.314
Iyx = 0.017	Iyy = 312.943	Iyz = -0.009
Izx = -0.314	Izy = -0.009	Izz = 435.553

Help Print... Copy to Clipboard

From the FEA, we got the results for the moment of inertia of the dish, which we found to be:

$$\mathbf{301\ Kgm^2\ along\ x-axis\ ,313\ Kgm^2 along\ y-axis\ ,436\ Kgm^2\ along\ z-axis}$$

The bottom one has taken as respective to coordinate system which is aligned to axis in the design.

6.1.4 Torque

In design the center of mass is at 3.7 cm, but it can be adjusted in the real telescope. Thus, rotating along the x-axis, torque required will be:

$$\tau_x = 301\ kg.m^2 \times 0.108\ s^{-2}$$

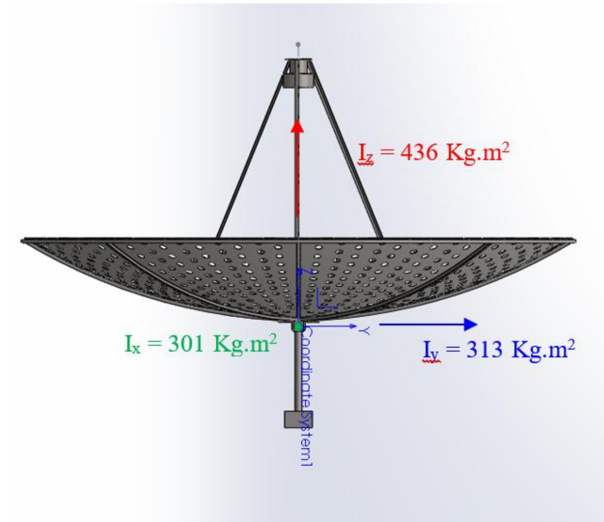
$$= 32.508\ Nm$$

$$\tau_y = 313\ kg.m^2 \times 0.108\ s^{-2}$$

$$= 33.804\ Nm$$

$$\tau_z = 436\ kg.m^2 \times 0.108\ s^{-2}$$

$$= 47.088\ Nm$$

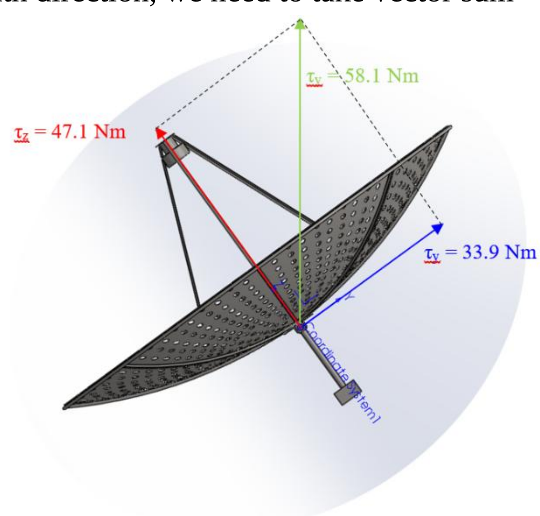


Now as you can see while taking rotation along altitude, we should take account for τ_x but for rotation along azimuth, we need to calculate vector sum of both τ_y and τ_z.

When the telescope rotates about some axis, the required torque will vary depending upon conditions. But the servo motor will adjust its torque accordingly. As there is counterweight, we do not need to worry about gravity. But we need to take account for the minimum required torque to rotate the antenna.

For Elevator, the maximum torque will always equal to be τ_x, torque along x-axis as it is always aligned to x-axis, τ_{el} max = 301 Kg.m2. For azimuth direction, we need to take vector sum of both y and z axis.

Therefore, the vector sum of the two torques:



$$\vec{\tau} = \tau_y \hat{j} + \tau_z \hat{k}$$

$$\therefore |\tau| = \sqrt{{\tau_y}^2 + {\tau_z}^2} = \sqrt{47.1^2 + 33.9^2}$$

$$= \sqrt{2218.41 + 1149.21}$$

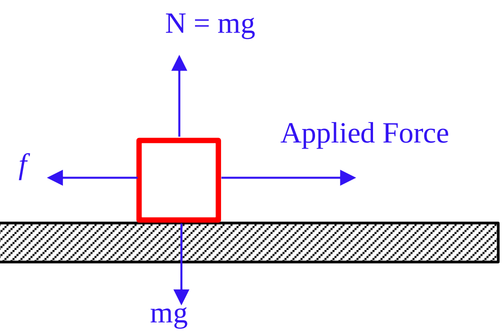
$$= 58.03\ N.m$$

Angle along x-axis: $\varphi = \tan^{-1}\frac{47.088}{33.804} = \tan^{-1} 1.393 = 54.33°$

Therefore, the azimuth drive will experience maximum torque when elevation is 35.67°.

6.1.5 Frictional Corrections

In real world application we cannot neglect friction. Although the exact calculation is more complicated, we will do a rough estimation of the frictional opposition. The coefficient of friction is given by:



$$f \leq \mu . N$$

$$f: Frictional\ force$$

$$\mu: Frictional\ coefficient$$

$$N: Normal\ Force$$

One thing needs to keep in mind that:

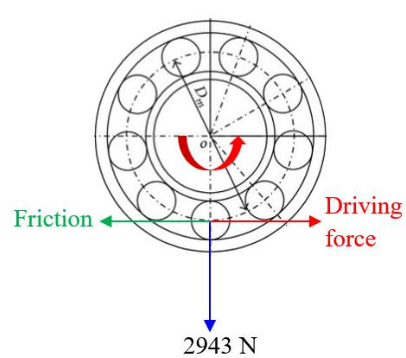
$$f = \begin{cases} f_a & : \quad f_a < \mu . N \\ \mu . N & : \quad f_a \geq \mu . N \end{cases}$$

Friction also two types, static and kinetic, which is friction applies on the body when the body is at rest and in motion, respectively so the coefficient of friction is defined. The table of frictional coefficients of some materials are given below:

Surface Type	μ_s	μ_k
Steel on Steel	0.74	0.57
Aluminium on Steel	0.61	0.47
Rubber on Concrete (dry, wet)	1.0, 0.3	0.8, 0.25
Wood on Wood	0.25-0.5	0.2
Glass on Glass	0.94	0.4
Metal on Metal with Lubrication	0.15	0.06
Ball Bearings	--	0.001 to 0.002

Elevation Case:

In elevation case, we only have 2 ball bearings, and the mass of dish is 300Kg (2943N). Thus, to find the frictional opposition, we need the exact dimensions of the bearing, but at this stage we have only data is bearing will be maximum 5cm wide.



From the diagram of the bearing, say D_m = 5cm = 0.05m

Normal Force N = 300 Kg = 2943 N

Therefore, frictional force $f = 0.002 \times 2943 = 5.89\ N$

Thus, frictional torque = $\tau_f = 5.89 \times 0.025 = 0.14725$

Then the frictional correction to torque:

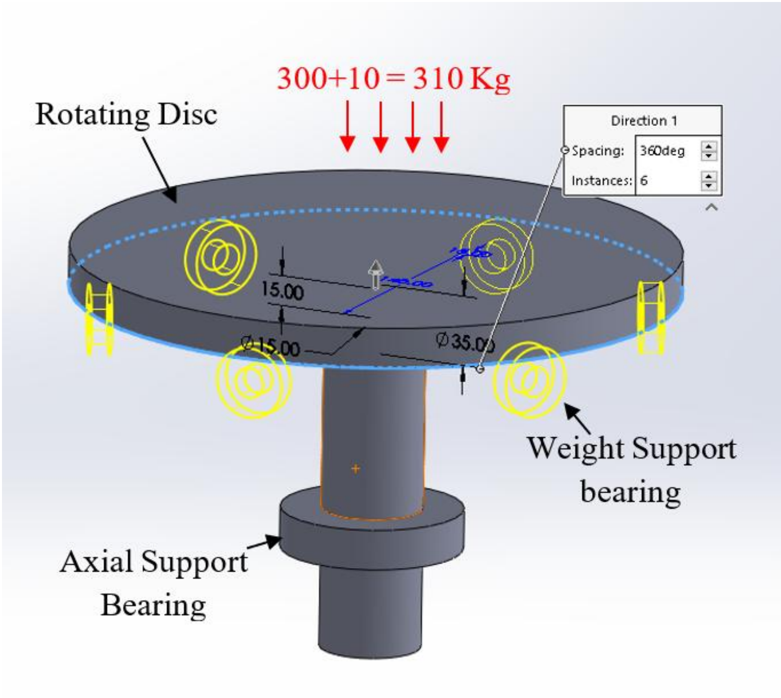
$$\tau_e = 32.508 + 0.14725 = 32.68825\ Nm$$

Rounding off to upper limit:

$$\tau_e = 32.7\ Nm$$

Azimuth Case:

In Azimuthal case, the design is planned like the disc along with elevation system will be on the top of a horizontal rotating disc. This disc will be held by a large ball bearing for concentricity and supported by 6 smaller bearings for weight support, as shown in diagram below.



The antenna will be mounted on the disc, the exact design is not made yet, the diagram shows the maximum size it could is 40cm wide. On this disc additional roughly 20Kg of load will be applied due to elevation motor and gearbox.

Therefore, for axial ball bearing, estimated 9cm wide:

Normal force = $320\ Kg = 320 \times 9.81 = 3134\ N$

Therefore, fictional force = $0.002 \times 3134 = 6.268\ N$

Then frictional torque = $\tau_f = 6.27 \times 0.045 = 0.282$

For the weight support bearing, as it is located at 0.2m from center, we need to calculate frictional force there and we can multiply it with this distance.

$$\therefore Normal\ force = \ 3134\ N$$

$$\therefore Frictional\ force = 0.002 \times 2943 = 6.268\ N$$

$$\therefore Frictional\ torque = \tau_f = \ 6.268\ N \times 0.2\ m = 1.254\ Nm$$

$$For\ 6\ such\ bearings, frictional\ torque = 7.524\ Nm$$

$$\therefore Total\ frictionl\ opposition = axial + weight\ support = 0.282 + 7.524 = 7.806$$

Thus, total torque required in azimuthal drive, we also need to calculate for the elevation movement system, if it is a uniform cylinder of 0.2m radius

$$I_{ed} = \frac{1}{2}MR^2 = 0.5 \times 20 \times 0.04 = 0.4\ Kgm^2$$

Previously calculated, angular acceleration $\alpha = 0.108\ rad/s^2$

$$\therefore \tau_{ed} = 0.4 \times 0.108 = 0.0432\ Nm$$

Thus, the frictional correction to azimuth drive:

$$\tau_a = 58.1 + 0.0432 + 7.806 = 65.95 Nm$$

Rounding off to upper limit:

$$\tau_a = 66\ Nm$$

Again, it is a rough estimation, we cannot make sure how much it will vary, as we have estimated almost all possible forces and torques, so if the result decreases than calculation no problem, but what if the result increases? So, we can estimate that it cannot vary more than 1 or 2 Nm if we consider there were 10 balls in a ball bearing and so on, so what we are going to do is we will give an input torque way large than the maximum torque.

6.1.6 Gear Ratio

Now we must give an input torque to the drive, around 100 Nm, no motor can provide that much amount of torque. So, we need a gearbox. The standard gearbox easily available in the market in the gear ratio are from 1:2, 1:5, 1:10, 1:20, 1:25, 1:50, 1:100, 1:200 etc.

As we are using Delta Servo Motor for application, a list of the motor power and output torque I found on the manual:

ECMA	C△04	C△06		C△08		C△09		C△10		C△13
	01	02	04□S	04	07	07	10	10	20	30
Rated power (kW)	0.1	0.2	0.4	0.4	0.75	0.75	1.0	1.0	2.0	3.0
Rated torque (N-m) [*1]	0.32	0.64	1.27	1.27	2.39	2.38	3.18	3.18	6.37	9.55
Max. torque (N-m)	0.96	1.92	3.82	3.82	7.16	7.14	8.78	9.54	19.11	28.65
Rated speed (r/min)	3000									

As the maximum required torque is 64 Nm, we can use the 200W motor with 0.64 Nm torque. With a 1:100 gear ratio we can have 64Nm output torque, but we also need to overcome the wind conditions at the site, so let us go for higher output torque.

One of the easily available and lower cost motor is the 400W one. Its output torque is 1.27Nm. With the 1:100, we will get an output torque of 127 Nm, enough for rotating the motor and overcome wind speed.

6.2 Designing The Trusses

The whole system is meant to be mounted on a truss base, it will significantly lower the material cost, easy to make and assemble and it is easily available. Th design is shown in the figure. It will be made from Mild Steel Angle Bar, 25mm x 25mm x 3mm. It will be joined by nut and bolts and some places by welding. Some steels plates will be attached to mount motors, gearboxes, electronic parts etc. There are 3 Trusses: 1. Base Truss, 2. First Truss and 3. Second Truss. Let's Start with the first Truss, as base truss can be derived from it.

6.2.1 First Truss

The first truss is a simple truss with dimensions 500x500x1000mm. To model this, start with a square 500x500 mm with hollow region with your design. Then boss extrude it accordingly. After extruding the wall of the angle bar, extrude the 4 pillars and mirror the bottom square with a mid-point reference plane. Then add the crossbars and one side of middle square, add walls to them, and them circular pattern them with an axis at the center. Then you are done.

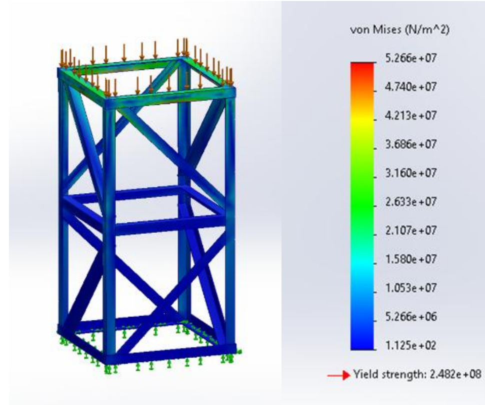
Then a FEA study is done and the result is shown below along with parameters.

Maximum Stress: 52.66 MPa

Yield Strength: 248.2 MPa

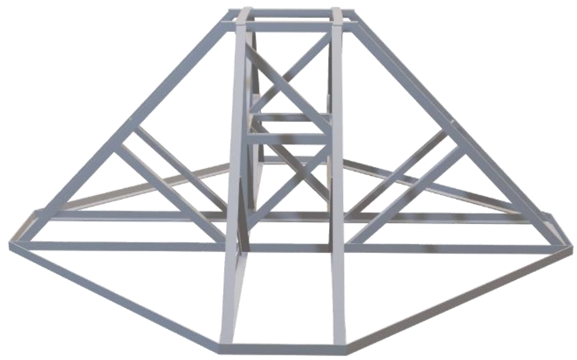
LOAD: 500 Kg

Safety Factor: 4.7



6.2.2 Base Truss

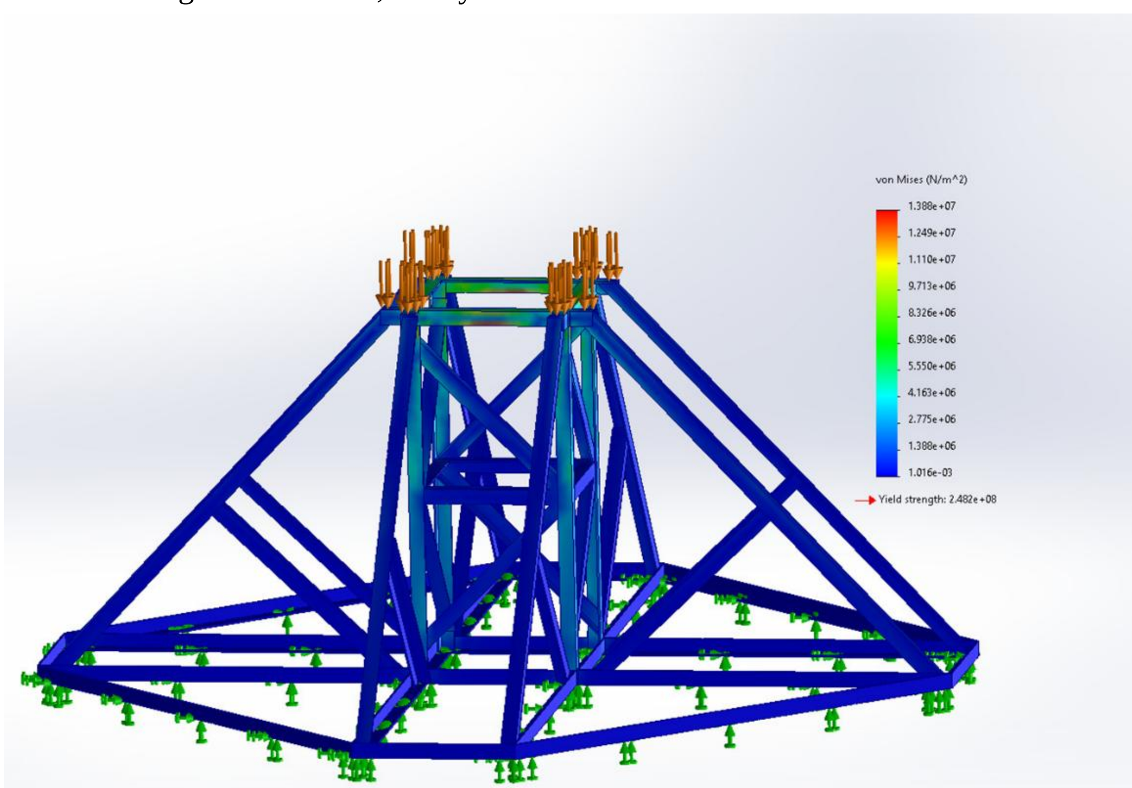
To model this first make a copy of first truss. Then add small extrusions from the sides to add bars, then circular patter them with respect to a central axis. Similarly add the supports on one side, and circular pattern them. At last, add the cross connections to ensure sturdily. Its height is about the same as first truss, the base width becomes 2.5m as we have added 1m of support on both sides.



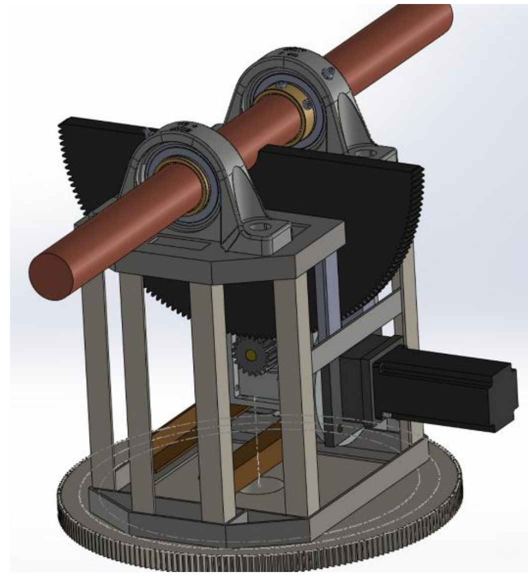
Similarly, an FEA study is done and the result is shown below.

Maximum Stress: 13.88 MPa, LOAD: 500 Kg

Yield Strength: 248.2 MPa, Safety Factor: 17.9



6.2.3 Second Truss

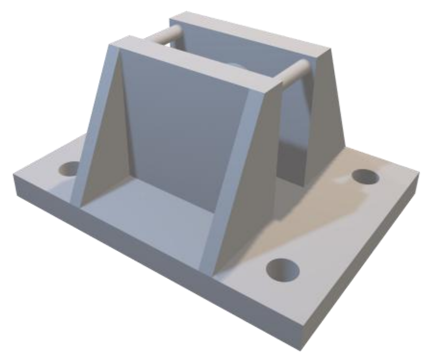


The second truss is a crucial part of the telescope. It's really simple to make. Just follow the instructions from first truss. The base is drilled to attach with AZ gear, there are some bars added to attach gearbox, these bars can move up-down and the gearbox can slide forward and backward to fit the pinion gear perfectly. Lastly there are 20mm holes to mount the pillow bearings and crossbars too (not shown in diagram).

The FEA results of first and base truss are shown below. Due to the small size and compact fitting of the second truss, it's believably strong enough to withstand the load, so no FEA is done.

6.3 Designing Shafts, Gears & Other Parts

6.3.1 Bearing Block



The bearing block holds the 6304 bearing, on which the whole AZ and ELV system rotates. The bearing block is made from 10mm and 5mm MS Plates. Height of 6cm with 12 × 8 cm base with more than 500 Kg Capacity. It's able to move up-down to align the Az gear.

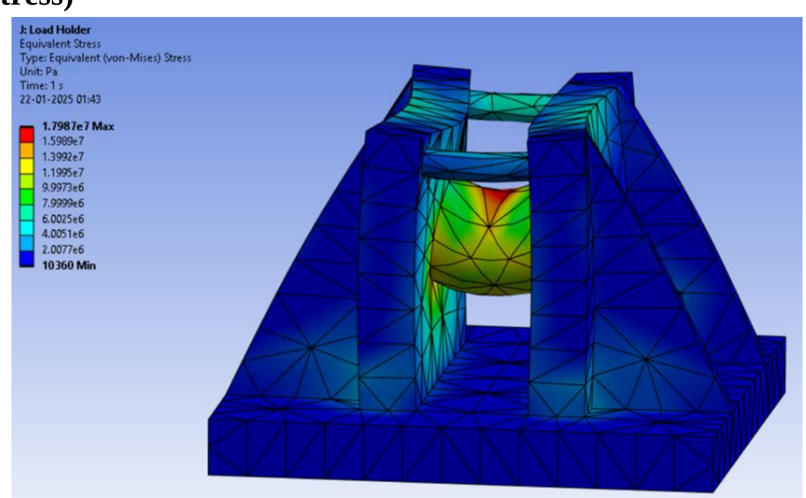
Let's see some FEA Results of it.

6.3.1.a Static Structural Analysis (Stress)

Maximum Stress: 17.98 MPa

Yield Strength: 248.2 MPa

Load: 500 Kg

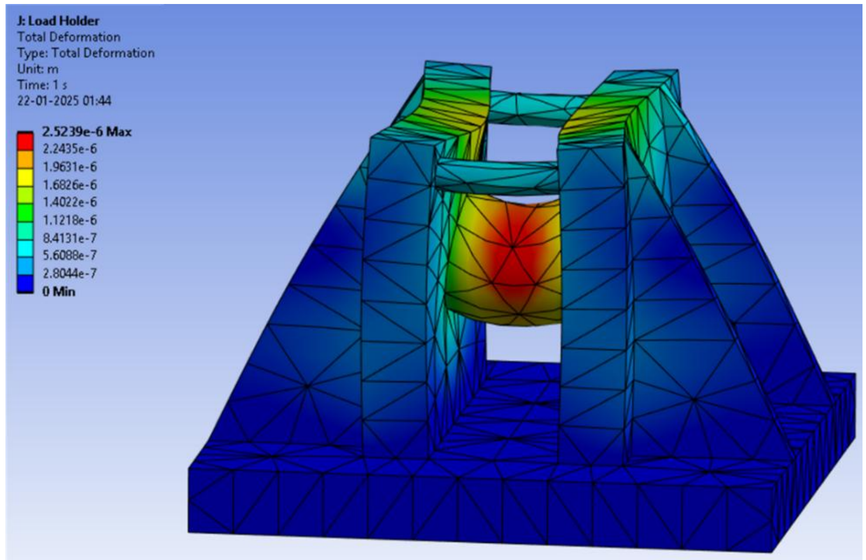


6.3.1.b Static Structural Analysis (Deformation)

Maximum Deformation:

2.5 µm

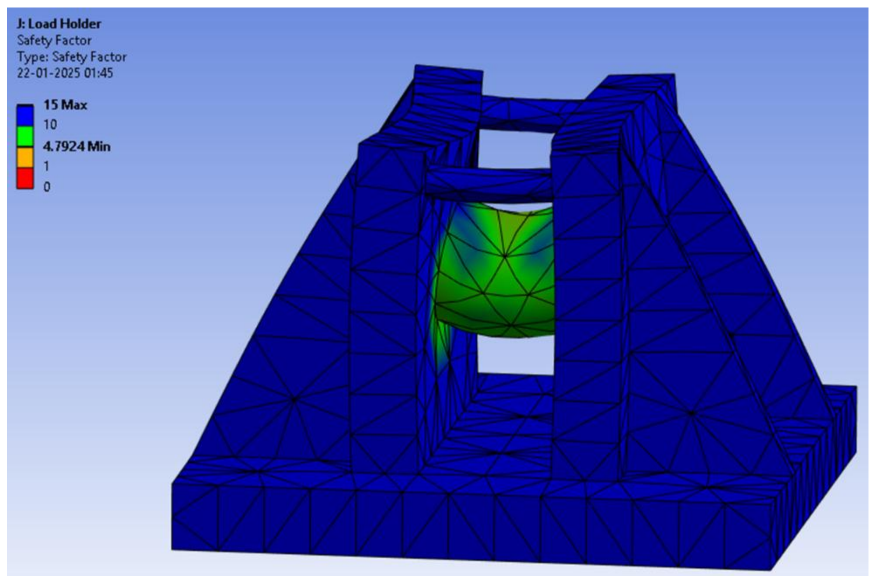
Load 500 Kg



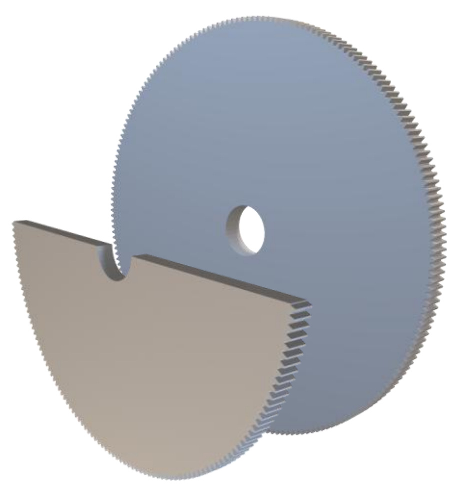
6.3.1.b Static Structural Analysis (Safety Factor)

Min Safety Factor: 4.8

Load: 500 Kg



6.3.2 Main Gears



In main gear we have two 400mm wide spur gears. One is full and one is half, thickness of 20mm gives it good strength to hold all the weight. It has a 50mm bore diameter to support the torque required. It's made from MS Low carbon steel.

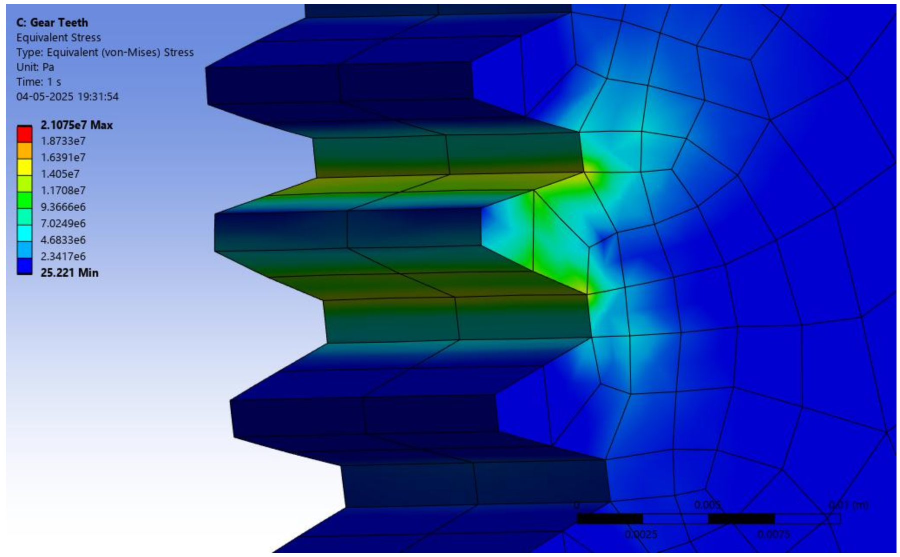
As most of the load will be applied on its one tooth, FEA is made to ensure it will not break.

6.3.2.a Static Structural Analysis (Stress)

Max. Stress: 21 MPa

Yield Strength: 248.2 MPa

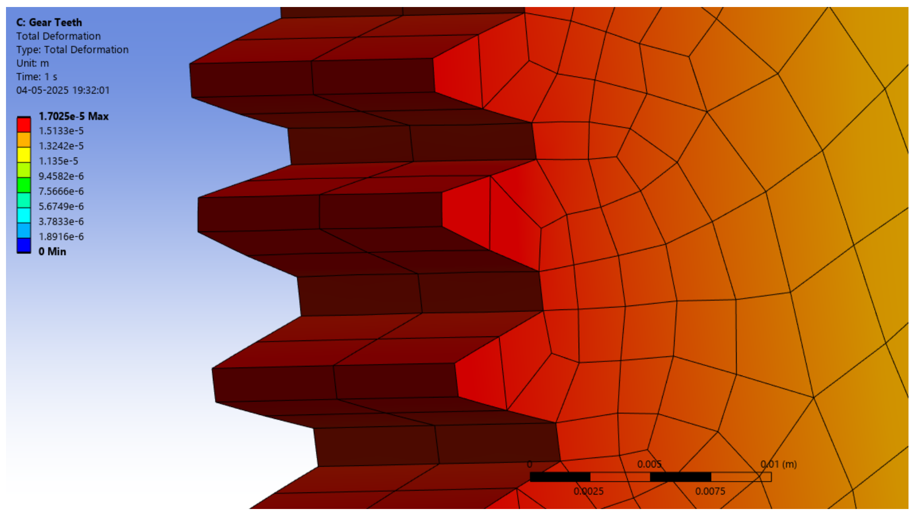
Load: 561 N



6.3.2.a Static Structural Analysis (Deformation)

Total Deformation: 17 µm

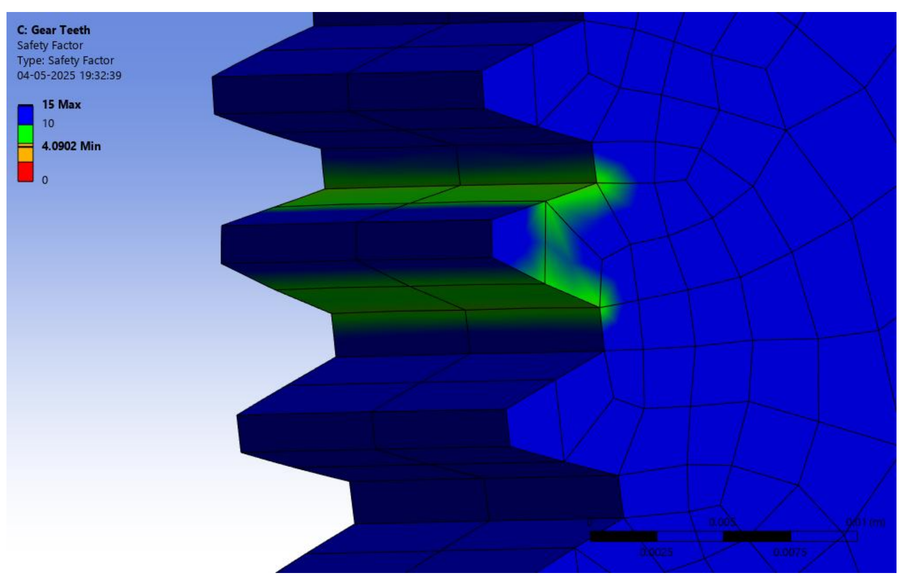
Load: 561 N



6.3.2.a Static Structural Analysis (Safety Factor)

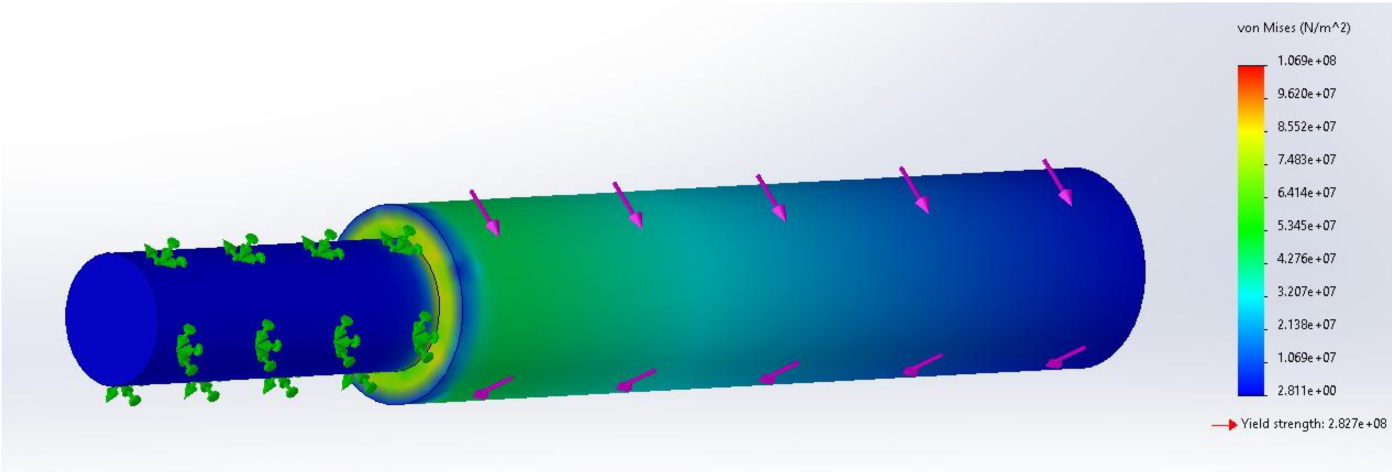
Min Safety Factor: 4.1

Load: 561 N



6.3.3 Driving Shaft:

The driving shaft is one more important part. It will the main gears with a pinion and it will be attached to a pinion gear. As it will experience a lot of torque, it’s made from a HSLA Steel of 282.7 MPa yield strength. It has a diameter of 18 and 12 mm and 110mm height. A static structural study result is shown below with the required torque.



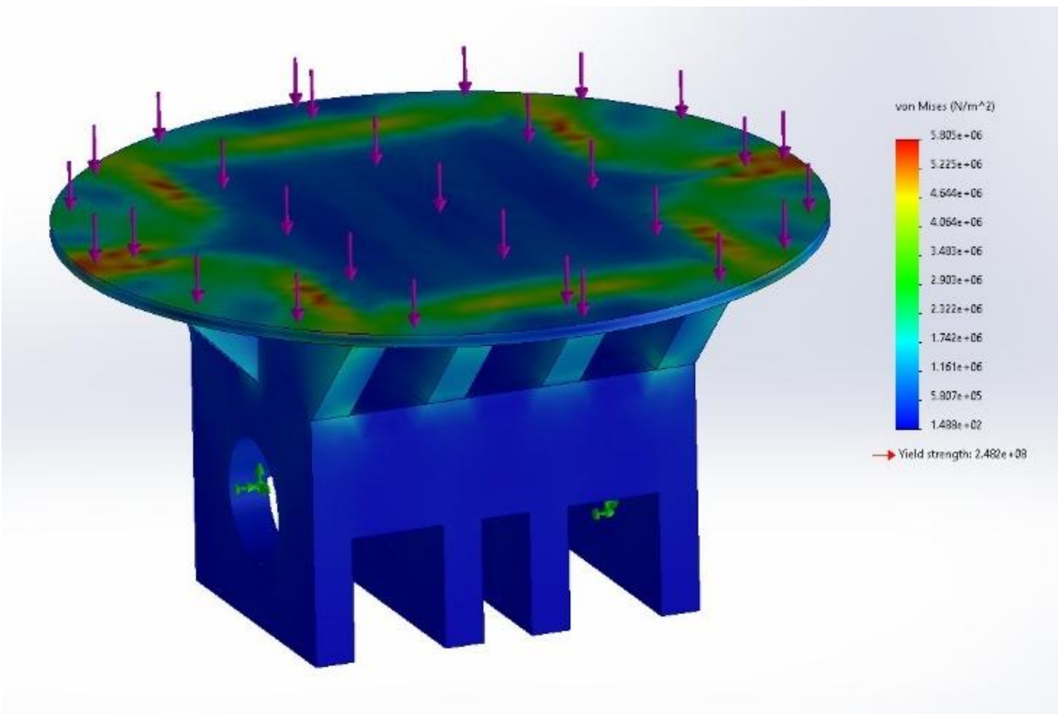
Torque Applied: 20Nm

Yield Strength: 282.7 MPa

Maximum Stress: 106.9 MPa

6.3.4 Dish Mount

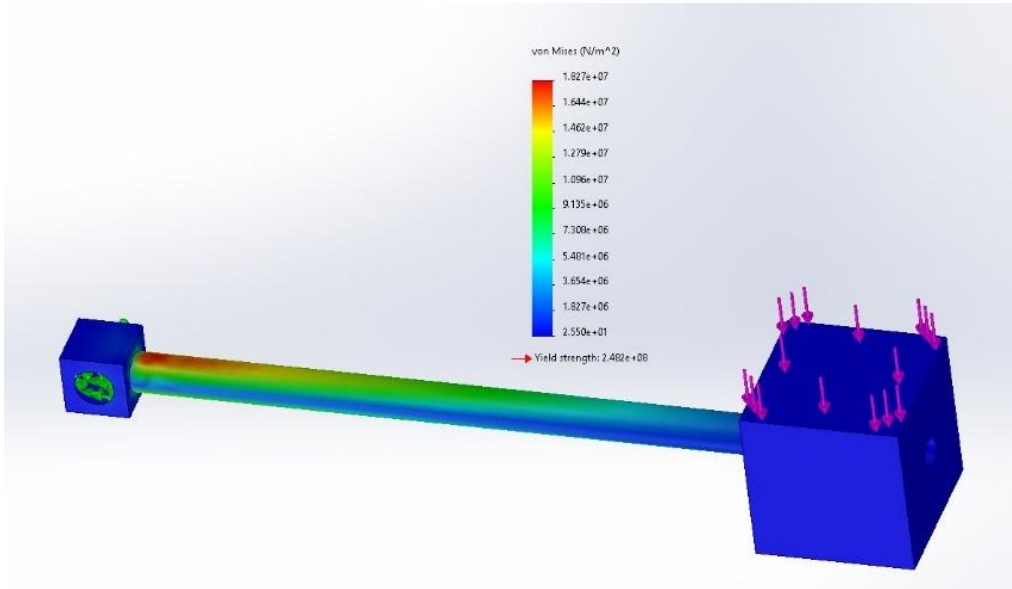
The dish mount is made to hold the load of the dish. It should be able to withstand the 300kg of load, so a stress analysis is done.



Load: 300 Kg Yield Strength: 282.7 MPa Maximum Stress: 5.8 MPa

6.3.5 Counterweight

The counterweight is 100cm long, thus it should with stand a 30 Kg of load, thus 15 Kg each side. The result of stress analysis is shown below.



Load: 15 Kg Yield Strength: 282.7 MPa Maximum Stress: 18.27 MPa

These are the crucial parts that are tested and optimized for the best performance. There are many more designs that are not included, as they don’t experience much load. After all models are made it’s time to assembly.

6.4 Assembly of Models

The assembly of models is an important step, it ensures there’s no interference between parts, and it also helps us create models of individual parts separately and join them. Also, we can do

motion study and final distance measurements with it. So, an assembled model of all parts is shown below:

First add the base truss into SolidWorks assembly, join the first truss with coincident mate, similarly all the weight holders. Add AZ shaft and Flange bearing by coincident and concentric mate with truss surface and truss axial hole. Add the 6304 bearings, theirs shafts respectively, also add the AZ gear with concentric mate. Note that bearings, gears and nut-bolts can be added from the SolidWorks toolbox. Then add the second truss and ELV gear by this, you can also add the gearbox and pinion gear for a perfect fit with gear mate. Then add the pillow bearing, ELV shaft and dish mount by concentric and coincident mate. Finally add the dish and the counterweight and the assembly is done.

The End

Chapter 7

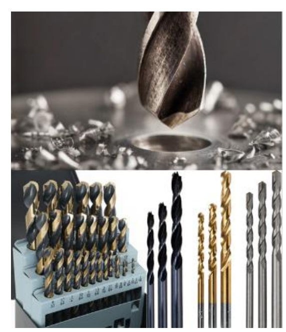
Production & Assembly

In this chapter we will see how to build the Radio Telescope from the materials we can afford. This chapter involves selection and the industrial manufacturing processes of all the parts we need.

7.1 Manufacturing Processes

It will be made from 6 simple manufacturing processes:

7.1.1 Drilling



It's used to make hole through workpiece.

It requires drilling bit for the purpose.

It comes with HSS, Steel and Carbide like many materials and with many shapes & sizes.

7.1.2 Milling

Milling is a subtractive Manufacturing process. The milling bit carves out material from a block to get desired shape.

It uses a milling bit which also comes with many materials and sizes.

It's helpful in making complex parts & making slots and grooves.

7.1.3 Turning

Turning is the process where a material is rotated in very high speed and a cutting tool cuts from the surface.

In this process you get Φ Symmetric Parts. It's useful in making shafts.

It's done in a special machine called Lathe Machine.

The bits inserted are called Lathe Inserts.

7.1.4 Welding

In welding, metal parts are joined together by melting the contact line.

Many types or welding processes are there like gas welding, plasma arc welding and electrode arc welding. Among of them we used the most common one – the electrode arc welding.

7.1.5 Machining:

In machining we include all the cutting, grinding, polishing work.

7.1.6 Hobbing:

Hobbing is the process where a gear is manufactured. A special machine "Hobbing Machine" do the job.

7.2 Gathering Materials

The materials we need are divided into 2 groups, electrical and mechanical parts mentioned in the tables below with number of items.

Mechanical Items		
S.n	Materials	Quantity
1	MS Angle Bar 40x40x5mm	1m long 16 units
		1.5m long 16 units
2	MS Angle Bar 30x30x3mm	1m long 20 units
		1.5m long 16 units

3	MS Plate	16mm 50x50cm 2 units
		10mm 50x50cm 2 units
		10mm 30x30cm 2 units
		5mm 50x50 cm 1 unit
4	SS Hex Nut Bolts	M20 100mm 8 nos
		M16 100mm 8 nos
		M10 100mm 40 nos
		M10 50mm 100+ nos
		M5 20mm 50 nos
5	Black Oxide Allen Grub Screw	M5 16mm 30 nos
6	Ball Bearings	UCP 210 2 units
		UCF 210 2 units
		6304 6 units
		6200/6000 12 units
7	Gear Box	1:100 gear ratio
8	Gears	2M 200T 20mm thick 50mm bore 2 units
		2M 20T pinion 2 units
		2M pinion 3 units
9	MS Square Pipes 1mm 1inchx1inch	2.5m long 6 units
10	Steel Shafts	50mm OD 40mm ID Hollow 1m long 2 units
		50mm Solid 1m long 2 units
11	Consumables (As needed)	Grease
		Enamel Paint
		Paint Solvent
		Electrical tape
		Welding Bead
		Heat Shrink Tube
		Quick Adhesive

Electrical Parts		
S.n	Item	Quantity
1	Servo Motor + Driver (Ex. Delta ASD 400W)	2
2	PLC (Ex. Delta AS228T)	1
3	SMPS 24V 2A	1
4	MCB (20A)	1
5	Magnetic Contactor (SIEMENS 3TF32)	1
6	EMI Filter	1
7	EM Brake	2
8	Rotary Encoder (Autonics >7200 PPR)	2
9	Relay Board	8 channel 1 unit
10	Wires	14G L 100m
		14G N 100m
		14G G 100m
		18G 100m
11	Switches and Indicators	As needed
12	Filters (mini-circuits)	As needed
13	Amplifiers (mini-circuits)	As needed
14	Gigabit Ethernet Cable 100m	1
14	Network Switch (gigabit 100)	1

7.3 *Building The Truss Skeleton*

The TRUSS is the exoskeleton of the Radio Telescope. This will be built by welding and joining via Nut-Bolts. Let's go through all three trusses.

7.3.1 First Truss

The First Truss will be made by 3mm MS Angle bars. To start with build two 500x500mm base from MS Angle Bars, let's start with one. Cut two 1m Angle bars in half with 45-degree angle at end with Metal Cutter for this purpose, you should get four numbers of 500mm angle bars. Then drill 10mm hole at the ends with 12-15mm offset from end and 12mm offset from one side on the 90-degree face. Be mindful that only 2 angle bars will be drilled and 2 will not. There will be total 4 holes, 2 each on 2 bars.

Place 2 drilled bars and 2 non-drilled bars facing each other. Join them by welding, first tap weld (just a single touch of welding bead) the corners, then verify if the diagonals are equal to ensure you've got a square, not rhombus. If the diagonals aren't equal, hit the longer side by placing it on ground to adjust it. After the diagonal becomes equal, complete the welding. Copy it for the second one. Note that there will be millimeters loss as cutting wheel removes length equal to its thickness (usually 3mm).

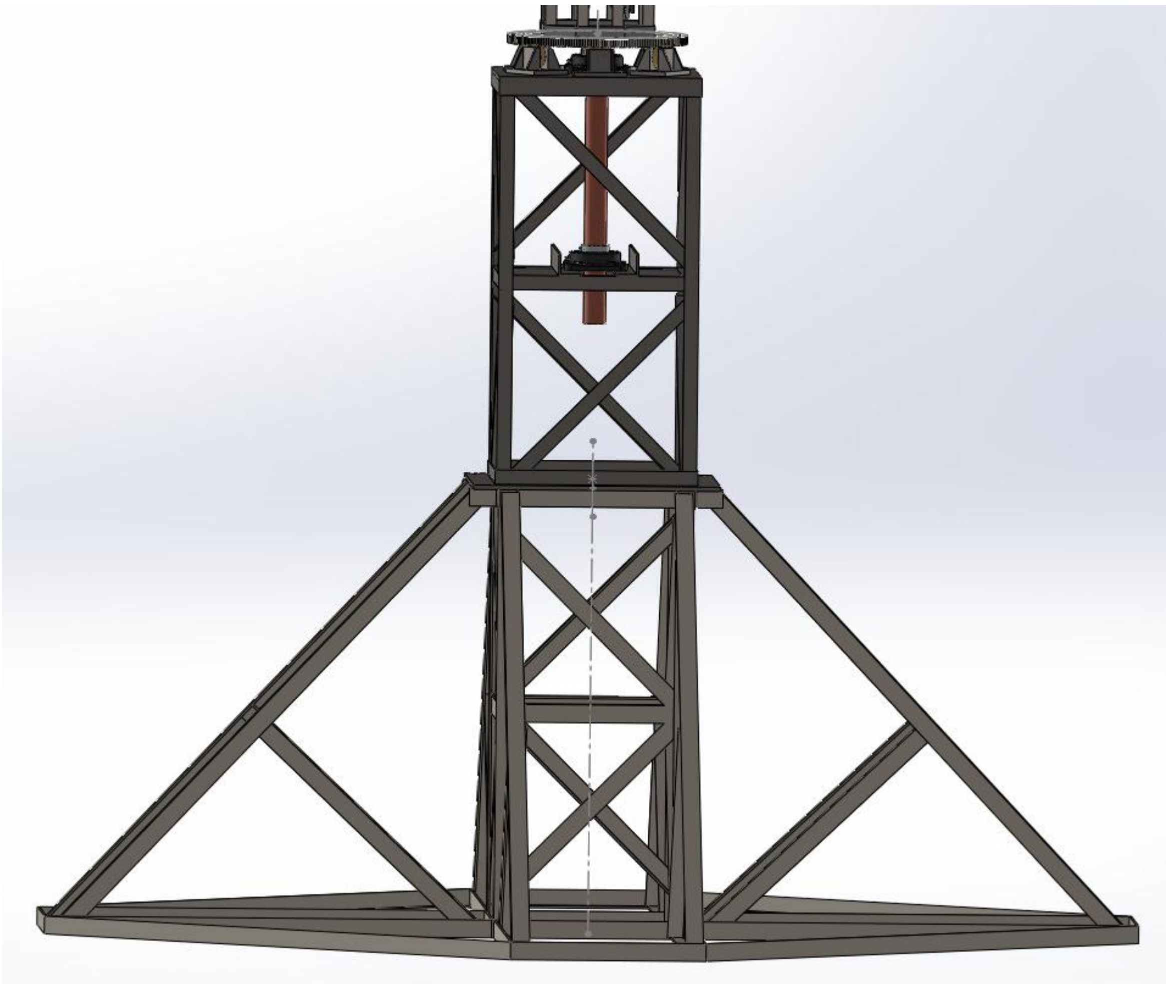
Then with four more 3mm 1meter long Angle bars add the pillars to the truss, mark them with numbers/alphabets with corners of the base square. Mark drill points by aligning the pillars with the holes of the base. Join them with SS M10 50mm Nut Bolts.

With measuring the inner distance between pillars, build another square of angle bars with side length equal to inner distance between pillars to fit inside them. Also add drills at the end as mentioned above. Mark the drill points by aligning it with the pillars with it's one face midpoint to the 500mm point / midpoint of the pillar and mark the corners with alphabets/numbers. Remove the pillars from the structure and drill 10mm hole in them. After that joint them using nut-bolts.

Then to add crossbars, measure the distance of the diagonal and cut appropriate length and angled angle bars. Drill with appropriate offsets and put a mark on pillars to drill on it. At this point be careful about the alignment of the bars, and also put markings on it. Then after drilling on the pillars, add the crossbars to it. Now the First Truss is ready.

7.3.2 Base Truss

To build the base truss, first built a similar truss as first truss with same dimensions. Then Extrusions at the end squares by welding. Drill some holes at the extrusions as mentioned above dimensions to add the angled 1.5m, you might need to cut it to appropriate length to fit. Also add the 1m long padding leg to it and join them together. Add the cross bars as per need and repeat it for rest three. The base truss is now ready.



7.3.3 Second Truss

Building the second truss is easy, first build the 250x250mm base, then add side welds. Repeat this for top parts as well, then add the 250mm pillars at the corners and join them, except the inner 4 pillars, they need to be joined by nut-bolts to ensure that gearbox can get inside. Add the crossbars as per design and the second truss is also ready.

7.4 Building The Motion Mechanisms

The motion mechanisms include the bearings, the gears, the gearboxes, Az and Elv Shafts and a feedback pulley wheel. Let's go through the order.

7.4.1 Bearings, Shafts and Weight Holder

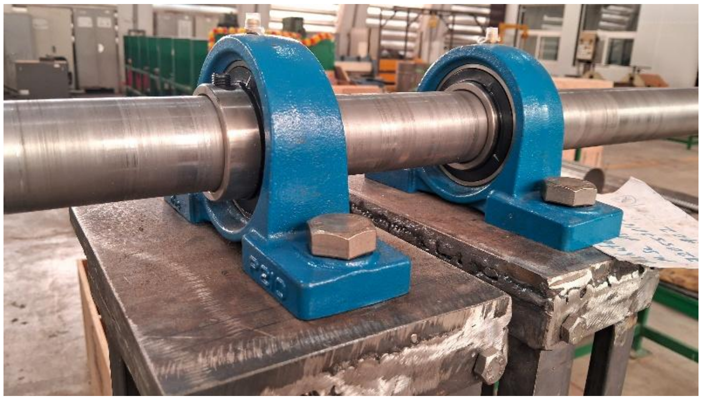
 

The radio telescope contains 3 types of bearings, 1. Two UCF210 flange bearing, 2. Two UCP210 pillow bearing and 3. Six 6304 regular ball bearing. First add a 500x500mm 10mm thick steel plate at the top of first truss to build a support surface by drilling at the corners, join by nut-bolts. Build a weight holder to support the bearing by cutting 10mm and 5mm MS plates and join by welding. Then make some 20mm diameter shaft to fit as 6304 bearing axes, and also to fit in with weight holder. Keep the diameter optimized that the shaft slides freely through bearing and weight holder hole. Add 4 more holes fit it in the support surface. Repeat the process for 5 more times to get 6 units of them.

Then build the AZ shaft by turning via lathe machine so that the UCF210 easily passes through it. Mark the drill points on the truss by putting both shaft and the flange bearing and drill 16mm holes. Mount them ensuring the shaft rotates freely 360-degree. Then add the M10 100mm nut bolts at the mounting holes of weight holder. First tighten every bolt with one nut, then add one more nut which can move up or down to balance the AZ gear, add the weight holder and add one more nut from the top to ensure tight fit. Then add the 6304 bearings and the 20mm shaft.



Then build the ELV shaft in the same way in accordance with the UCP210 bearing. Mount them to second truss at the center after adding another supporting plate of 16mm, ensuring it rotates freely.

7.4.2 Gears & Feedback Pulley

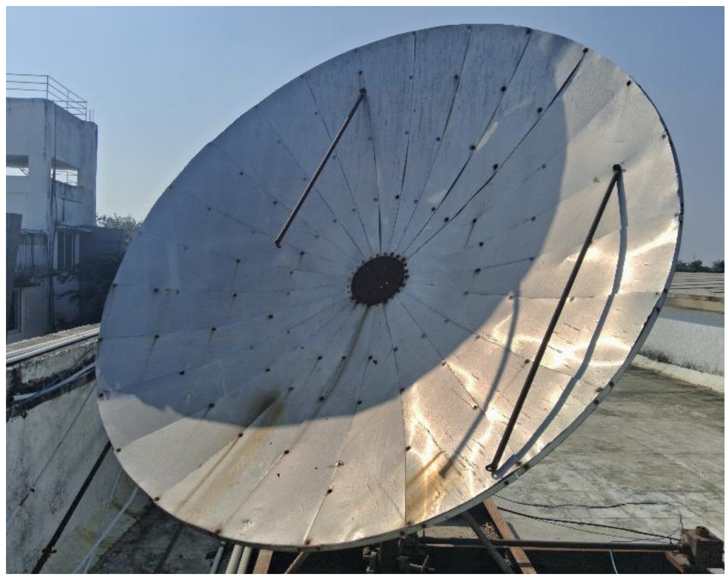
There are 2 main gears, the AZ full gear and the ELV half gear, both gears have module 2, 50mm bore and 20mm thickness. Drill some mounting holes for second truss on Az gear and mount it on top of the AZ shaft. Ensure the level via digital spirit level, adjust it with the up-down movement of weight holder. Then mount the second truss on the AZ gear by nut bolts and mount the ELV shaft. To mount the ELV gear, we must build another part, which we will see soon. Building gears requires precision Hobbing Machine. You may find it in some workshops in town or some manufacturers. Then you can easily find pinion gears of same module online or you can also make them. Then build a feedback pulley wheel from aluminum, recommended to use GT2 pulley dimensions as for the encoder we have to buy GT2 pulley wheel and GT2 timing belt.

7.5 Building Remaining Parts

Other remaining parts are gearbox holders, gearbox shafts, motor holders, dish mounts etc. First let’s see the dish mount. First build a circular disc of 300mm diameter and drill appropriate holes as per the dish. Then add four steel plates by welding, make sure the plates have 50mm holes to support the ELV shaft and add middle two plates must be separated by 20mm to mount the ELV gear between them. Then the gearbox must have some mounting holes, as every gearbox is different, it's recommended to find an own way, in my case the ELV gearbox is supported by some more angle bars, and in case of AZ gearbox, it's supported by another small truss. They are mounted by M10 nut-bolts, but they have capsule like slots instead of holes to ensure tight alignment. Then shafts are as per the design discussed earlier, they can be easily made from turning via lathe machine.

7.6 Building The Dish

To build the dish one must bend the perforated steel sheets. As bending a 4m diameter sheet is really difficult, it's recommended to build it from small individual units. First a mold needs to be made by 3D printing, then joining 6-8 such molds we get a mold unit, after a base mold and another press mold is made, they need to be connected to a hydraulic press to give the required shape. As the dish is z-axis symmetric, one mold can build all the remaining parts of its kind. In such case we just need 2-3 such mold units to build the complete dish.



After all the required plates are made, they can be joined by welding to nut-bolts to a skeleton truss for the dish. The skeleton for dish has 2-structured, 1. straight steel pipes for tangential support where the dish will be bolted, 2. Curved steel/aluminium pipes to maintain its curvature.

After the curved sheets are mounted on the skeleton, a tripod structure needs to be made to mount the receiving waveguide. It needs to be mounted on the steel pipes of the dish skeleton. At the and a MS plate needs to be welded to the skeleton base to enable it to be mounted on the ELV shaft.

7.7 *Assembly*

Assembling the parts is a critical step. One must take care that one thing must not be like it cannot go inside a structure due to block or not enough space. Order of assembly also matter. To start with, first assemble the gearbox inside the second truss, ensure that the pinion gear fits perfectly. Then mount the second truss on the AZ gear with nut bolts.

After that drill 2-3 holes on each side of the bottom square of first truss and top square of base truss with perfect alignment. Then join the 2 trusses with nut and bolts. You may also add a 500m500x10mm MS plate for better strength. After that add the weight holder and 6304 bearings as mentioned in Motion Mechanisms section (8.3.2), and place the both AZ gear and second truss. After that add AZ gearbox assembly and servo motors to turn the dish and complete the wiring of electrical box. For electrical box it's recommended to buy one as it's tested against weather and harsh conditions and also, it's easy to mount and sturdy.

Now after that mount the dish on the top with appropriate nut-bolts, then you are ready to start observations. The picture above shows amount of completion done in time.

The End

Chapter 8

Electronics of the Radio Telescope

8.1 *Introduction*

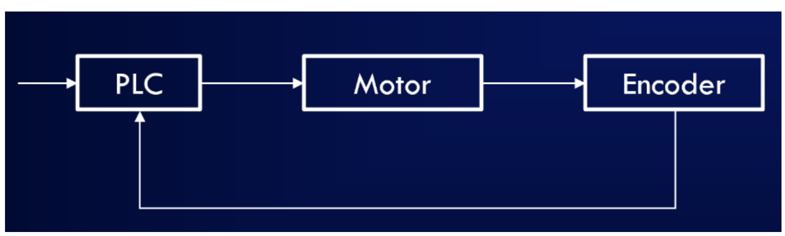
As stated earlier, in radio telescope, mainly two groups of electronics are seen: 1. Control System and 2. Data Acquisition system (DAQ). Control system are the electronics that control the movement of telescope where DAQ receives and stores data from space. As a full working code is not done by me, I will only share the parts name and circuit diagram. Let's start.

8.2 *Control System*

The control system electronics includes PLC, Servo Motor System, Feedback Encoder, Ethernet System etc. Also, some passive components like SMPS, Relay, I/Os etc. Let's see them:

8.2.1 PLC

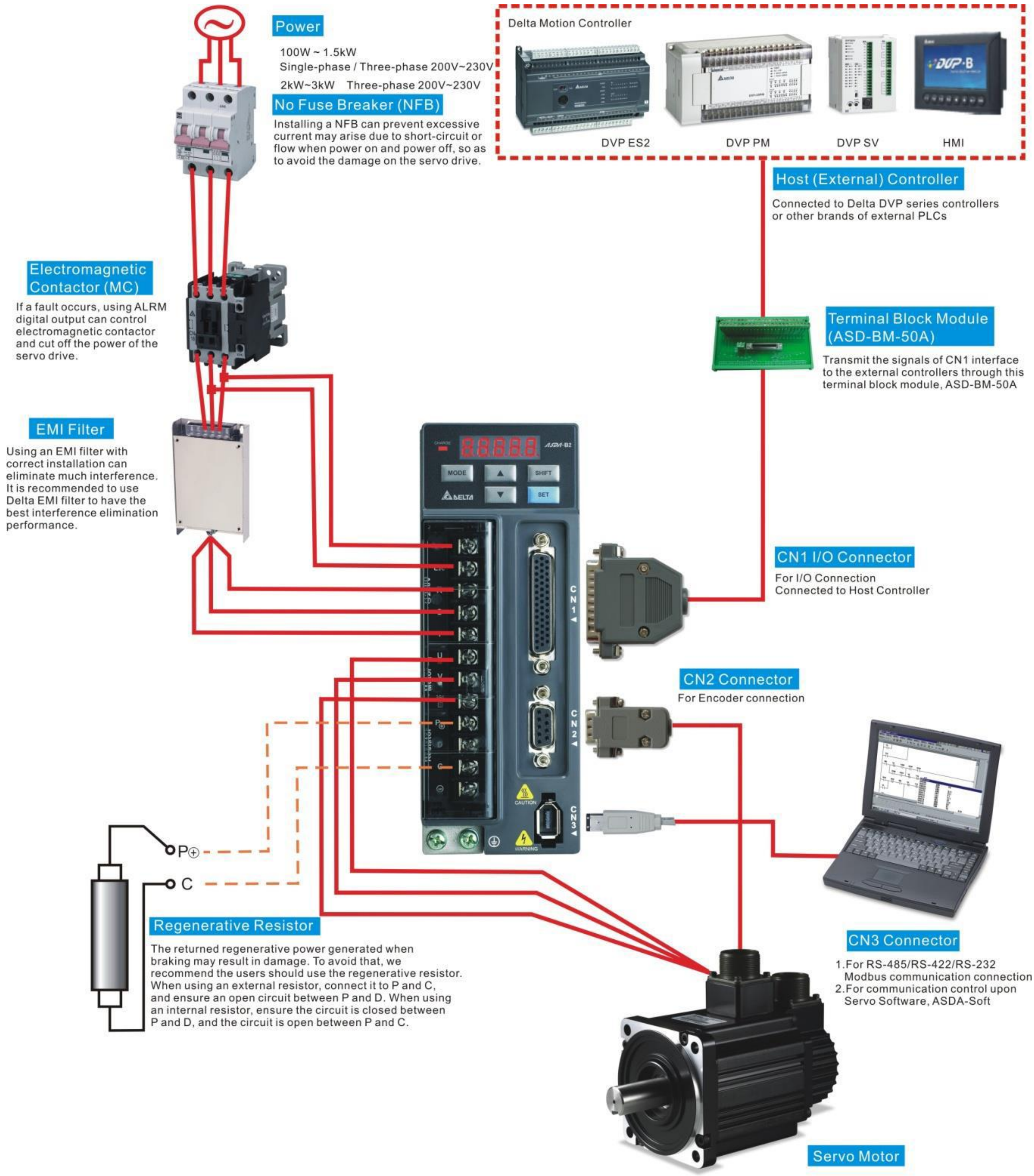
We are using Delta AS228T PLC. It has 28 I/O pins and 64K steps. This has a special feature that it can be programmed in C and has inbuilt PID block. Along with ethernet connection and USB compatibility it is a good choice for a PID controller. We will use this to run the motor and read from the encoder to firm a closed loop control system.



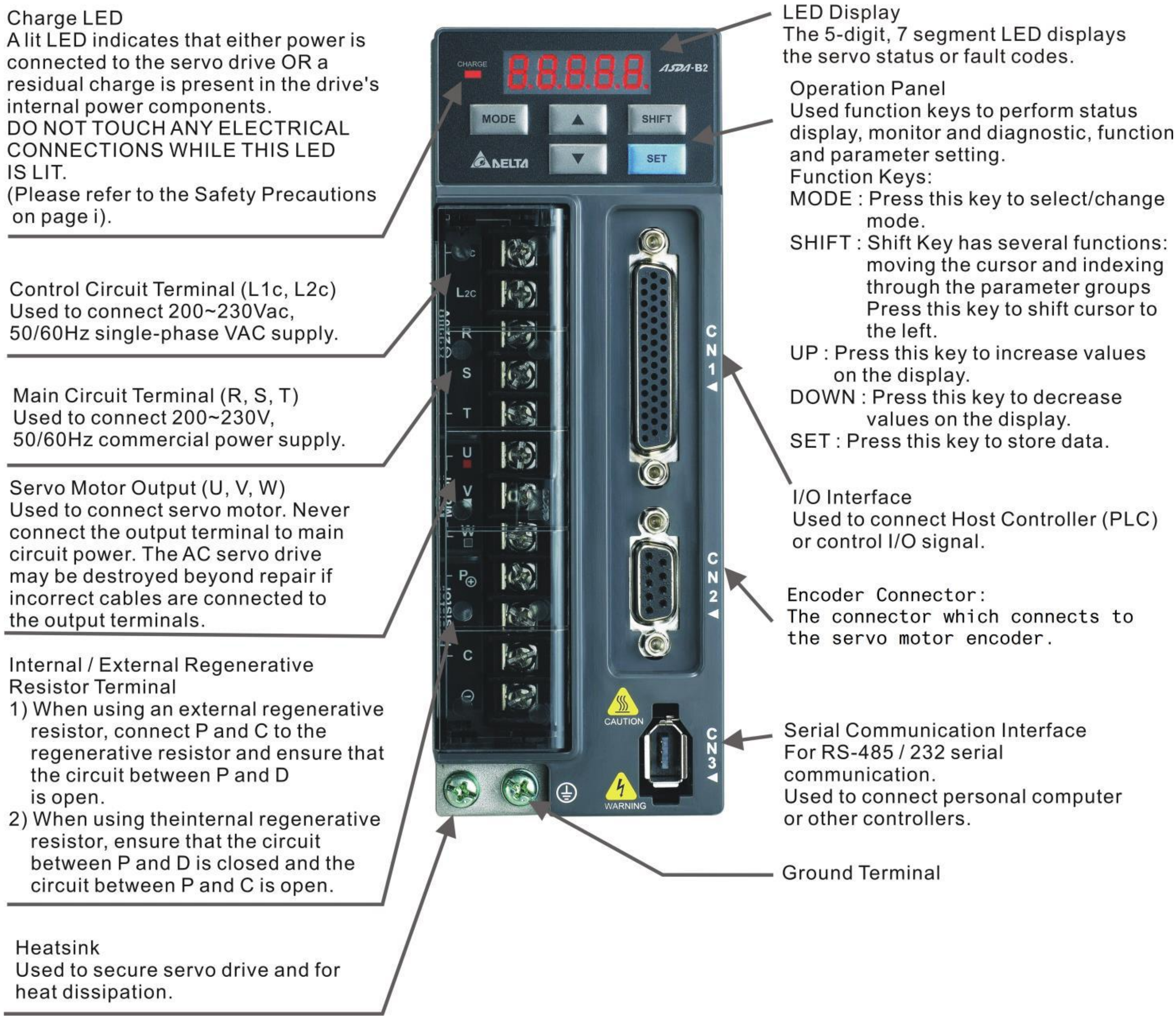
8.2.2 Servo Motor

The Servo Motor we are using is also from Delta ASD series servo motor. It's a 400W 10000 PPR high precision servo used for industrial applications. It has very large number of pins, but in a gist, I would say there are: 1. 220V power input port, 2. 24V controller input port (CN1), Encoder port (CN2) and CAN, RS232 like many more.

From their manual available, the circuit diagram is given below.


Power
100W ~ 1.5kW
Single-phase / Three-phase 200V~230V
2kW~3kW Three-phase 200V~230V
No Fuse Breaker (NFB)
Installing a NFB can prevent excessive current may arise due to short-circuit or flow when power on and power off, so as to avoid the damage on the servo drive.
Delta Motion Controller
DVP ES2
DVP PM
DVP SV
HMI
Host (External) Controller
Connected to Delta DVP series controllers or other brands of external PLCs
Electromagnetic Contactor (MC)
If a fault occurs, using ALRM digital output can control electromagnetic contactor and cut off the power of the servo drive.
Terminal Block Module (ASD-BM-50A)
Transmit the signals of CN1 interface to the external controllers through this terminal block module, ASD-BM-50A
EMI Filter
Using an EMI filter with correct installation can eliminate much interference. It is recommended to use Delta EMI filter to have the best interference elimination performance.
MODE
SHIFT
SET
CN1
CN2
CN3
CN1 I/O Connector
For I/O Connection
Connected to Host Controller
CN2 Connector
For Encoder connection
P⊕
C
Regenerative Resistor
The returned regenerative power generated when braking may result in damage. To avoid that, we recommend the users should use the regenerative resistor. When using an external resistor, connect it to P and C, and ensure an open circuit between P and D. When using an internal resistor, ensure the circuit is closed between P and D, and the circuit is open between P and C.
CN3 Connector
1.For RS-485/RS-422/RS-232 Modbus communication connection
2.For communication control upon Servo Software, ASDA-Soft
Servo Motor

There are a lot more thing to learn about this servo system, it’s recommended that one would go through their manual before using it.



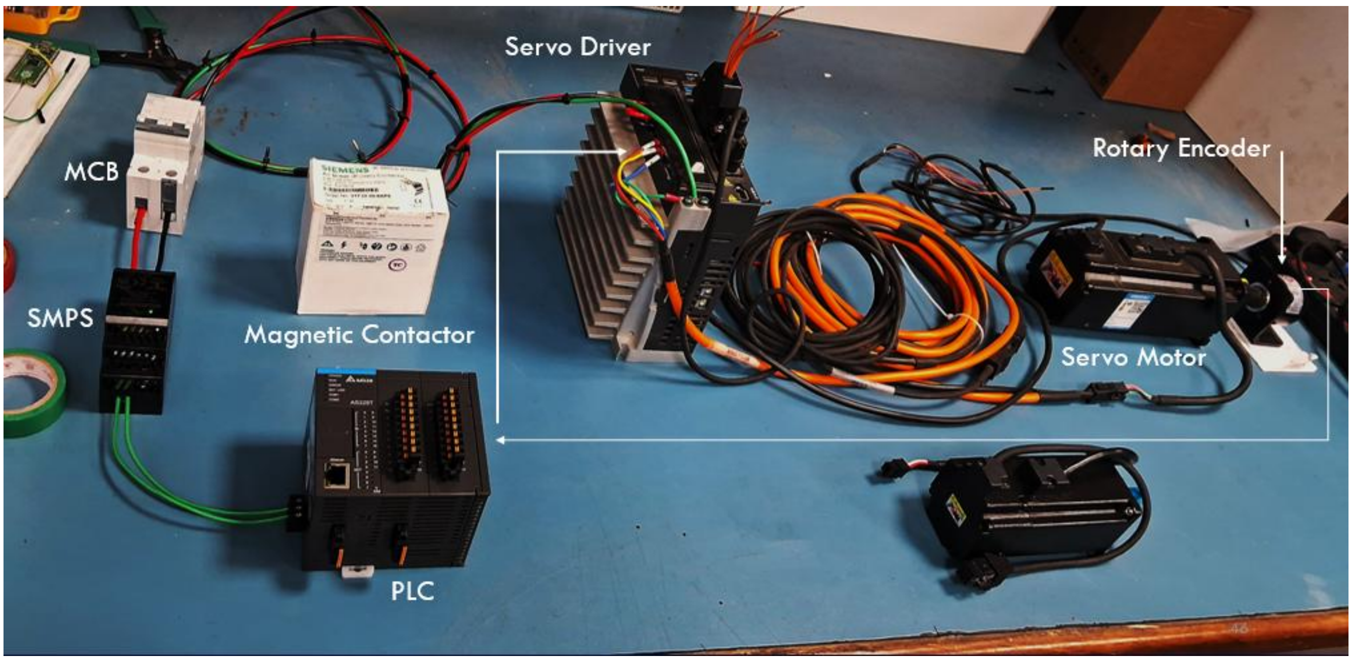
8.2.3 Encoder

The encoder is a device that reads the angle of rotation on its axis. For radio telescope applications, it must have a very high resolution like 7200 PPR. However, there is a trick to increase the resolution is to use pulley and timing belt. Just like gears, if we use a 60 teeth pulley on shaft and connect it with a 20 teeth pulley via timing belt, we would get 3 times more resolution. As timing belts has no backlash it’s highly recommended to do this.

There are 2 types of encoders: 1. Rotary Encoders and Absolute Encoder. In rotary encoder you will get pulses as it rotates, like if its 360 PPR encoder, you will get 1 pulse every 1-degree revolution. And the absolute encoder gives you the angle value in binary format. As this is a sensitive equipment, careful application nis highly recommended.

8.2.4 Feedback Loop

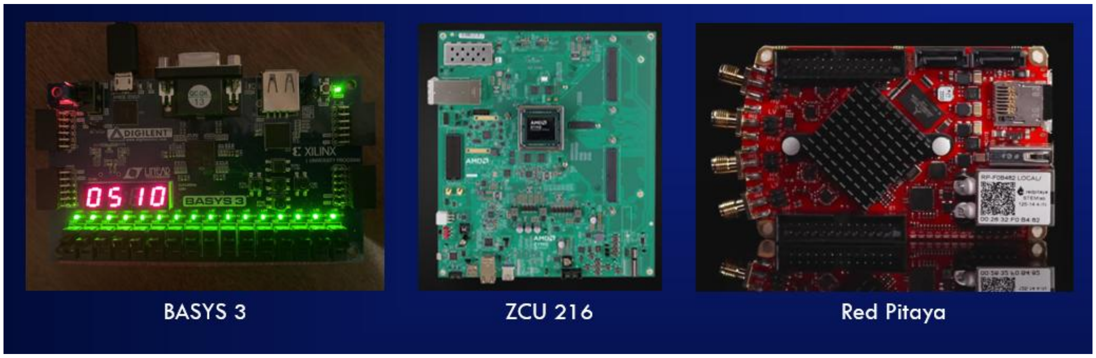
A PID feedback loop needs to be implemented to the telescope. The PLC will command the servo motor and reading will be given as feedback from the encoder. The PLC model AS228T has an inbuilt PID block, so it must be used properly. As the programming is not done by me, I will only show you the wiring diagram. It also shows a simplified wiring system.



8.3 Data Acquisition System

In Data acquisition system, previously the signal was read from a waveguide, then it was passed through series of band pass filter and amplified by a Low Noise Amplifier (LNA). Then it would send via LMR cable to a far building from telescope to be sampled, digitized and stored.

However, there are lot of issues like EMI disturbance and signal loss in the LMR cables. So, it was proposed that digitizing the signal on top of the Radio Telescope itself by a FPGA and ADC board, and then send it via ethernet or mass storage. Some good FPGA are shown below for RF applications:

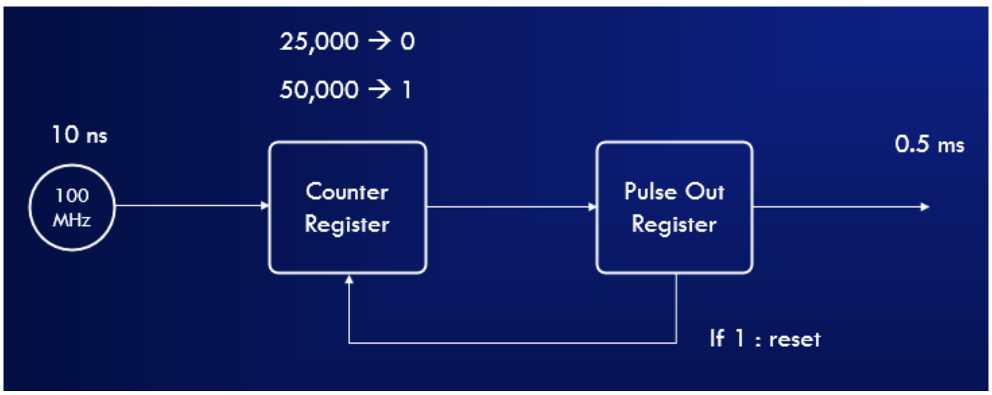


It also needs to be programmed. As a proper DAQ hasn't been done yet, but trying to implementing this, we have learned how to program an FPGA using XILINX Vivado. Also, a motor driving system has been made, just in case of future development.

8.3.1 Motor Driving System in FPGA

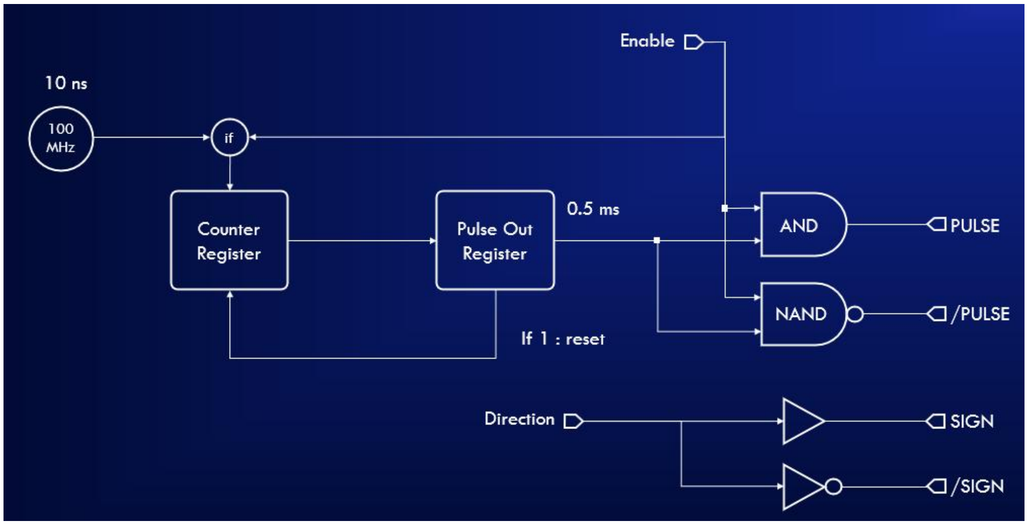
A servo motor needs two signals to run: PULSE & SIGN. SIGN tells which direction to rotate and PULSE tells how much to rotate. For ex: in a 10,000 PPR servo motor, in 10,000 pulses, it will complete a revolution, and so on.

But, most of the time, FPGA has very small base pulse length. So, to get pulse to fit in the pulse window of the servo motor (0.2 – 0.5 ms), we used the counter register method. We used the BASYS 3 – Artix 7 FPGA for the purpose. Here's a block diagram of the same.



The base clock generates a 10ns pulse. A counter register counts every 25,000 and 50,000 pulses and produce 0 and 1 respectively, which is now input for a pulse out register and it gives output respectively. The output of pulse out register resets the counter register and the process repeats, eventually the 10ns pulse becomes 500 us or 0.5 ms which is required pulse width.

With a little change, we get a SIGN & /SIGN - basically negative inverted SIGN and PULSE & /PULSE which is inverted PULSE. Only these 4 pins are required for the motor to run. The block diagram is shown below.

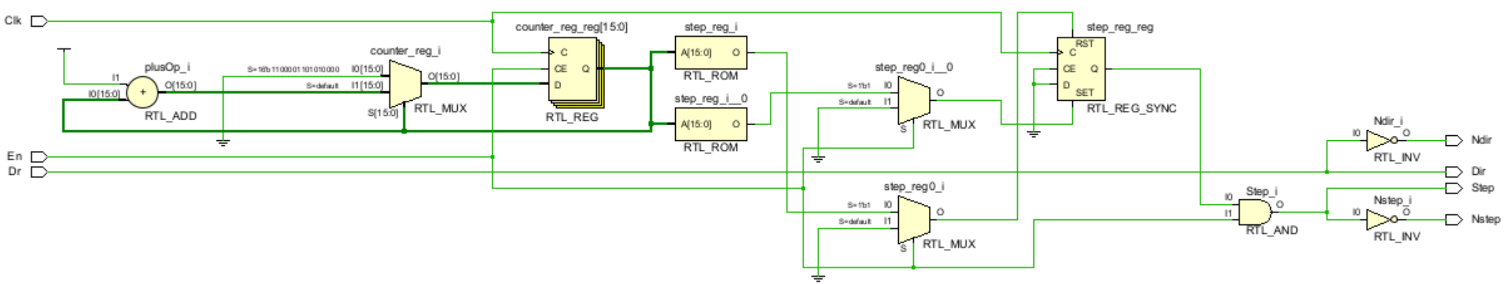


The code of this is in VHDL and is shown below: 1st two are VHDL & last one is .XDC file.

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;
use IEEE.NUMERIC_STD.ALL;

entity Loop_Control is
    Port (
        Clk : in STD_LOGIC;          -- Clock input
        En : in STD_LOGIC;           -- Enable1 input
        Dr : in STD_LOGIC;           -- Direction Input
        Step : out STD_LOGIC;        -- Step output
        Nstep : out STD_LOGIC;       -- Step output
        Dir : out STD_LOGIC;         -- Direction output
        Ndir : out STD_LOGIC         -- Direction output
    );
end Loop_Control;

architecture Behavioral of Loop_Control is
    signal counter_reg : unsigned(15 downto 0) := (others => '0');  -- 15-bit counter
    signal step_reg : std_logic := '0';                              -- Step toggle signal
begin
    process(Clk)
    begin
        if rising_edge(Clk) and En = '1' then
            if counter_reg = "110000110101000" then        --110000110101000b = 25000d
                --counter_reg <= (others => '0');
                step_reg <= '1';
            end if;
            if counter_reg = "1100001101010000" then        --1100001101010000b = 50000d
                counter_reg <= (others => '0');
                step_reg <= '0';
            else
                counter_reg <= counter_reg+1;
            end if;
        end if;
    end process;
    Step <= step_reg and En;
    Nstep <= step_reg nand En;
    Dir <= Dr;
    Ndir <= not Dr;
end Behavioral;

-----------------
```

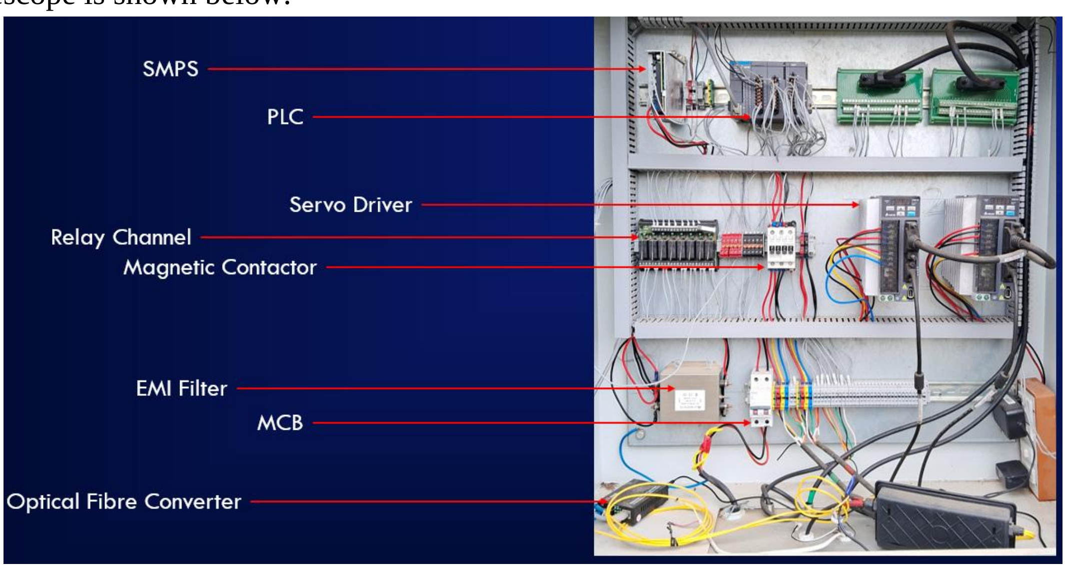
```
set_property PACKAGE_PIN W5 [get_ports Clk]
    set_property IOSTANDARD LVCMOS33 [get_ports Clk]
    create_clock -add -name sys_clk-pin -period 10.00 -waveform {0 5} [get_ports Clk]

set_property PACKAGE_PIN J1 [get_ports {Step}]
    set_property IOSTANDARD LVCMOS33 [get_ports {Step}]

set_property PACKAGE_PIN H1 [get_ports {Nstep}]
    set_property IOSTANDARD LVCMOS33 [get_ports {Nstep}]

set_property PACKAGE_PIN V17 [get_ports {En}]
    set_property IOSTANDARD LVCMOS33 [get_ports {En}]

set_property PACKAGE_PIN L2 [get_ports {Dir}]
    set_property IOSTANDARD LVCMOS33 [get_ports {Dir}]

set_property PACKAGE_PIN K2 [get_ports {Ndir}]
    set_property IOSTANDARD LVCMOS33 [get_ports {Ndir}]

set_property PACKAGE_PIN R2 [get_ports {Dr}]
    set_property IOSTANDARD LVCMOS33 [get_ports {Dr}]
```

Here is the synthesized design:



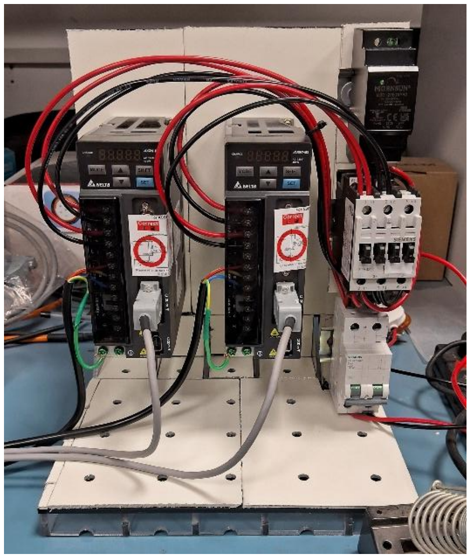
8.4 Auxiliary System

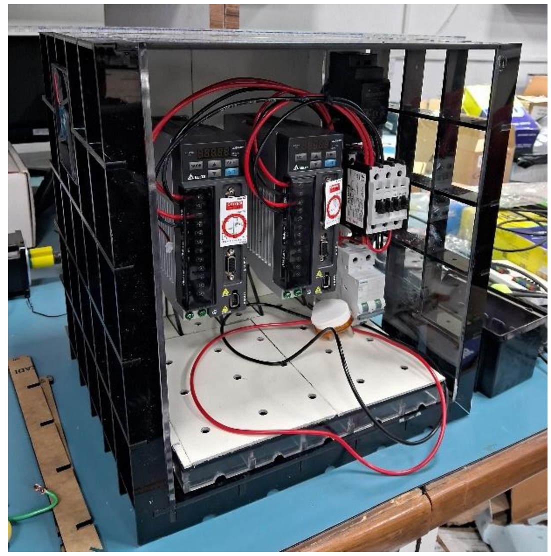
Some mandatory parts like MCB, MC, EMI Filter, cooling Fan and SMPS are must. They ensure proper power supply. Also, some I/O parts like indicators and switches are also needed. Relay may be used to upshift/downshift applications. A photo with electronics connection of IIRI Telescope is shown below.



8.4.1 *Electronic Box*

The electronic box will contain all the electronics components. It should be rainproof, heat insulated, sturdy and fit in the telescope. As we want to put all the electronics inside the truss, and market available boxes are not cost effective, we went to build one from acrylic sheet and Laser cutting. A photo of it before installation is shown below:



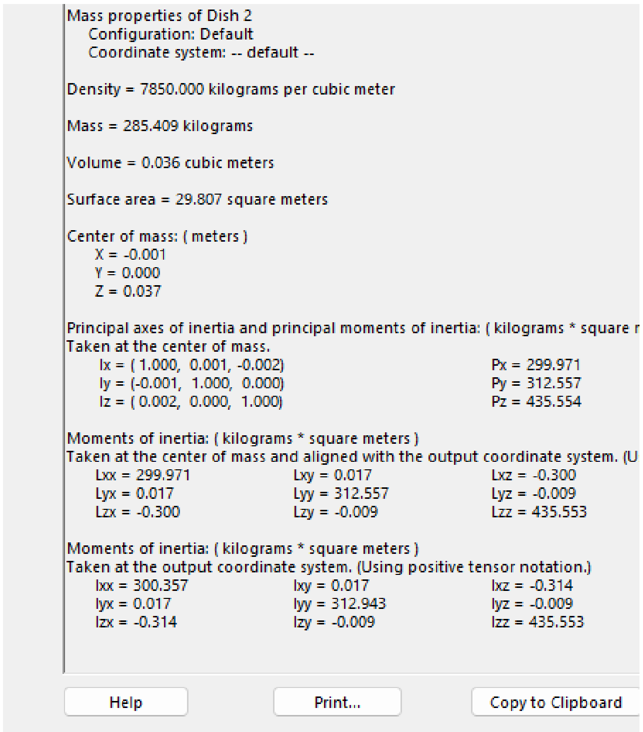


The box contains extra support structure which makes it sturdy. It will be covered with polyurethane to insulate from heat and there is also a cooling fan to exhaust hot air. There are holes for ventilation of cool air from bottom. Also, there is an inner lining of aluminium partition, a fire-resistant material to reduce the risk of fire from short circuit. Also, the aluminium will provide a shielding to electromagnetic interference.

The End

Results And Analysis

- The mass properties of the DISH are found to be:



Mass properties of Dish 2
Configuration: Default
Coordinate system: -- default --

Density = 7850.000 kilograms per cubic meter

Mass = 285.409 kilograms

Volume = 0.036 cubic meters

Surface area = 29.807 square meters

Center of mass: (meters)
X = -0.001
Y = 0.000
Z = 0.037

Principal axes of inertia and principal moments of inertia: (kilograms * square r
Taken at the center of mass.
Ix = (1.000, 0.001, -0.002) Px = 299.971
Iy = (-0.001, 1.000, 0.000) Py = 312.557
Iz = (0.002, 0.000, 1.000) Pz = 435.554

Moments of inertia: (kilograms * square meters)
Taken at the center of mass and aligned with the output coordinate system. (U

Lxx = 299.971	Lxy = 0.017	Lxz = -0.300
Lyx = 0.017	Lyy = 312.557	Lyz = -0.009
Lzx = -0.300	Lzy = -0.009	Lzz = 435.553

Moments of inertia: (kilograms * square meters)
Taken at the output coordinate system. (Using positive tensor notation.)

Ixx = 300.357	Ixy = 0.017	Ixz = -0.314
Iyx = 0.017	Iyy = 312.943	Iyz = -0.009
Izx = -0.314	Izy = -0.009	Izz = 435.553

Help Print... Copy to Clipboard

- The Torque requirements or the DISH are found to be 33 Nm along Elv & 66 Nm along Az. Sec. 6.1.5.

- Required motor & gearbox specifications are: more than or equal to 400W & 1.27 Nm torque motor and 1:100 gear ratio. Sec. 6.1.4, 6.1.5 & 6.1.6.

- FEA static structural study was done to every important part and the maximum stress limit was both found or set to way below maximum allowed limit. Results can be found in respective sections.

- Most of the parts are assembled now and it was found to be excellent in terms of fixtures, strength and precise motion. A diagram can be found on Sec. 7.7.

- All the electronic component's function were thoroughly studied and wired accordingly.

Conclusion & Scope For Future Work

- The Telescope was built in the estimated cost. At this point, 90% of the work has been completed and will be fully completed soon.
- A wide range of knowledge were gain expanding the boundary of making a telescope in Radio Instrumentation.
- As a student, it was a great opportunity to be a part of industrial manufacture, it helped me and acknowledged person gain experience in this field.
- The Telescope is dedicated to the Nation, for the scientific and astronomical developments.

- The first goal is to build a large observatory of such telescopes and take clear observations.
- An opportunity is reserved for programming the telescope's both PID control loop and Data acquisition system.
- A second opportunity lies in upgrading it to Version 2 with better design and motion system, and build many of it.
- The Radio Telescope can be work on its own or it can be added to IIRI expanding its capability.

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