DESIGN AND FABRICATION OF HARMONIC GEARBOX

A Final Year Project Report

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Bachelors of Mechanical Engineering

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ABSTRACT

A harmonic gearbox is a precision mechanical transmission that employs the elastic deformation of flexible components to achieve high gear reduction ratios with low backlash and high precision. Harmonic gearboxes are a type of strain wave gear that have found widespread applications in various fields, including robotics, aerospace, and automotive engineering.

The report provides an overview of the fundamental principles and working mechanisms of harmonic gearboxes, highlighting their advantages and limitations compared to alternative gearbox types. The report then details the design process, which involves the selection of materials, optimization of the geometry of the flexible components, and assessment of performance metrics such as gear ratio, torque capacity, and efficiency. The design is validated through Finite Element Analysis (FEA) simulation.

The report also describes the fabrication process, including the production of flexible components, gearbox assembly, and performance testing. The performance testing includes gear ratio, torque capacity, and efficiency measurements, as well as evaluations of backlash, noise, and durability. Finally, the report summarizes the key findings, limitations, and potential enhancements of the harmonic gearbox design and fabrication and provides recommendations for the future development of the technology in various engineering applications.

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ABBREVIATIONS

WG	Wave Generator
CS	Circular Spline
FS	Flex Spline
EDM	Electrical Discharge Machining
FEA	Finite Element Analysis
RPM	Rounds per Minute
CAD	Computer Aided Design

CHAPTER 1: INTRODUCTION

A harmonic gearbox, also known as a strain wave gear or harmonic drive, is a type of gear system that uses an elastic deformation of a flexible metal spline to transmit torque from the input shaft to the output shaft. The unique design of a harmonic gearbox allows for high precision, high reduction ratios, and a compact form factor, making it an ideal solution for many industrial and robotic applications.

The basic components of a harmonic gearbox include a circular spline, a flexible metal spline, and a wave generator. The circular spline is fixed to the gearbox casing, while the flexible metal spline is attached to the output shaft. The wave generator is a disc-shaped component with an irregular shape that is driven by the input shaft. As the wave generator rotates, it causes the flexible metal spline to deform and mesh with the circular spline, transmitting torque to the output shaft.

One of the primary benefits of a harmonic gearbox is its high precision. The elastic deformation of the flexible metal spline allows for a very tight mesh between the spline teeth, resulting in a low backlash and high positional accuracy. Additionally, the use of a flexible metal spline allows for a high reduction ratio in a small form factor, making harmonic gearboxes an ideal choice for applications where space is limited.

Harmonic gearboxes are commonly used in industrial robots, machine tools, aerospace equipment, and medical devices. They are also used in a variety of other applications where high precision and a compact design are essential. While harmonic gearboxes can be more expensive than other types of gear systems, their unique design and high performance make them an excellent choice for many challenging applications.

1.1 Problem Statement

"Harmonic gearboxes are used in different industrial applications for precision motion. Currently, there is no local manufacture of these systems."

Harmonic gearboxes have become increasingly popular in various industrial applications due to their high precision, high reduction ratios, and compact design. However, one major issue facing companies in need of these gearboxes is the lack of local manufacture of these systems. This means that companies have to rely on importing these gearboxes from other countries, which can be costly, time-consuming, and subject to potential supply chain disruptions.

The absence of local manufacture of harmonic gearboxes creates several problems for companies that need them. Firstly, importing these gearboxes can be expensive due to transportation costs, customs fees, and currency exchange rates. This can increase the overall cost of the equipment, making it more challenging for companies to justify the investment. Additionally, importing these gearboxes can take a long time, which can delay production schedules and hinder a company's ability to meet customer demands.

Another issue with the lack of local manufacture of harmonic gearboxes is the potential for supply chain disruptions. Importing these gearboxes means that companies are reliant on the supply chains of other countries. This can be problematic if there are issues with transportation, customs clearance, or if there are political or economic issues in the exporting country. These disruptions can impact on a company's ability to deliver products on time, potentially damaging its reputation and revenue.

In conclusion, the absence of local manufacturers of harmonic gearboxes is a problem for companies that require precision motion in their industrial applications. Therefore, it is imperative that efforts be made to establish local manufacture of harmonic gearboxes to ensure the availability of these critical components and mitigate the associated risks.

1.2 Objective

The objective of this project is to establish local manufacture of harmonic gearboxes to address the problem of relying on imports for these critical components. By setting up local production of harmonic gearboxes, the project aims to reduce costs, shorten lead times, and mitigate supply chain risks for companies that require these gearboxes for precision motion in their industrial applications.

Specifically, the project aims to design, develop, and manufacture harmonic gearboxes that meet the high standards of quality, precision, and reliability required in industrial applications. This will involve identifying suitable materials, selecting appropriate manufacturing processes, and testing the gearboxes to ensure they meet performance requirements.

Furthermore, the project aims to establish a local supply chain for the production of harmonic gearboxes. This includes sourcing raw materials, developing partnerships with local suppliers, and building a network of distributors to supply the gearboxes to end-users. By establishing a local supply chain, the project aims to reduce lead times and costs associated with importing these components from other countries.

Overall, the objective of this project is to provide a cost-effective and reliable solution to the problem of relying on imports for harmonic gearboxes. By establishing local manufacture of these critical components, the project aims to promote local economic growth and support industrial development while meeting the needs of companies that require precision motion in their applications.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The design and fabrication of harmonic gearboxes have gained significant attention in the field of mechanical engineering due to their potential applications in various industries, including robotics, aerospace, and automotive sectors. Harmonic gearboxes, also known as strain wave gears, are precision mechanical devices that offer high gear reduction ratios, compact size, high torque density, and low backlash [1][2].

This literature review aims to provide a comprehensive overview of the existing knowledge in the area of harmonic gearboxes. By referring to significant publications such as books and research papers, this review will summarize the historical development of harmonic gearboxes, explain the fundamental principles underlying their operation, discuss design considerations, highlight state-of-the-art designs, explore their applications in various industries, and identify gaps in the current knowledge that necessitate further research.

2.2 Historical Development of Harmonic Gearboxes

2.2.1 Early Development

The historical development of harmonic gearboxes can be traced back to the mid-20th century when Clarence Musser invented the basic concept of harmonic gearing in 1955.

Musser's early work laid the foundation for subsequent research and development in this field [3].

Musser's groundbreaking design consisted of an elliptical wave generator and a flexible splined cup that deformed under the action of the wave generator. This deformation resulted in the transmission of torque through the engagement of the flexible cup with a rigid outer gear, known as the circular spline. Musser recognized the potential of harmonic gears in achieving high gear reduction ratios in a compact package, and his work sparked further investigations into the design and optimization of these mechanisms.

2.2.2 Contributions by Musser

Notable publications by Musser include "Design and Analysis of Harmonic Drives" and "Mechanics of the Strain Wave Gear" [4][5]. These publications provided detailed analyses of the kinematics and dynamics of harmonic gears, as well as design guidelines for achieving desired performance characteristics.

Musser's work highlighted the importance of wave generation and spline flexibility in achieving the desired motion transmission and torque capacity. He also emphasized the need for proper lubrication and control of backlash in harmonic gear systems.

2.2.3 Advancements by Other Researchers

In the following decades, researchers and engineers expanded upon Musser's work and made significant contributions to the understanding and advancement of harmonic gear technology.

Researchers such as Shoham and Aharoni focused on the design and analysis of harmonic drives with elastic circular splines [6]. Their work explored the effects of spline flexibility on the performance and efficiency of harmonic gear systems.

Smith and Preish conducted extensive research on the manufacturing processes and materials used in harmonic drives [7]. Their work addressed the challenges associated with achieving high precision and durability in gear manufacturing, including the selection of suitable materials, heat treatment techniques, and surface finishing processes.

2.3 Fundamentals of Harmonic Gear Mechanisms

To comprehend the necessity of the project, it is crucial to understand the fundamental principles underlying harmonic gear mechanisms.

2.3.1 Components of Harmonic Gearboxes

Harmonic gearboxes consist of three main components: a wave generator, a flexspline, and a circular spline [8]. The wave generator, typically an elliptical cam, creates a wave motion that deforms the flexspline, which results in the transmission of torque. The circular spline engages with the flexspline to transmit torque and provide the necessary reduction ratio. The flexspline, often made of a thin-walled, high-strength material, undergoes elastic deformation as it engages with the wave generator. This deformation allows the flexspline to maintain contact with the circular spline and transmit torque while accommodating the relative motion between the wave generator and the circular spline.

2.3.2 Functioning of Harmonic Gear Mechanisms

The functioning of harmonic gear mechanisms can be explained through the following steps:

1. The wave generator imparts a wave motion to the flexspline, causing it to deform and form teeth that mesh with the circular spline.
2. As the wave generator rotates, the teeth of the flexspline engage and disengage with the circular spline, resulting in the transmission of torque.
3. The wave motion of the flexspline and the engagement of its teeth with the circular spline produce a gear reduction effect, enabling the output shaft to rotate at a slower speed and with increased torque compared to the input shaft.

The deformation of the flexspline is a critical aspect of harmonic gears, as it allows for the high gear reduction ratios and compactness characteristic of these mechanisms. The precise control of the wave motion and the interaction between the flexspline and the circular spline determine the performance parameters such as torque capacity, backlash, and efficiency.

2.4 Design Considerations for Harmonic Gearboxes

The design of harmonic gearboxes involves several critical considerations to achieve optimal performance, reliability, and manufacturability.

2.4.1 Parameters for Design Optimization

Design parameters such as the gear ratio, torque capacity, backlash, efficiency, and size and weight constraints play a crucial role in determining the suitability of harmonic gears for specific applications. Optimization techniques are employed to find the best combination of design parameters that meet the desired performance requirements.

The gear ratio determines the reduction or amplification factor between the input and output shafts. Harmonic gearboxes can achieve high gear reduction ratios in a single-stage design, making them attractive for applications where compactness is crucial.

Torque capacity is an essential consideration, particularly in applications requiring high torque transmission. The design should ensure that the flexspline can withstand the applied loads without exceeding its material limits.

Minimizing backlash is important to achieve accurate motion control and prevent positioning errors. Backlash in harmonic gears can arise from various sources, such as manufacturing tolerances, elastic deformation of components, and meshing clearances.

Efficiency is another critical performance parameter. The design should aim to minimize energy losses due to friction, deformation, and other sources. Efforts are made to reduce frictional losses through proper lubrication, surface treatments, and material selection.

2.4.2 Optimization Techniques

Research publications have addressed these design considerations and proposed methodologies to optimize the design of harmonic gearboxes. Optimization techniques, such as finite element analysis (FEA), numerical optimization algorithms, and multi-objective optimization, are employed to find the optimal combination of design parameters [9].

FEA allows for the analysis of stress, deformation, and contact characteristics within harmonic gear systems. It enables the identification of critical areas that may experience high stresses or deformations, aiding in the optimization of component geometries and material selections.

Numerical optimization algorithms, such as genetic algorithms and particle swarm optimization, can be used to explore the design space and find optimal solutions considering multiple objectives and constraints. These algorithms iteratively modify design parameters and evaluate the resulting performance until the best solution is found.

Multi-objective optimization techniques consider conflicting objectives, such as maximizing torque capacity while minimizing size and weight. These techniques help in identifying trade-offs and finding Pareto optimal solutions that represent the best compromise between different design objectives.

2.5 State-of-the-Art Harmonic Gearbox Designs

In recent years, significant advancements have been made in the design and fabrication of harmonic gearboxes, resulting in state-of-the-art designs that offer improved performance, reduced size and weight, and enhanced overall efficiency.

2.5.1 High-Torque Lightweight Harmonic Drive

One notable state-of-the-art design is the "High-Torque Lightweight Harmonic Drive" developed by Huang, Chen, and Wu [10]. This design incorporates advanced materials and optimization techniques to achieve a compact and lightweight harmonic gearbox with high torque capacity. The use of innovative flexspline materials and geometries allows for increased torque transmission while maintaining overall system stiffness and durability.

2.5.2 Torque-Splitting Harmonic Gearbox

Another notable advancement is the "Torque-Splitting Harmonic Gearbox" proposed by Li, Zhang, and Wang [11]. This design introduces a novel concept of splitting the input torque into multiple paths within the flexspline, resulting in increased torque capacity and reduced stresses on individual components. The torque-splitting approach offers the potential for higher torque transmission and improved system reliability.

2.6 Applications of Harmonic Gearboxes

Harmonic gearboxes find applications in various fields, including robotics, automation, aerospace, and automotive industries.

2.6.1 Applications in Robotics

The use of harmonic gearboxes in robotics has been explored extensively, offering advantages such as compactness, high torque capacity, and precise motion control. They are used in robotic arms, humanoid robots, exoskeletons, and other robotic systems that require compact and lightweight power transmission solutions [12].

2.6.2 Aerospace Applications

Harmonic gearboxes have also found applications in aerospace systems, including satellite mechanisms and aircraft control surfaces. The compact nature of harmonic gears makes them suitable for space-constrained environments, and their high torque capacity and low backlash characteristics are desirable for precision positioning and control applications [13].

2.6.3 Automotive Applications

In the automotive industry, harmonic gearboxes are used in various applications, including hybrid and electric vehicles, power steering systems, and engine accessories. Their compact size, high gear reduction ratios, and efficiency make them suitable for optimizing power transfer and achieving desired performance characteristics in automotive systems [14].

2.7 Summary and Gap Analysis

In summary, this literature review has provided an overview of the historical development, fundamental principles, design considerations, state-of-the-art designs, and applications of harmonic gearboxes. It has highlighted the contributions of early researchers such as Musser and the advancements made by subsequent researchers.

By addressing these gaps and building upon the existing knowledge, the proposed project on the design and fabrication of harmonic gearboxes can make significant contributions to the field. Further research is needed to explore novel materials, advanced manufacturing techniques, and optimization strategies to improve the performance, efficiency, and reliability of harmonic gearboxes. By addressing these gaps, researchers can develop innovative designs that meet the evolving needs of industries requiring compact, high-performance power transmission solutions.

CHAPTER 3: METHODOLOGY

The project consists of completely mechanical components. It has three main parts i.e., Circular Spline, Flex Spline, and a Wave Generator. In this project we will be working on the design and as well as fabrication of the harmonic gearbox. Firstly, a basic design was finalized as per the requirements, then prototyping was done to verify its mechanisms and then finally machining is to be done.

3.1 Preliminary Design Approach

There are several types of harmonic gearboxes, which differ in their gear geometry, number of flex spline teeth, and other design features.

3.1.1 Basic design consideration

Strain wave gearing:

Strain wave gearing is the most widely used type of harmonic gearbox. It consists of three main components: a wave generator, a flex spline, and a circular spline. The wave generator is a flexible ring that deforms as it rotates, causing the flex spline to mesh with the circular spline and produce the required motion. Strain wave gearing is known for its high torque-to-weight ratio, high precision, and low backlash.

Cycloidal gearbox:

This type of gearbox uses a cycloid disc to transfer torque between the input and output shafts. The cycloid disc is made up of a series of pins that rotate around a central hole, and it meshes with a stationary ring gear and a rotating cam. As the cam rotates, it pushes the pins of the cycloid disc, causing it to rotate and transfer torque to the output.

Epicyclic gearbox:

This type of gearbox uses a system of gears to transfer torque between the input and output shafts. The gears are arranged in a planetary configuration, with a sun gear at the center, planet gears that rotate around the sun gear, and a ring gear that meshes with the planet gears. As the sun gear rotates, it causes the planet gears to rotate around it, which in turn causes the output shaft to rotate.

Planetary gearbox:

This type of gearbox is similar to the epicyclic gearbox, but it does not have a sun gear. Instead, the input shaft drives a planet carrier that rotates around a stationary ring gear. The planet gears mesh with the ring gear and the planet carrier, transferring torque to the output.

3.1.2 Strain Wave Gearing

Strain wave gearing, also known as harmonic drive, is a type of gearbox that uses an elastic element, such as a flex spline, to transfer torque between the input and output shafts. As the wave generator rotates, it produces a wave motion that travels around its circumference. The wave motion causes the flex spline to bend and twist, which causes the teeth on the flex spline to mesh with the teeth on the circular spline, producing the required motion.

The flex spline is a thin, flexible metal ring with a series of external teeth. The wave motion from the wave generator causes the flex spline to deform, allowing its teeth to mesh with the teeth on the circular spline. As the wave generator rotates, the flex spline rotates in the opposite direction at a reduced speed, transferring torque to the output shaft. The circular spline is a rigid ring with a series of internal teeth that mesh with the teeth on the flex spline. The circular spline is fixed in place and does not rotate during operation.

3.2 Components

3.2.1 Circular Spline

A Circular Spline is a ring-shaped component with a series of internal teeth that mesh with the teeth on a FS in a strain wave gearbox. The CS is a fixed component and does not rotate during operation, but its internal teeth are designed to mesh with the teeth on the FS across the major axis of the Wave Generator ellipse to produce the required motion.

3.2.2 Flex Spline

The Flex Spline is a thin cylindrical cup made from alloy steel with external teeth on the open end of the cup. The FS is radially compliant but torsionally is very stiff. When the Wave Generator in inserted into the FS the gear takes on its elliptical shape. The FS is used as the output and is connected to the output flange. The deformation of the FS allows it to achieve a high gear reduction ratio while maintaining high precision and low backlash.

3.2.3 Wave Generator

The Wave Generator is comprised of a rectangular piece of steel with two cylinders extruded out at each end. The ball bearings are mounted on the cylinders and kept in place by snap rings. This serves as a high efficiency torque converter and is used as the input of the gear and is connected to the motor shaft. The outer surface of the Wave Generator plug has an elliptical shape that is carefully machined to a precise specification. The Wave Generator is typically used as the input, usually attached to a servo motor.

3.3 Design Calculations:

The harmonic drive base design parameters generally vary with the application. But for this project the parameters are constrained to gear reduction ratio 50:1 and operating at 1500 rpm where input shaft diameter is 22mm. And the required output is 8NM.

Table 1 Design Parameters

Sr. No.	Description	Value
1	Motor Available RPM	1500 rpm
2	Required Torque	8.5 NM
3	Required Gear Ratio	50:1
4	Input Shaft Diameter	22 mm

3.3.1 Design of Circular Spline:

Number of teeth = 102 teeth

TPI = 25

Diametral Pitch Pd = $\frac{25}{25.4} = 0.984251969$ mm

Pitch circle diameter of circular spline $\boldsymbol{Dp_c} = \frac{102}{0.984251969} = 103.632$ mm

3.3.2 Design of Flex Spline:

Number of teeth = 100 teeth

TPI = 25

Diametral Pitch Pd = $\frac{25}{25.4} = 0.984251969$ mm

Pitch circle diameter of circular spline $\boldsymbol{Dp_f} = \frac{100}{0.984251969} = 101.6$ mm

3.3.3 Total Deflection:

Total deflection d = $Dp_c - Dp_f$

$= 103.632 - 101.6$

$= 2.032$ mm

3.3.4 Addendum:

Addendum a = $\frac{7}{16} * \text{Total Deflection}$

$$= \frac{7}{16} * 2.032 = 0.889 \text{ mm}$$

3.3.5 Dedendum:

Dedendum b = $\frac{9}{16} * \text{Total Deflection}$

$$= \frac{9}{16} * 2.032 = 1.143 \text{ mm}$$

3.3.6 Clearance:

Clearance c = $\frac{1}{8} * \text{Total Deflection}$

$$= \frac{1}{8} * 2.032 = 0.254 \text{ mm}$$

3.3.7 Tooth Thickness:

Tooth Thickness t = $\frac{11}{8} * \text{Total Deflection}$

$$= \frac{11}{8} * 2.032 = 2.794 \text{ mm}$$

3.3.8 Working Depth:

Working Depth w = $0.77 \ * \text{Total Deflection}$

$$= 0.77 * 2.032 = 1.56464\text{mm}$$

3.3.9 Inside Diameter:

Inside Diameter Di = $Dp_f - \frac{7}{8} * d$

$$= 101.6 - \frac{7}{8} * 2.032$$

$$= 99.822 \text{ mm}$$

3.3.10 Outside Diameter:

Outside Diameter Do = $Dp_f + \frac{7}{8} * d$

$$= 101.6 + \frac{7}{8} * 2.032$$

$$= 103.378 \text{ mm}$$

3.3.11 Relaxed Static Diameter:

Relaxed static diameter = $Dp_f - \ 0.0416 * d$

$$= 101.6 - \ 0.0416 * 2.032$$

$$= 101.5155 \text{ mm}$$

3.3.12 Contact Ratio = 44 – 55

3.3.13 Pressure Angles:

Pressure angle for circular spline = $\tan^{-1}\frac{1.091*180}{2*3.14}$

$$= 28.62697946$$

Pressure angle for flex spline = $\tan^{-1}\frac{1.091}{2} + \tan^{-1}\frac{0.458 * d * 4 *180}{Dp_c *3.14}$

$$= 30.68529265$$

3.4 3D Modeling:

3D CAD models of the components were made in Solidworks to visualize the components.

3.4.1 Circular Spline:

In a strain wave gearbox, a Circular Spline is a ring-shaped component that has teeth on the inside which meshes with the teeth on a Flex Spline to ensure the motion transfer.

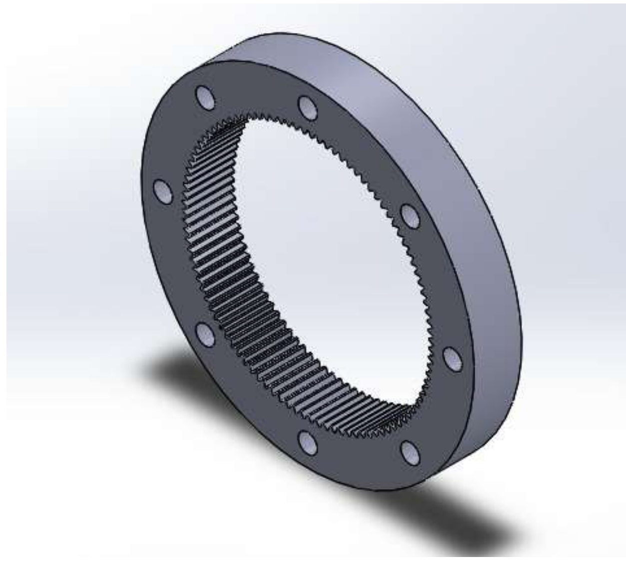

Figure 1. 3D model of Circular Spline

3.4.2 Flex Spline:

The Flex Spline of a strain wave gearbox is a cylindrical cup made of alloy steel and features external teeth on its open end. It is the flexible part of the gearbox and that’s why it is made thin.

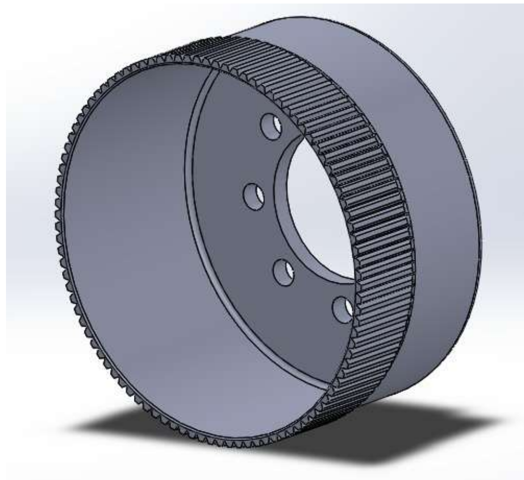

Figure 2. 3D model of Flexspline

3.4.3 Wave Generator:

The wave generator deforms the flex spline, causing its teeth to engage with the circular spline. This mechanism creates gear reduction with zero backlash.

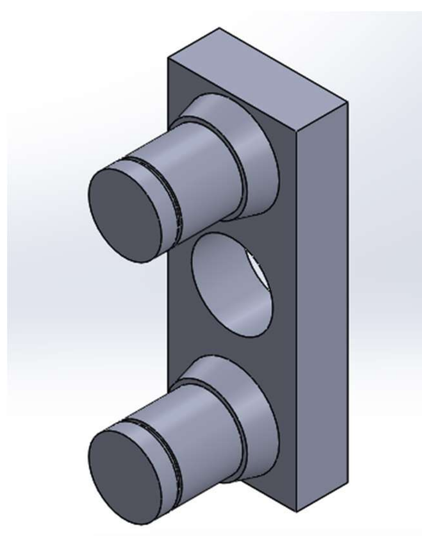

Figure 3. 3D model of Wave generator

3.5 Material Selection:

Material selection was one of the most crucial processes in the "Design and Fabrication of Harmonic Gearbox". The functioning of the components varies and as a result the material properties required for these components are also different. The CS is a rigid component whereas the FS must retain the shape of an ellipse and hence flexible material was required for that purpose. To achieve the optimum deflection in the FS, for proper meshing, flexible material was needed. But on the other hand, the strength requirement was also high. The material selection for these components were done by using "Hit and Trial" method after the simulation in FEA software. The material was selected on the basis that they meet the basic strength and durability requirement. During the process different material was used for the simulation and following materials were selected.

Table 2 Material Selection

Components	**Material Selected**
Circular Spline	Mild Steel
Flex Spline	AISI 4140 (Alloy Steel)
Wave Generator	Bearing Steel 52100

3.6 FEA Analysis:

Finite Element Analysis (FEA) is a computer-based numerical method used to solve complex engineering problems. It is a powerful tool that can be used to analyze the structural behavior and performance of the components under different loads and conditions.

The basic principle of FEA is to divide a complex structure or system into a finite number of smaller, interconnected elements or "finite elements". The behavior of each element is then modeled using mathematical equations that describe its physical properties and behavior. These equations are then solved simultaneously for all the elements to obtain a comprehensive understanding of the behavior of the entire system.

FEA analysis of individual components of the Harmonic gearbox was necessary before the manufacturing to get an insight of the component's behavior under different loading conditions. The Flex spline plays an important role in the accurate working of the harmonic gearbox and hence it was analyzed using finite element analysis. An appropriate amount of deflection was required for the proper meshing between the flex spline and circular spline teeth.

The Flex spline was analyzed for the elongation along the major axis to determine its displacement. The FS was subjected to boundary conditions (stresses) at two opposite points within its yield strength and the displacement was observed. For this purpose, two additional surfaces were made on the inner surface of FS to avoid point loading.

CHAPTER 4: RESULTS AND DISCUSSIONS

Results were obtained by conducting Finite Element Analysis of Components in Solidworks to obtain the expected stresses and deformation of the components against the required operating conditions. The FEA analysis of the 3 components i.e., Flex spline, Circular spline and wave generator were conducted separately meanwhile a complete analysis of the assembly part was also conducted.

The Results comprise of the deflection in Flex Spline, the stresses generated in the FS and CS.

4.1 FEA Analysis

There were 3 separate FEA Analysis conducted in Solid works.

1. FEA Analysis of Flex Spline
2. FEA Analysis of Circular Spline
3. Combined analysis of FS and CS.

4.1.1. FEA Analysis of Flex spline

For the Purpose of Finite Element Analysis rectangular protrusions were modeled to stimulate the two points of contact where the force is to be applied for the required deflection of the Flex Spline.

Analysis and Results:

A force of 500N was applied to each rectangular protrusion to stimulate the points of contact and find the deflection, following results were obtained.

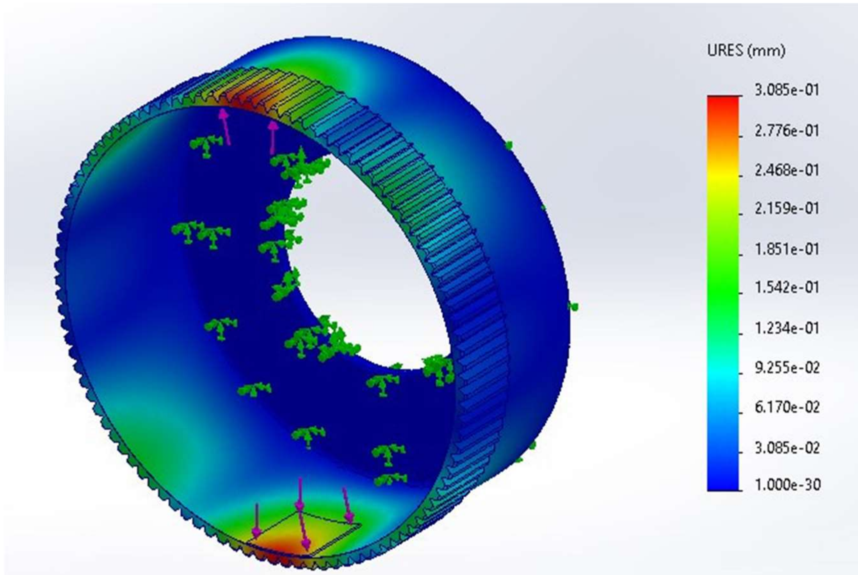

Figure 4. Maximum deflection required in Flexspline

For the applied load conditions a maximum deflection of $3.085 \times 10^{-1} mm$ was obtained at the points of contact.

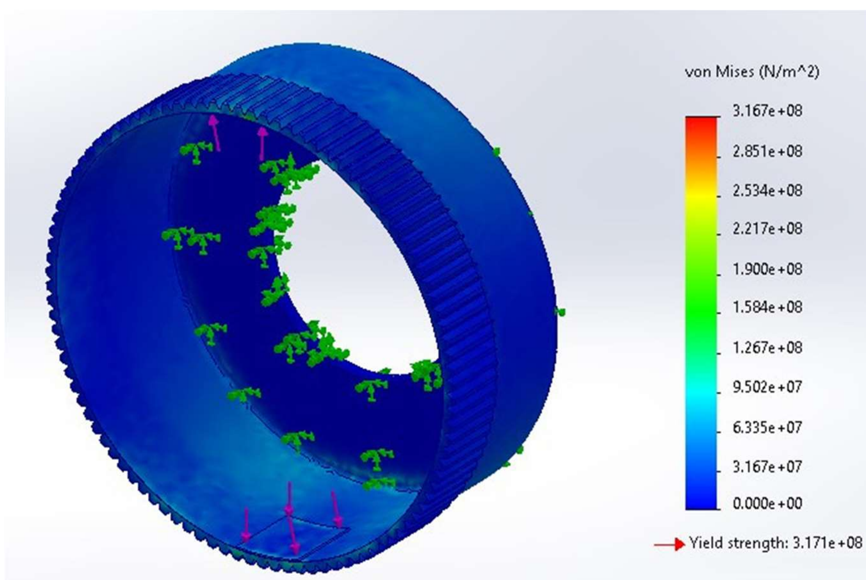

Figure 5. Maximum stress generated in Flexspline

The stress generated for the desired deflection lies within the yield strength limit of the material.

4.1.2. FEA Analysis of Wave Generator

Analysis and Results:

For the analysis, fatigue test was performed for the life cycle of wave generator and following results were obtained.

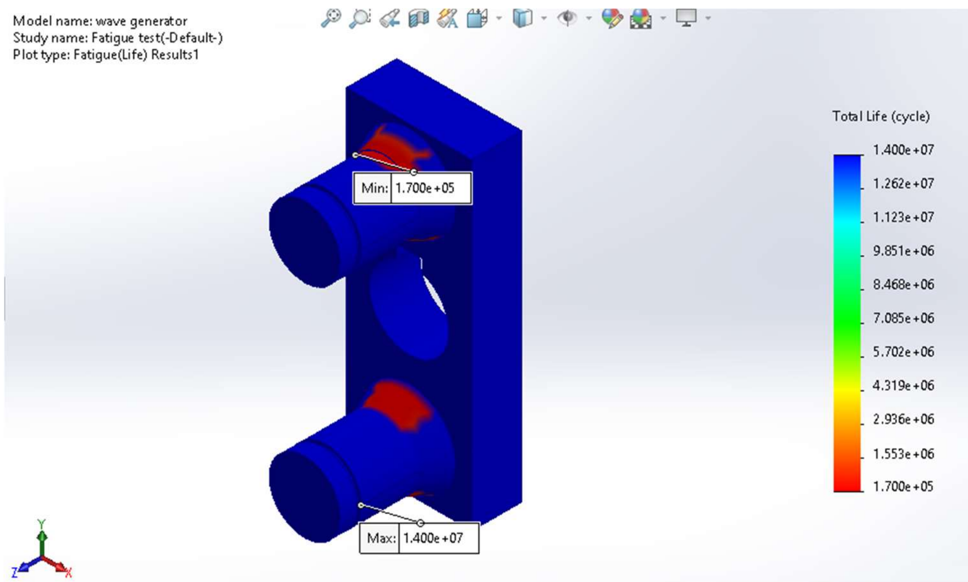

Figure 6. Fatigue Analysis of Wave generator

4.2 Prototype Testing

A 3D Printed Prototype was also created to check the dimensionality of the design while also checking the authenticity of the FEA analysis conducted.

Prototype Geometry:

Figure 7. Assembled 3D model

4.3 Material Sheet

Table 3 Material Sheet

Sr No.	Nomenclature	Quantity	Rate	Amount
1.	Alloy Steel AISI 4140	12.4kg	500	6200
2.	Mild Steel	15	300	4500
3.	Bearing Steel 52100	8	450	3600
4.	Machining	-	-	21000
5.	3D Printing	-	-	3500
6.	Ball Bearings 6303	2	600	1200

4.4 Machining

For flexspline and circular spline, turning and EDM wirecut have been used. The reason for the use of EDM wirecut is that extreme precision was required for the machining of tooth profile of the circular spline and flexspline. The 2mm thickness of flexspline constrained the normal machining operations for gear tooth.

For Wave Generator, a block of bearing steel has been machined and a rectangular piece with two cylinders at each end has been extruded out. The ball bearings have been mounted on the cylinders and kept in place by snap rings

Figure 8. Machined Circular Spline and Flexspline

Figure 9. Machined and Assembled wave generator

4.5 Assembly

Prior to assembly, all components were inspected to ensure their integrity and compatibility with the harmonic gearbox model. The components included the wave generator, flex spline, circular spline, bearings, and other supporting parts.

The flex spline, a flexible outer ring with teeth, was carefully examined for any damage or debris. It was cleaned thoroughly to ensure optimal performance. A thin layer of lubricant was applied to the teeth and inner surface of the flex spline. The appropriate bearings were mounted onto the wave generator, ensuring proper alignment and fit. These bearings provide support for the rotational movement of the harmonic gearbox. The wave generator, a critical component responsible for deforming the flex spline, was inserted into the flex spline with precision, ensuring a secure fit. The proper orientation and alignment were confirmed. The wave generator and flex spline assembly were aligned with the circular spline. The teeth of the flex spline were meshed with the teeth of the circular spline, guaranteeing accurate engagement. Following the manufacturer's specifications, the necessary screws and fasteners were used to securely hold the components in place.

Once the assembly was complete, a thorough inspection was conducted to verify the alignment and security of all components. The input shaft was manually rotated to test the smooth operation of the harmonic gearbox. No unusual noise or resistance was detected. Minor adjustments were made to optimize performance.

The assembly of the harmonic gearbox was successfully completed according to the manufacturer's guidelines. The harmonic gearbox exhibited smooth operation during testing, indicating the correct engagement of the flex spline and circular spline.

Figure 10. Final assembly of gearbox

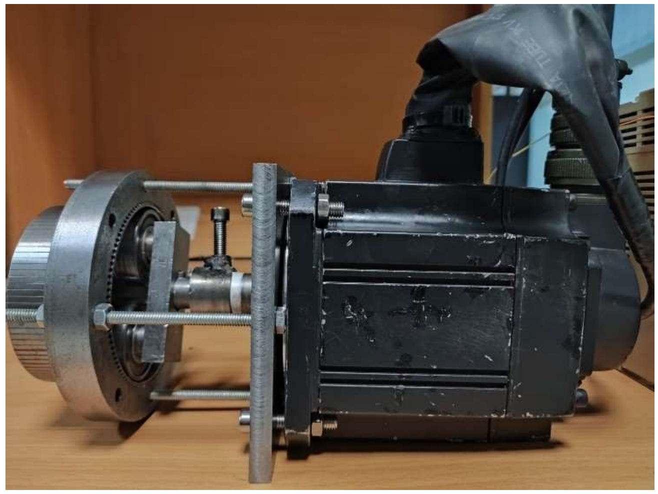

Figure 11. Gearbox assembled with motor

Figure 12. Gearbox mounted on motor

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

Before delving into the discussion on the design and fabrication of a harmonic gearbox, it is essential to highlight the significance of this technology in the field of power transmission. Harmonic gearboxes offer compactness, precision, and backlash-free operation, making them ideal for various industrial applications. However, it is crucial to explore the performance, limitations, and potential improvements of harmonic gearboxes to further enhance their efficiency and applicability.

5.1 Discussion

The design and fabrication of a harmonic gearbox have successfully addressed the limitations of conventional gearboxes and introduced a compact, lightweight, and high-precision solution for power transmission systems. The project aimed to provide improved efficiency, reliability, and performance in various industrial applications.

The fabrication process involved carefully manufacturing the major components of the harmonic gearbox using suitable materials and precision techniques. By incorporating the principles of harmonic drive technology, the gearbox achieved high gear reduction ratios, excellent torque-to-weight ratio, and backlash-free operation.

The harmonic gearbox demonstrated several significant features and advantages. Its compact and lightweight design makes it ideal for applications where space and weight restrictions are critical. The reduced size and weight facilitate easy integration into existing systems and contribute to lower overall system inertia.

In terms of performance, the harmonic gearbox exhibited exceptional precision and repeatability, making it well-suited for applications that require accurate motion control and positioning. The absence of backlash in the gearbox improves reliability and ensures smooth and efficient power transmission.

However, it is important to acknowledge certain limitations. One limitation is the relatively lower torque capacity compared to traditional gearboxes. The harmonic gearbox may not be suitable for applications that demand significant power transmission and high torque requirements. Careful consideration of the intended application's torque needs is essential to ensure proper gearbox selection.

Furthermore, the fabrication process of the harmonic gearbox can present challenges, particularly in terms of tolerances and assembly complexity. Precision manufacturing techniques are required to produce the specialized components and ensure proper alignment and gear meshing. Attention to detail and expertise in assembly are crucial to achieving optimal gearbox performance.

5.2 Limitations

Despite the advancements made in the design and fabrication of the harmonic gearbox, several limitations should be acknowledged.

- The primary limitation is the relatively lower torque capacity compared to traditional gearboxes.

- The harmonic gearbox may not be suitable for applications that require high-torque transmission capabilities.
- It is crucial to carefully assess the torque requirements of the intended application and consider alternative gearbox solutions for high-torque scenarios.
- Additionally, the fabrication process of the harmonic gearbox can be intricate and time-consuming.
- The precision manufacturing techniques and tight tolerances required for the specialized components and gear meshing demand expertise and attention to detail.
- As a result, the fabrication process may be costlier and more complex compared to conventional gearboxes.
- Another limitation to consider is the potential sensitivity of the harmonic gearbox to operating conditions.
- Variations in speed, temperature, and load may impact the gearbox's performance and longevity.
- Careful monitoring and adherence to recommended operating parameters are necessary to ensure optimal and reliable gearbox operation.

5.3 Recommendations

To address the identified limitations and further enhance the design and fabrication of harmonic gearboxes, several recommendations can be made:

- Firstly, ongoing research and development efforts should focus on improving the torque capacity of harmonic gearboxes without compromising their compactness and precision.
- Exploring advanced materials and manufacturing techniques, such as optimized tooth profiles and enhanced surface treatments, can help increase the gearbox's load-bearing capabilities.
- Furthermore, efforts should be made to streamline the fabrication process of harmonic gearboxes, aiming for improved efficiency and cost-effectiveness.
- Research into automation possibilities, improved assembly techniques, and reduced tolerances can help simplify and expedite the production process while maintaining high-quality standards.
- Additionally, conducting comprehensive performance testing and validation of harmonic gearboxes under various operating conditions is crucial.
- This will provide valuable insights into the gearbox's capabilities and limitations, enabling designers to optimize its performance for specific applications.
- Thorough testing should encompass factors such as speed, torque, temperature, and vibration to ensure reliable and efficient gearbox operation.
- Collaboration with industry partners and researchers in the field of power transmission systems can foster knowledge exchange and innovation.
- Sharing experiences, best practices, and case studies can contribute to the continuous improvement and advancement of harmonic gearbox technology.

5.4 Conclusion

In conclusion, the design and fabrication of a harmonic gearbox offer significant advancements in power transmission technology. The harmonic gearbox showcases remarkable compactness, precision, and backlash-free operation, making it a valuable solution for various industrial applications.

However, to further enhance the harmonic gearbox's performance and applicability, it is important to address certain considerations. One key aspect is improving the torque capacity to make it suitable for high-torque applications. This can be achieved through research and development efforts focused on optimizing gear tooth profiles and exploring advanced materials.

Streamlining the fabrication processes of harmonic gearboxes is another crucial aspect to consider. This includes identifying opportunities to improve efficiency, reduce complexity, and lower costs. By refining manufacturing techniques, reducing tolerances, and exploring automation possibilities, the fabrication process can be optimized for consistent and high-quality production.

Thorough performance testing and validation under different operating conditions is essential to ensure the harmonic gearbox's reliability and efficiency. This will provide valuable insights into its capabilities and limitations, allowing for the determination of optimal operating parameters such as speed, torque, and temperature for specific applications.

Collaboration between researchers and industry professionals is vital for knowledge exchange and innovation in the field of harmonic gearboxes. Sharing experiences, best practices, and case studies can contribute to further advancements and the continuous improvement of harmonic gearbox design and fabrication.

In summary, the design and fabrication of a harmonic gearbox offers significant benefits in power transmission technology. By addressing considerations related to torque capacity, fabrication complexity, and operating conditions, researchers and industry professionals can contribute to further enhancing the performance and applicability of harmonic gearboxes in various industrial applications.

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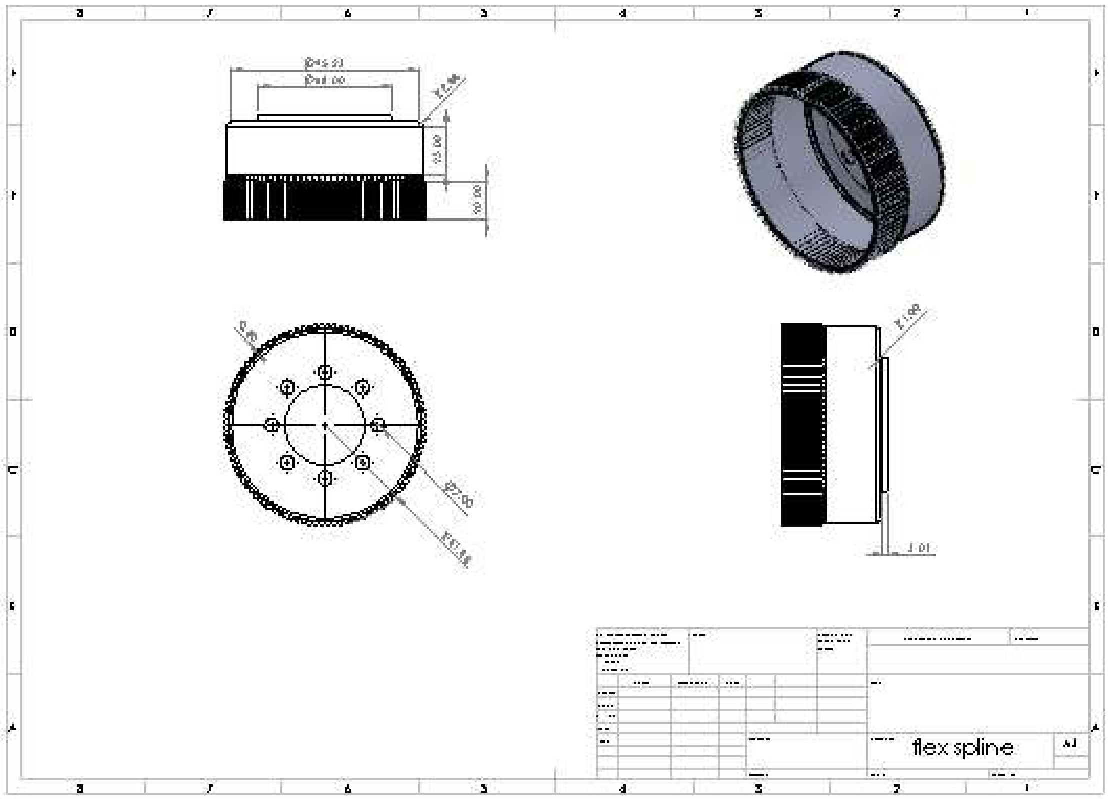
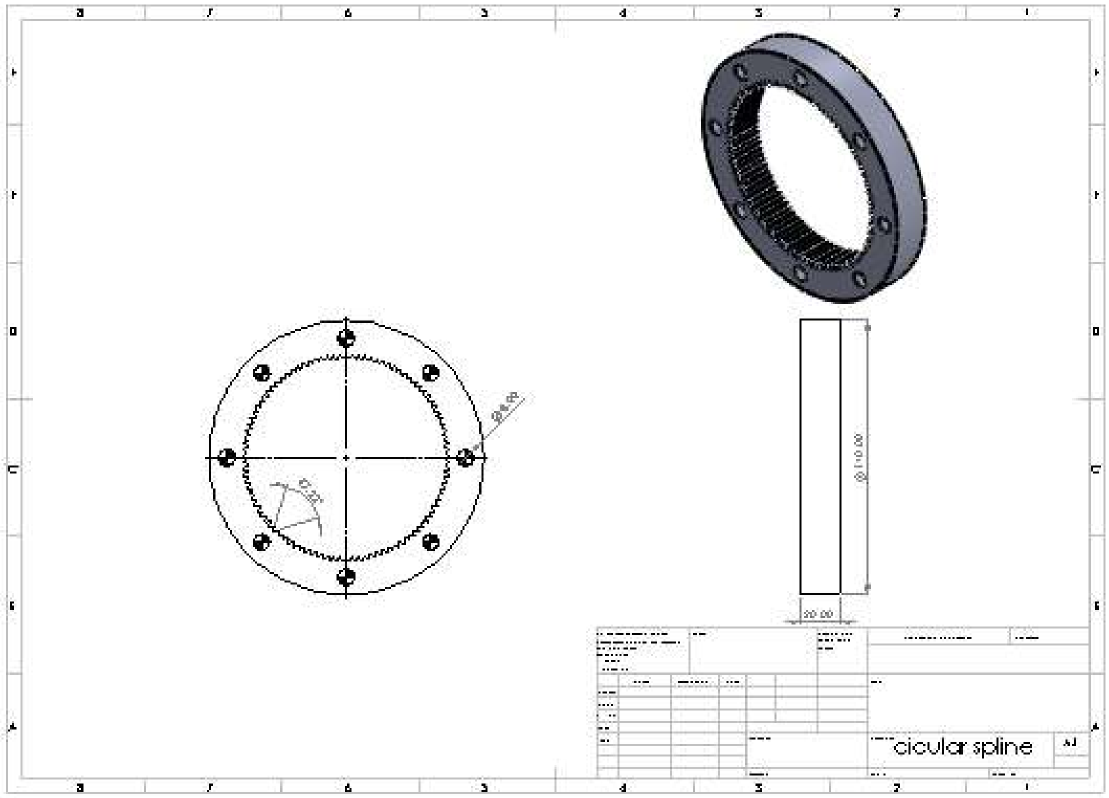
APPENDIX I: DRAWINGS OF COMPONENTS





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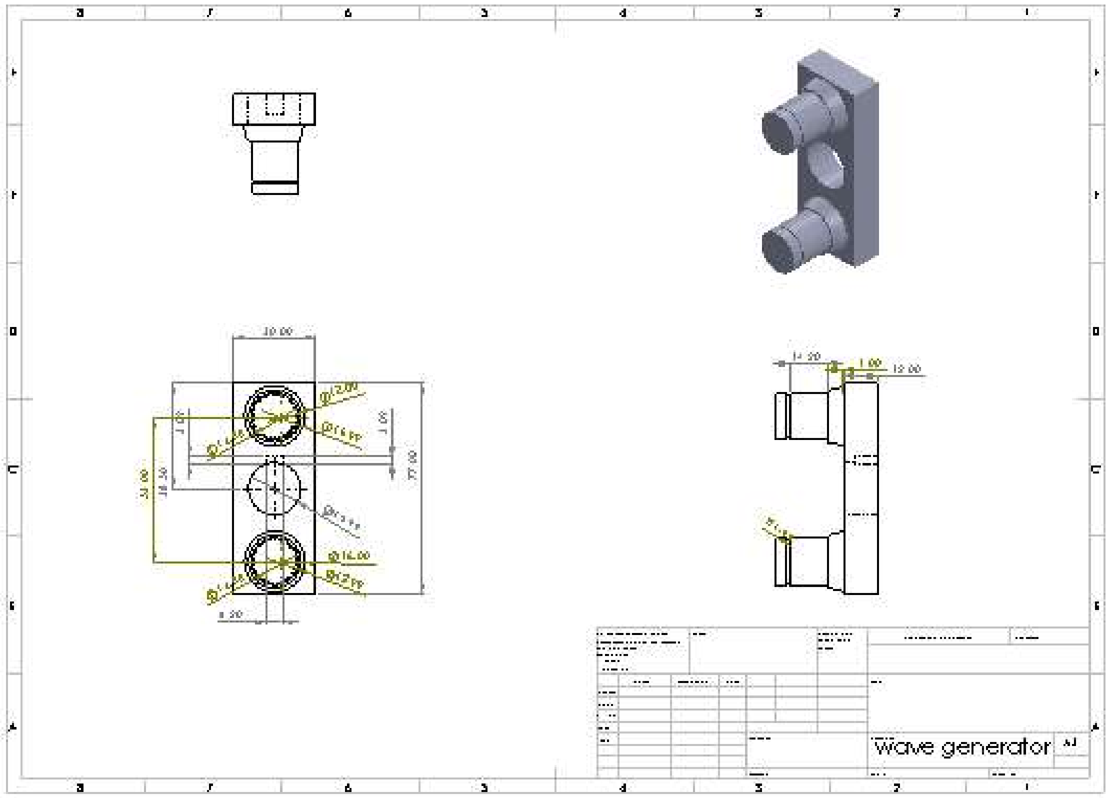
Wave generator