A Comprehensive Study on Optimizing Reduction Gearbox Efficiency through Cycloidal Innovations and Future Trends Insights

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ABSTRACT

This comprehensive literature survey delves into the transformative potential of modified cycloidal gearboxes in the Indian market, emphasizing cost-effective manufacturing strategies to rival imported counterparts. In addition to exploring gear materials and their heat treatment processes, the study broadens its scope to enhance overall performance and durability. Emphasizing the distinctive design principles of cycloidal gearboxes, including space efficiency, minimal backlash, increased load capacity, and cost advantages, the research provides comparative analyses with other gearbox types, demonstrating the suitability of modified cycloidal gearboxes for India's cost-conscious manufacturing and emerging robotics sectors. Through meticulous literature reviews, the study identifies a substantial opportunity and demand for the widespread adoption of modified cycloidal gearboxes in the Indian market.

The project's innovation thrust involves the redesign of the cycloidal disc, integrating novel materials and alternative shapes to develop cutting-edge yet cost-effective solutions. This approach aims to challenge the dominance of large-scale companies by proposing locally manufactured alternatives that are not only economically viable but also uphold high-quality standards. The envisioned outcome is a paradigm shift, establishing cycloidal gear mechanisms as a prevalent force in India's manufacturing and robotics sectors. This endeavor significantly contributes to fostering a more competitive and technologically advanced landscape, aligning with the nation's aspirations for industrial growth and innovation.

CHAPTER 1
INTRODUCTION

1.1 Introduction and Scope of Study

The proposed project embarks on a mission to address a crucial gap in the Indian market concerning the under-utilization of cycloidal gearboxes in comparison to conventional drives. The focus revolves around the RV or cycloidal gear mechanism, an under-explored avenue among Indian gearbox manufacturers. This hesitancy is primarily attributed to the perceived lack of demand for high precision in specific applications and the formidable presence of global industry leaders such as Nabtesco, Nidec-Shimpo, SEW, and Sumitomo. These corporations not only command a substantial market share but also distinguish themselves through cutting-edge technology and precision manufacturing, resulting in products with minimal backlash during transmission.

In the Indian manufacturing sector, the use of high-precision CNC or VMC machines is constrained by their hefty price tags. These machines come with significant costs, mainly due to intricate sub components, including highly precise gearboxes. The cycloidal gearbox, a key element, significantly contributes to the overall cost. To foster a more economically sustainable manufacturing environment, there's a critical need to shift towards producing cycloidal gearboxes within India.

The robotics industry in India faces a similar challenge. Cycloidal and Planocentric gearboxes dominate the sector, providing an opportunity for innovation to create cost-effective, locally produced solutions. This emphasizes the urgency to introduce new manufacturing approaches, particularly concerning cycloidal discs. Such innovation has the potential to reshape and redesign these essential components, integrating new materials or alternative profile shapes to enhance efficiency and simultaneously reduce manufacturing costs.

Furthermore, in various industrial applications such as robotics, machine tools, and manufacturing equipment, precise positioning accuracy is crucial. Traditional gear drives like spur and planetary gear systems are commonly used, but they might fall short in achieving the desired high reduction ratios without sacrificing space. Cycloidal drives, with their compact design and ability to achieve higher reduction ratios, offer a compelling alternative. However, the under-utilization of cycloidal drives in these applications indicates a need for enhanced understanding and promotion of their advantages. Beyond manufacturing and robotics, sectors like renewable energy and automotive systems could greatly benefit from optimized cycloidal gear mechanisms. For instance, in the renewable energy sector, where efficient power transmission is vital for maximizing energy output, the incorporation of advanced cycloidal gearboxes could lead to more effective and sustainable energy solutions. Similarly, in automotive systems, where minimizing weight and space is critical, the adoption of high-efficiency cycloidal gear systems could revolutionize transmission mechanisms.

Hence, the need for this study extends beyond manufacturing and robotics, encompassing diverse sectors that stand to gain from the improved efficiency and functionality offered by enhanced cycloidal gear mechanisms. Addressing this need requires not only innovation in design but also a comprehensive understanding of the unique requirements and challenges across different industries. The primary objective of this comprehensive study is to foster innovation within the cycloidal gearbox domain, aiming to make them more adaptable for widespread adoption in the Indian market. This entails a meticulous redefinition and redesigning of the cycloidal disc, integrating innovative approaches like the consideration of new materials or alternative profile shapes. The goal is to cultivate cost-effective solutions that not only rival but surpass the precision and performance standards set by established international players.

Moreover, this study seeks to navigate the intricacies of the current market dynamics where major companies exert dominance through technological prowess and precision manufacturing capabilities. The ultimate ambition is to disrupt this hierarchical structure by introducing locally manufactured, cost-effective alternatives. By doing so, the project aspires to usher in a new era, increasing the prevalence of cycloidal gear mechanisms in both the manufacturing and robotics sectors within India.

CHAPTER 2
OVERVIEW

2.1 Cycloidal Gearbox

A cycloidal gearbox, also known as a cycloidal drive or cycloidal reducer, is a type of speed reducer used in mechanical power transmission systems[13]. The general term for a "Speed Reducer" is the "Gearbox." This apparatus consists of gears mounted on shafts, supported by bearings, and arranged within a sealed, lubricant-tight enclosure at both ends. Its primary function is to convert high-speed rotary input power, characterized by low torque, into a correspondingly low-speed, high-torque output power. This output power is harnessed in the mechanisms of machines to carry out various tasks. The ratio between the output and input speeds is referred to as the transmission (or speed) ratio. Gear transmissions are indispensable for three core reasons:

1. Inertia Matching.
2. Speed Reduction.
3. Torque Magnification [13][21].

2.2. Components of a Cycloidal Gearbox

(i) High-Speed Input Shaft: The gearbox begins with a high-speed input shaft that is typically connected to a motor or power source [3][4].

(ii) Eccentric Bearing or Cycloidal Cam: The high-speed input shaft drives an eccentric bearing or cycloidal cam. The eccentric motion of this component is a key element in the functioning of the cycloidal gearbox [3][4].

(iii) Cycloidal Disks or Cam Followers: Two cycloidal disks or cam followers are driven by the eccentric motion of the bearing. These disks have lobes or teeth that engage with the rollers on the ring gear [3][4][13].

(iv) Ring Gear with Pins and Rollers: The ring gear houses pins and rollers that engage with the lobes on the cycloidal disks. This interaction results in reverse rotation at a reduced speed [3][4][13].

(v) Slow-Speed Output Shaft: The reduced rotation is transmitted to the slow-speed output shaft through the holes in the cycloidal disks. The output shaft delivers the desired output speed and torque [3][4][13].

(vi) Cycloidal Disks Arrangement: Two cycloidal disks are typically placed 180 degrees out of phase to compensate for unbalanced forces caused by the eccentric motion. This arrangement ensures smoother operation, especially at higher speeds [3][4][13].

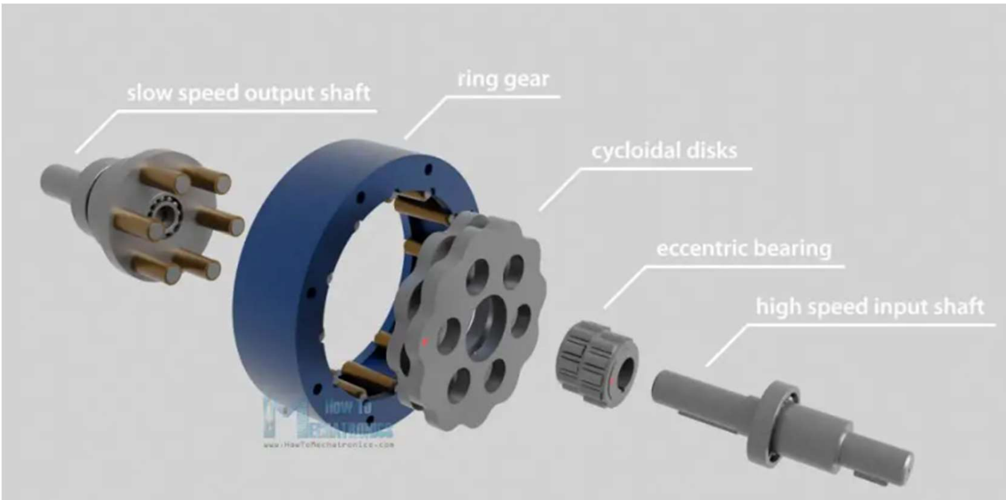

Figure (2.2.a): Components of a Cycloidal gearbox [13]

2.3 Comparison of Cycloidal vs. Planetary Gearboxes

Planetary gears can operate at elevated speeds. Cycloidal gears excel in handling exceptionally heavy loads. Planetary gears are suitable for applications requiring very low ratios. Cycloidal gears function effectively at higher ratios, demanding less power [20].

When positioning accuracy and lost motion are not critical, planetary gears are a viable choice. On the other hand, cycloidal gears are optimal for applications where high positioning accuracy and minimal lost motion are crucial [20].

For applications where regular "monthly maintenance" is acceptable, planetary gears are satisfactory. In contrast, cycloidal gears are the preferred option when minimal maintenance and prolonged gear life are essential [20].

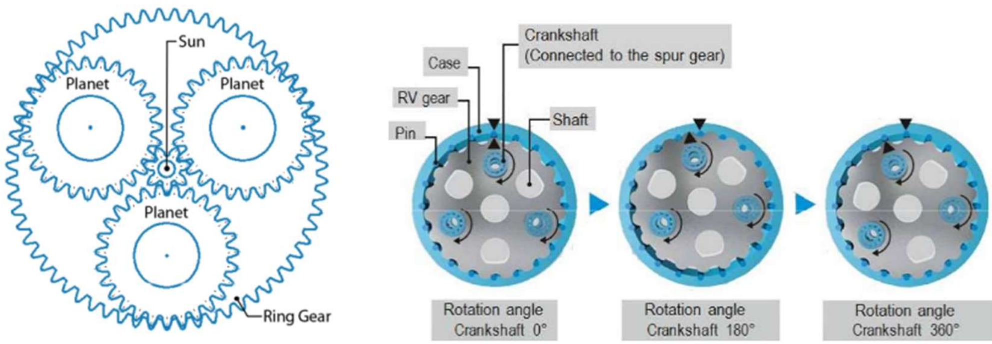

Figure (2.3.a): Components of a Planetary & Cycloidal gearbox [20]

2.4 Working of a Cycloidal Gearbox

- The input shaft drives an eccentric bearing or cycloidal cam.
- The eccentric motion of the bearing causes two cycloidal disks to move around the internal circumference of the ring gear housing.
- The cycloidal disks engage with the rollers of the ring gear, producing reverse rotation at a reduced speed.
- The reduced rotation is then transmitted to the output shaft through the holes in the cycloidal disks.
- The design includes two cycloidal disks, placed 180 degrees out of phase, to compensate for unbalanced forces and ensure smoother operation [10][21].

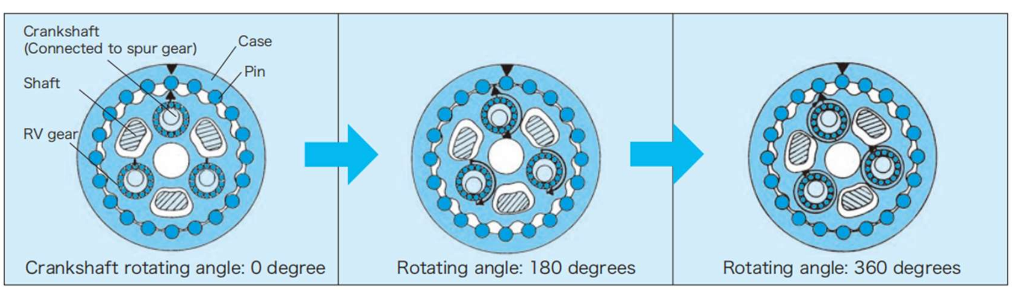

Figure (2.4.a): Typical working of a Cycloidal gearbox [10]

2.5 Planocentric Gearbox by Nabtesco

Nabtesco's Planocentric Gearbox, epitomized by the RV and RV-E series, stands as a pinnacle of precision reduction gears renowned for their compact design and exceptional accuracy. The gearbox features a high-speed input shaft connected to precision gears supported by a patented cage mechanism, ensuring a balanced load distribution and increased durability. Notably, the arrangement of components within the gearbox emphasizes a meticulous design strategy, optimizing the distribution of forces [10].

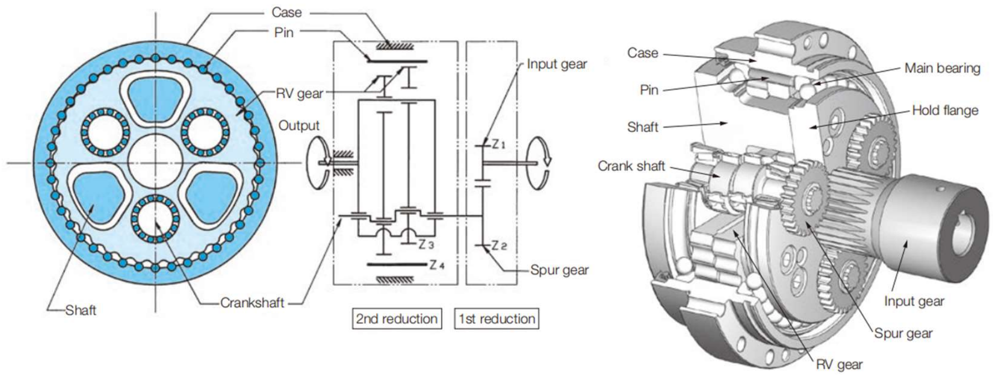

Figure (2.5.a): Cross sectional view of Nabtesco RV gearbox [10]

This thoughtful arrangement, combined with a commitment to minimizing backlash, makes Nabtesco's Planocentric gearboxes integral to diverse industries, including robotics, automation, aerospace, and medical devices. Integrating seamlessly with servomotors and control systems, these gearboxes provide precise and dynamic motion control, making them indispensable in scenarios demanding high precision and reliability. The RV-E series, representing the latest advancements, further solidifies Nabtesco's position at the forefront of Planocentric gearbox technology, meeting the evolving demands of modern industrial applications [10].

2.6 Market share of Precision Reduction gearboxes in Global & Indian Markets

In 2021, the precision gearbox market was driven by the robotics application segment, which generated over 19% of the worldwide revenue. In 2021, the Asia Pacific region dominated the market and generated more than 64% of worldwide revenue. Because modern material handling equipment and robotics and automation technologies are increasingly being used in several industries, including machine tools, metallurgy, and cement, the region holds the biggest market share. Companies in sectors like steel and cement are investing heavily in China, India, and Japan in order to implement cutting-edge methods and boost their production capacity [25].

Figure (2.6.a): Global Precision Gearbox Market share by application in 2021 [27]

With the increasing need for automation across various industries, the demand for gearboxes and gear-motors is growing rapidly. For example, in the food and beverage industry, gear motors are used in conveyor systems to move products through the manufacturing process [25].

The global market for industrial automation is expected to grow at a CAGR of 7.3% from 2023 to 2029. These products are used in various automation applications, such as robotics, conveyor systems, and packaging equipment, among others [28],[29].

Cycloidal Gearbox Market size was valued at USD 2,000.8 Million in 2022, expanding at a CAGR of 4.8% from 2023 to 2030 [24].

Figure (2.6.b): Precision Gearbox Market share of Key Players [25]

Expected to have a value of around USD 9.11 billion by 2032, the global precision gearbox market is predicted to develop at a compound annual growth rate (CAGR) of 8.90% from 2023 to 2032. The market was valued at USD 4.23 billion in 2023. With a 21% revenue share in 2022, the robots category led the market in terms of application. In 2022, the Asia Pacific region's revenue share was 64%. The precision gearbox market in Asia Pacific was estimated to be worth USD 2.71 billion in 2023 and is projected to increase at a compound annual growth rate (CAGR) of 9% to reach USD 5.88 billion by 2032 [33].

Geographically speaking, the Asia Pacific area has dominated the industry because to the enormous supply and demand it has seen. Over the course of the projected period, the growing need for robots in nearly every industry in this area has proven to be a significant driving factor for the market's expansion. With the aid of cutting-edge technologies, the systems utilized by businesses and manufacturers have been automated to provide better, more precise outcomes quickly, increasing productivity and yielding a high rate of return on investment [33].

Substantial funding is made by manufacturers in China, India, and Japan to automate their systems utilizing cutting-edge technologies to boost their companies' overall production capacity [33].

Figure (2.6.a): Precision gearbox market size 2023 to 2032 (USD Billion) [33]

2.7 Usage in Indian Markets

In India, the manufacturing sector often faces cost constraints, and the adoption of high-precision CNC or VMC machines is limited by their associated costs. The robotics industry in India also seeks cost-effective solutions, making the adoption of efficient gear systems, including cycloidal gearboxes, beneficial [10].

2.8 Gear Ratio Findings in Cycloidal Gearbox

The gear ratio in a cycloidal gearbox is determined by the number of pins on the ring gear. For example, if there are 12 pins on the ring gear, and one less cycloidal lobe on the disk (11 lobes), the ratio is 11:1 for one full rotation of the eccentric bearing. The reduction ratio is solely dependent on the number of pins, providing a straightforward way to customize gear ratios for specific applications. This flexibility in gear ratio customization adds to the versatility of cycloidal gearboxes in various industrial applications [4][13].

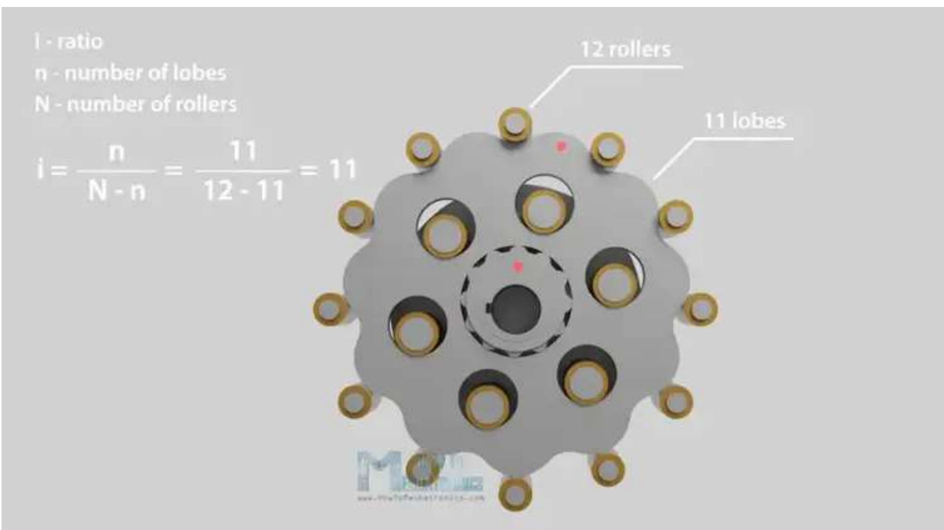

Figure (2.8.a): Typical arrangement of Cycloidal disc with pins [13].

2.9 Operating a Cycloidal Gearbox with a Servomotor, Servo Drive, and HMI

(i) Servomotor:

An actuator that rotates and provides accurate control over acceleration, velocity, and angular position is called a servomotor. The high-speed input shaft of a cycloidal gearbox is linked to the servomotor. Servomotors are selected because they can precisely and quickly control the gearbox's rotation [5],[8],[14].

(ii) Servo Drive:

The servo drive is an electronic amplifier that powers the servomotor. It receives control signals from a controller (such as a PLC or HMI) and amplifies them to provide the necessary power to the servomotor. In the operation of a cycloidal gearbox, the servo drive ensures precise and dynamic control of the motor, allowing for adjustments in speed, position, and torque [5],[8],[14].

(iii). HMI (Human-Machine Interface):

An HMI is a graphical interface that allows operators to interact with and control machinery. In the context of a cycloidal gearbox, the HMI can be used to set parameters such as speed, direction, and torque limits. Operators can monitor the gearbox's performance through the HMI, which may display key metrics such as speed, temperature, and torque [5],[8],[14].

The integration of a cycloidal gearbox with a servomotor, servo drive, and HMI enables precise and dynamic control over the operation of the gearbox, making it suitable for applications where accurate speed, torque, and position control are essential.

2.10 Types of Gear Materials:

Gears are essential parts of equipment that require a variety of materials to meet certain performance standards. Making this choice is essential to provide strength, resilience against deterioration, and protection from the elements. We examine five different kinds of gear materials in our investigation, each created to address certain industrial requirements [23].

(i) S45C (Medium Carbon Steel grade)

S45C is a commonly used steel with a 0.45% carbon content. It may be obtained easily and is used in the manufacturing process of gear racks, worm gears, bevel gears, spur gears, and helical gears [23].

Symbol	Chemical Composition %				
	C	Si	Mn	P	S
S45C	0.42 - 0.48	0.15 - 0.35	0.60 - 0.90	<0.030	<0.035

Table (2.10.a): Chemical Composition of S45C [23].

- Heat Treatment and Hardness:
- None: Less than 194HB

This indicates that if S45C undergoes no specific heat treatment, its hardness will be less than 194 on the Brinell Hardness scale (HB) [23]

- Thermal Refining: 225 – 260HB

This refers to the hardness range achieved when S45C undergoes thermal refining as a heat treatment process. In this case, the hardness will be in the range of 225 to 260 on the Brinell Hardness scale [23]

- Induction Hardening: 45 – 55HRC

This specifies the hardness range achieved through induction hardening, another heat treatment method. In this case, the hardness is measured on the Rockwell Hardness scale (HRC), and it falls within the range of 45 to 55 HRC [23].

(ii) SCM440 (Chrome-molybdenum Alloy Steel)

SCM440 is a chromium-molybdenum alloy steel characterized by a moderate carbon content of 0.40%. With superior strength compared to S45C, it is commonly utilized in gear manufacturing processes where it undergoes either induction hardening or thermal refinement [23].

Description	Symbol	Chemical Composition %						
		C	Si	Mn	P	S	Cr	Mo
Type 4	SCM440	0.38 - 0.43	0.15 - 0.35	0.60 - 0.90	<0.030	<0.030	0.90 - 1.20	0.15 - 0.30

Table (2.10.b): Chemical Composition of SCM440 [23].

- Heat Treatment and Hardness:
- Thermal Refining: 225 – 260HB

This indicates that when SCM440 undergoes thermal refining, a heat treatment process, the resulting hardness will fall within the range of 225 to 260 on the Brinell Hardness scale (HB) [23]

- Induction Hardening: 45 – 60HRC

  This specifies the hardness range achieved through induction hardening, another heat treatment method. In this case, the hardness is measured on the Rockwell Hardness scale (HRC), and it falls within the range of 45 to 60 HRC [23].

(iii) SCM415 (Chrome-molybdenum Alloy Steel):

SCM415 is a commonly used low-carbon alloy steel (C = 0.15%). Typically carburized for use, it offers more strength than S45C or SCM440. It implies that when SCM415 is carburized (a process involving the addition of carbon to the surface of the steel for increased hardness), the resulting surface hardness is expected to be between 55 and 60 HRC. This level of hardness suggests enhanced strength and wear resistance, making SCM415 suitable for applications where such properties are crucial, especially when compared to materials like S45C or SCM440 [23].

Description	Symbol	Chemical Composition %						
		C	Si	Mn	P	S	Cr	Mo
Type 4	SCM415	0.13 - 0.18	0.15 - 0.35	0.60 - 0.90	<0.030	<0.030	0.90 - 1.20	0.15 - 0.25

Table (2.10.c): Chemical Composition of SCM415 [23].

(iv) SUS303 (Stainless Steel: 18Cr-8Ni Stainless Steel):

SUS303, being a rust-resistant steel, exhibits non-magnetic properties. It finds common use in gear applications where the presence of rust is undesirable, particularly in machinery used for food processing. Another variant of stainless steel, SUS304, offers even higher corrosion resistance. [23].

(v) Copper Alloy Casting:

Frequently selected as materials for worm wheels, phosphor bronze casting (CAC502) and aluminum-bronze casting (CAC702) are popular choices. Complementary to these, iron metals such as S45C, SCM44, and SCM415 are commonly utilized for mating worms. The use of different materials for each paired worm and worm wheel is aimed at preventing galling or seizure due to slippage [23].

2.11 Gear Damages, Causes Preventive measures & Solutions

2.11.1 Gear Tooth Wear

Tooth surfaces experience wear in various ways, with run-in wear being a minor asperity that occurs during start-up and typically causes no operational issues. Critical wear, on the other hand, involves scraping away a small quantity of material from the tooth surface, and if it progresses to deform the tooth profile, proper meshing becomes impossible. Tooth surface fatigue arises from repeated loading or forces exceeding the material's endurance limit. This leads to surface fatigue manifestations such as pitting, case crushing etc. Critical wear or progressive pitting can result in increased noise or vibration, excessive temperature in the gear device, elevated lubricant smear, and increased backlash [26][23][30]. Addressing the causes of these issues is crucial in preventing damage. The following context outlines the causes of tooth damage and their equivalent solutions

(1) Insufficient Tooth Surface Strength Against Load:

- **Solution 1**: Overcoming weak tooth surface strength under stress requires comprehensive solutions. One strategy is to increase the tooth surface strength by changing the material. For example, you could go from a material like S45C to one that is stronger, such as SCM440 or SCM415. To better disperse the weight, it should also be taken into account to increase the gear size, module, or tooth count. Strengthening the gear by expanding its face is an additional feasible approach. Moreover, the problem of inadequate tooth surface strength under high loads can be greatly mitigated by a deliberate switch to stronger gear types having helical gear teeth, such as switching from Spur gear to Spiral gear or Straight Bevel gear to Spiral bevel gear [26][30].

- **Solution 2:** Reducing the load is another way to address the issue of tooth surfaces' lack of strength at high loads. Changing the driving circumstances is one way to achieve this. We can reduce the strain on the tooth surfaces by adjusting the settings or optimizing the load distribution of the machinery. This method provides a comprehensive way to address the problem of weak tooth surfaces under different stresses, when paired with advancements in material and design [26][30].

(2) Improper Tooth Contact Due to Bad Mounting:

- **Solution:** One way to solve the problem of incorrect tooth contact resulting from inadequate mounting is to adjust the tooth contact by hand using techniques designed for various kinds of gears. We may correct and optimize the tooth contact by performing adjustments depending on the unique features of each gear type, which helps to mitigate the issue of inappropriate contact resulting from mounting issues. This focused approach offers an efficient way to guarantee appropriate tooth engagement and performance, especially when combined with an attention to gear type details [26][30].

(3) Partial Contact Due to Bad Mounting:

- **Solution:** A common method to deal with the problem of partial contact resulting from incorrect mounting is to strengthen the bearing, shaft, and gear designs. The goal is to improve tooth contact by improving overall stiffness in these parts. Improving the structural integrity of gears, shafts, and bearings helps to solve the partial contact issue that results from inadequate installation and improves tooth engagement. This method, which emphasizes additional stiffness in the important components, works well to provide improved and more reliable tooth contact [26][30].

(4) Poor Lubrication Conditions:

- **Solution:** Ensuring lubrication practices are optimal is one way to solve issues caused by insufficient oil conditions. This entails providing the appropriate kind of oil, modifying its viscosity to meet specifications, and keeping the appropriate amount in place. We can solve the problem of insufficient lubrication conditions by following these instructions. This method, which strongly emphasizes precision in lubrication procedures, is essential for fostering effective gear running and avoiding potential issues brought on by inadequate or incorrect lubrication [26][30].

2.11.2 Gear Breakage

There are several types of gear breakage, including fatigue breakage from repeated loading, overload breakage from unexpectedly high loads, and tooth fracture from partial contact, which is most commonly seen in spur or bevel gears. The causes and solutions for these breakages are described in the section that follows [26] [23] [30].

1. Tooth Breakage from Impact Load:

- **Solution 1**: To prevent tooth breaking as a result of impact loads, one way to prevent this from happening is to increase gear strength, also known as bending capability. This can be achieved by implementing policies that, similar to surface strength improvement strategies, entail changing the material or extending the module. Enhancing the gear's bending strength makes it more resistant to impact loads and reduces the possibility of fracture. This method, which combines material and structural modifications, offers a practical way to improve the resilience of gears in impact scenarios [26].

- **Solution 2**: Another way to solve the problem of impact-induced tooth breaking is to reduce or eliminate the impact load. A workable way to accomplish this is to lower the rotational speed. Reducing the rotational speed can significantly mitigate the risk of tooth breakage owing to high-impact loads by reducing the force and impact on the teeth. This simple method provides an efficient way to increase the gear teeth's toughness and longevity, particularly when they are exposed to potentially harmful impact forces [26].

2. Fatigue Breakage from Cyclic Loading:

- **Solution 1**: The best way to address the problem of fatigue breaking brought on by cyclic loads is to make the gear stronger overall. This entails using meticulous techniques in line to strengthen the tooth surfaces of the gear. We can successfully reduce the danger of fatigue-induced breaking by putting procedures into place to strengthen the gear's structural integrity, especially in response to cyclic loading circumstances. This all-encompassing strategy, which focuses on fortifying the gear, specifically addresses the problem of fatigue failure brought on by repeated loading [26].

- **Solution 2**: Another way to lower the danger of fatigue breaking caused by cyclic loading is to reduce the load or rotation that is put on the system. By using this method, the materials' stress during repetitive loading is decreased, which lessens the chance of fatigue-related breakages. This approach offers a workable plan to improve the system's lifetime and durability under cyclic loading conditions by controlling the load and rotation parameters [26].

3. Breakage due to Progressing Wear and Thinning of the Tooth:

3.a Breakage at Gear Flank of Gears

There are several reasons why fracture occurs at the gear flank. Errors in design cause a significant difference between the gear's theoretical strength and the actual load it faces. Instances of abrupt and severe over-stress on the gear are caused in part by unstable load circumstances. The gear may also be subjected to severe impact loads during operation, which increases the chance of breaking. This damage phenomenon is also influenced by other operational incidents [26][30].

- **Solution1**: A detailed reevaluation of the design is necessary to correct the defects in the design and close the gap between gear strength and practical load. This entails locating and fixing any flaws that may compromise the strength and structural integrity of the gear [26].

- **Solution 2**: Maintaining the load during operation is essential to reducing the effects of unstable load circumstances. By putting policies in place to guarantee a steady and equitable distribution of loads, one can mitigate abrupt and severe strain on the equipment and increase its adaptability to changing operating environments [26].

- **Solution 3:** Considering all of the impact loads that occur during operation, it becomes essential to put appropriate measures in place to lessen or absorb these loads. This could involve altering operational protocols or adding dampening systems to reduce the force imparted to the gear during impact events [26].

- **Solution 4:** Comprehensive preventive measures and improved safety regulations should be put in place to address the role that operational incidents play in gear breaking. This entails thorough training, routine equipment upkeep, and the installation of safety measures to reduce the possibility of mishaps when using the gear [26].

3.b Breakage at gear face of gears

During this scenario, breaking mostly happens at the end of a single-gear edge. The breakage surface of the acute injury has a sharp edge and is free of plastic deformation, displaying metal crystal graininess. The primary reasons for this fracture include excessive stress concentration brought on by a concentration of load at the gear end, mistakes in gear shaft alignment causing stress concentration, and insufficient stiffness of the gearbox or support frame [26].

- **Solution 1:** It is essential to increase the parallel accuracy between gear shafts to deal with the concentration of load at the gear end and the subsequent concentration of stress. This involves careful alignment and adjustment procedures to guarantee uniform load distribution among the gears [26].

- **Solution 2:** One way to address the concentration of stress brought on by misaligned gear shafts is to apply strengthening techniques to increase the stiffness of the gear box and support structure. This could involve adding more supports and other structural improvements to better distribute and absorb loads [26]

- **Solution 3:** Cutting the space between gear shaft bearings is a useful countermeasure to lessen the problem of the gear box's or support frame's inadequate stiffness. By increasing the system's overall rigidity and stability, this tactic lowers the chance of a break [26]

- **Solution 4:** Another effective solution is to oversize the gear shaft. By increasing the size of the gear shaft, it improves its load-bearing capacity, thereby reducing stress and minimizing the risk of acute damage [26]

3.c Damage Phenomenon: Fatigue Failure of Gears

Chronic aging damage is indicated by the observed damage phenomena, which is characterized by smooth blocks with directed fibrous metal flows and a lack of metal crystal graininess on the fracture surface. Several factors are responsible for this, including material fatigue from extended high-speed operation, irregular gear surface with small concave-convex, scratches, and craquelure that cause stress concentration, inadequate design consideration of the endurance limit resulting in poor material endurance tension, and the fatigue failure susceptibility of eroding and rusted gears [26].

- **Solution 1:** It is possible to reduce material fatigue during prolonged high-speed operation by reevaluating the endurance limit factor in the design stage. This involves determining an admissible stress that corresponds with the endurance capacity of the material. Redesigning everything from the ground up with the unique needs of continuous high-speed operation in mind can help reduce the damage caused by chronic ageing [26].

- **Solution 2:** It is recommended to utilize quenching hardening to prevent surface abnormalities on the gear, such as microscopic concave-convex, scratches, and craquelure. This is heating the material at a certain temperature and quickly cooling it to increase its hardness. Furthermore, surface treatment methods like gear grinding can greatly increase fatigue resistance, guaranteeing a smoother and more durable surface against ageing damage over time [26]**.**

- **Solution 3:** Comprehensive inspections are part of preventive processes to identify and avoid gears with tiny veins, crazing, scratches, and rough surfaces. This ensures the prompt detection of any issues that may cause long-term ageing damage. Another workable option is to replace the gear material with high-rigidity rolled steel, such as the SNCM series of JIS, which increases durability and reduces the possibility of fatigue failure [26]

2.12 Heat Treatments for Gears

Heat treatment is a process that controls the heating and cooling of a material, performed to obtain required structural properties of metal materials. Heating methods include normalizing, annealing quenching, tempering, and surface hardening. Heat treatment is performed to enhance the properties of the steel. as the hardness increases by applying successive heat treatments, the gear strength increases along with it; the tooth surface strength also increases drastically [23][30].

1. Quenching

Quenching is a steel treatment involving rapid cooling after heating at high temperatures (approximately 800°C). It is employed to adjust steel hardness and can be of various types, including oil quenching, water quenching, and spray quenching. After quenching, tempering is necessary to restore toughness to the steel, which may become brittle. While quenching cannot harden genuine steel, it is effective for steel with more than 0.35% carbon content [30].

2. Thermal Refining

Thermal Refining is a heat treatment to adjust the hardness, strength, and toughness of steel. This process involves quenching and tempering. Since machining is applied to products after thermal refining, it's crucial not to raise the hardness too high during quenching [30].

4. Induction Hardening

Induction Hardening is applied to harden the surface of steel with carbon content exceeding 0.35%, such as S45C or SCM440. While effective for hardening tooth areas in gears, precision may decline, requiring subsequent grinding for gear accuracy [30].

4. Carburizing

Carburizing is a heat treatment performed to harden only the surface of low-carbon steel. The precision of carburized gears may decline due to deformation or distortion, necessitating grinding for improved gear accuracy [30].

5. Nitriding

Nitriding is a heat treatment that hardens the surface by introducing nitrogen into steel. Particularly effective for steel alloys containing aluminum, chrome, and molybdenum, it enhances hardness. Nitriding is often performed in the final step of processing gears, offering high hardness without causing deformation or quenching cracks [30].

Heat Treatment	Carbon (C) %											
	0		0.1		0.2		0.3		0.4		0.5	
Carburizing				■	■	■						
Induction Hardening							■	■	■	■	■	■
Flame Hardening							■	■	■	■	■	■
Nitriding						■	■	■	■	■	■	■
Total Quenching										■	■	■

Table (2.11.a): Heat treatment & Percentage of Carbon content relation in Steel [30].

CHAPTER 3
REVIEW OF LITERATURE

In the rapidly evolving landscape of the Indian market, the significance of cycloidal gearboxes emerges as a pivotal theme, elucidated through a comprehensive exploration of diverse research papers. These papers span a range of topics, from innovative design approaches to fault diagnosis, load distribution analysis, and condition-based monitoring, collectively shaping the narrative of the role and potential advancements of cycloidal gear mechanisms in India.

Looking back to 1989, the cycloidal speed reducer, often referred to as a cycloid drive, becomes the focal point of a paper highlighting its remarkable efficiency and compact size. This design, characterized by an epicyclic gear train with a planet gear profile shaped like an epitrochoid, addresses the challenges of backlash and torque ripple. The analytical model presented incorporates machining tolerances to simulate real-world conditions, shedding light on the impact of manufacturing imperfections. The cycloidal drive's theoretical dimensions strive to eliminate both backlash and torque ripple, acknowledging the practical inevitability of machining tolerances. This paper serves as a foundational piece in understanding the complexities and trade-offs inherent in cycloidal gear mechanisms [1].

In 2004 a paper is introduced in China in which a patented innovation, the double crank ring-plate-type cycloid drive, which distinguishes itself by eliminating the need for an output unit and removing size limitations on the tumbler bearing. Unlike conventional planetary cycloid drives, this novel design surpasses them in terms of torque transfer capacity. The newly devised double crank ring-plate cycloid drive retains the standard benefits of planetary pin-cycloid drives. The paper delves into its operational principles, advantages, and design considerations, presenting promising outcomes from prototype testing. The double crank ring-plate-type cycloid drive proposed in this study features a simplified output shaft structure, enhanced stiffness, and a larger bearing size compared to traditional cycloidal drives. It maintains the favorable attributes of traditional cycloid drives, including a wide speed ratio range, compact structure, small volume, light weight, high transmission efficiency, and transmission stability. The inaugural double crank ring-plate-type cycloid reducer has been successfully developed and tested, demonstrating twice the load capacity of existing high-performance cycloid planetary drives with an equivalent pin roller center circle radius. Particularly suited for low-speed and heavy-load applications, this new double crank cycloid drive offers significant advantages. Furthermore, the double crank ring-plate-type cycloid reducer has been officially submitted to the patent office of China, and it has received approval [31].

Fast-forwarding to 2011, the exploration commences with a groundbreaking paper that introduces a novel design for a two-stage cycloidal speed reducer. Departing from conventional approaches, this design features only one cycloid disc per stage, resulting in a more compact structure with balanced load distribution and dynamic equilibrium. The use of finite element method (FEM) for stress state analysis underlines the paper's commitment to ensuring the functionality of the reducer even under demanding conditions. The findings pave the way for enhanced efficiency and durability, addressing critical aspects of cycloidal gearbox performance [2].

Research on the reconfiguration of the cycloidal drive for novel uses in devices for intelligent construction yards is being conducted as we go forward into 2013. the materials and standards needed for applications in construction yards. Due to limitations in the suggested applications and new materials, a unique selection of a Wolfrom cycloidal speed reducer is made, introducing an optimum topology for polymer production in industrial settings. The research's implications go beyond its particular use, demonstrating the ability of polymeric materials to build dependable transmissions in challenging industrial settings. [8].

In the year 2013, the exploration of cycloidal drives extends to an analysis of their efficiency, emphasizing the influence of design parameters. This paper investigates the relationship between design parameters and the efficiency of cyclo drives, emphasizing the impact of the number of housing rollers, the number of output mechanism rollers, the pitch radius of housing rollers, and the pitch radius of output mechanism rollers. The study contributes to a nuanced understanding of the interplay between design and efficiency, recognizing the role of friction, wear, and kinematic parameters in shaping the efficiency of cycloidal gear mechanisms [7].

Moving forward to 2014, the exploration of cycloidal gear mechanisms extends to the realms of stiffness, friction, and kinematic error in the Gear Bearing Drive (GBD), as elucidated in a paper. This innovative transmission system, inspired by NASA's advancements, exhibits a high gear ratio within a compact assembly, challenging traditional precision drive systems like harmonic drives. The GBD's potential for improved stiffness characteristics and a more predictable output speed response sets it apart from conventional counterparts. The comprehensive understanding of the GBD's experimental setup, characterization, and dynamic modeling contribute to a deeper insight into its behavior and performance under varying conditions [5].

In 2016, the exploration concludes with a study that investigates the dynamic characteristics and load-sharing behavior of planetary cycloidal gears. The research employs finite element analysis to delve into the influence of design parameters on dynamic characteristics, load-sharing behavior, and tooth contact patterns. The findings offer valuable insights into optimizing the design of planetary cycloidal gears for enhanced load-sharing capabilities, mitigating the risk of premature failure and ensuring a robust performance across diverse applications [10].

Moving forward to 2017, a team of researchers delves into the realm of space robotics, unveiling a compact high-torque robotic actuator designed for space mechanisms. The conventional approach of using off-the-shelf actuators and multi-stage transmissions is challenged by the introduction of a novel robotic hardware. This hardware consolidates the robot's joint drive system into a single compact device, optimized for size and maximum torque density. The research showcases the potential to yield shorter assemblies with significantly fewer parts while maintaining high torque output. The implications extend beyond the realm of space robotics, hinting at profound implications for other industries such as powered prosthetics and rehabilitation equipment [9].

Published in 2020, this paper presents an innovative approach to modifying the tooth profile of a cycloidal gear, considering crucial factors like pressure angle distribution, meshing backlash, and tooth tip and root clearance. The proposed method involves applying the modification value along the normal direction of the theoretical profile, aligning it with the force transmission direction. Through the utilization of various modification piece-wise functions and a comprehensive understanding of the mathematical relationship between modifications and pressure angle distribution, this approach provides flexibility in controlling the changing trend of the cycloidal profile. It facilitates the pre-control of transmission performance for the cycloid-pin gear, addressing issues inherent in traditional modification designs, such as uncontrollable tooth profile shapes and unstable meshing accuracy post-modification. The resulting modified cycloidal-pin gear pair demonstrates favorable meshing contact characteristics and enhanced force transmission performance. This method emerges as a promising avenue for designing modifications in precision reducer cycloidal gears, especially in the context of robotic applications [32].

The year 2020 sees a study emerge with a focus on elastic transmission error compensation in rotary vector speed reducers. This research proposes a method to enhance transmission accuracy through tooth surface modifications in cycloidal gears. The utilization of error sensitivity analysis and simulation results indicating a substantial reduction in transmission error underscore the paper's contribution to refining the precision of cycloidal gear mechanisms. The intersection of theoretical analysis and experimental validation enhances the credibility of the proposed elastic transmission error compensation method, positioning it as a potential game-changer in the realm of speed reducers [15].

In 2021, a study is dedicated to unraveling the impacts of a profile failure of the cycloidal drive of a planetary gear on transmission gear. The utilization of cycloidal drives has witnessed a surge due to their advantageous characteristics, such as large transmission capacity, efficiency, and high performance density. However, achieving production accuracy becomes imperative to guarantee dynamic, proper, and smooth operation. This research explores acceptable levels of production accuracy for small-scale and individually manufactured drives. The analytical equations formulated in this research serve as valuable tools for engineers, aiding them in determining appropriate tolerances for a given gear ratio fluctuation [12].

As the gears of progress turn, a 2022 research endeavor takes a stride towards advancing the field of robotics with a specific focus on gearboxes. Unlike previous studies that primarily assessed overall health during operation, this investigation delves into defect detection in a robotic gearbox. Vibrations signals under cyclostationary and non-cyclostationary conditions are scrutinized to identify damaged elements within gearbox components. The methodology involves an in-depth examination of the robotic gearbox, employing domain knowledge and an innovative data-driven approach. The study not only identifies artificially induced defects but also introduces a novel resampling method called Binning, showcasing strides towards automated predictive maintenance for robots in industrial applications [16].

In 2022, the exploration into cycloidal gear mechanisms ventures into the intricacies of load distribution analysis in mismatched cycloid-pin gear pairs. This study addresses the limitations of existing tooth contact analysis methods by introducing an enhanced load distribution model that accounts for deviations arising from manufacturing errors and elastic deformations. The parametric case studies and analysis of the impact of ring pin position deviations offer valuable insights into the distributed load, contact stress, loaded transmission error, and instantaneous gear ratio of the mismatched cycloid-pin gear pair. This nuanced understanding contributes to the refinement of gear design principles, aligning with the broader goal of advancing cycloidal gear technology [17].

In 2023, the trajectory of cycloidal gear research extends, with a focus on the dynamic characteristics of bearing reducers of the TwinSpin class during the startup phase and initial operating hours. The study investigates the impact of varying loads on the dynamic characteristics and wear of TwinSpin reducers, shedding light on the transient response during the startup phase and the subsequent operating hours. The comprehensive analysis encompasses the bearing contact pressure, contact deformation, and frictional work during the startup phase, offering valuable insights into the initial performance of TwinSpin class reducers under different load scenarios [18].

CHAPTER 4
CONCLUSION

In conclusion, the comprehensive literature survey conducted on cycloidal gearboxes highlights their significant potential and relevance in the Indian market, particularly within the context of cost-effective manufacturing strategies to compete with imported counterparts. The distinctive design and operational advantages of cycloidal gear mechanisms, such as high reduction ratios, minimal backlash, increased load capacity, and space efficiency, position them as promising solutions for India's cost-conscious manufacturing and burgeoning robotics sectors.

This conclusion is further enriched by the incorporation of critical aspects related to the heat treatment of gears and the exploration of gear materials, which are integral elements in enhancing the overall performance and durability of gear systems. The literature review has not only emphasized the evolution of cycloidal gear technology but has also identified key areas for improvement and innovation, particularly in the modification of gear materials and precision machining techniques. The focus on redesigning the cycloidal disc with new materials and alternative shapes signifies a strategic move towards enhancing the cost-effectiveness and performance of these gearboxes.

A crucial aspect addressed in the literature is the need for locally manufactured alternatives to challenge the dominance of established international products. By acknowledging the challenges posed by prominent companies, the project aims to introduce not only cost-effective but also high-quality, locally manufactured alternatives. The conclusion envisions overcoming market dynamics by making cycloidal gearboxes more affordable and accessible for widespread use in Indian industries.

The study recognizes the dominance of large companies in the current market due to advanced technology and precise manufacturing capabilities. However, the project's goal is to challenge this dominance by introducing locally made, cost-effective alternatives. The potential impact of this endeavor extends beyond addressing current market dynamics, aiming to usher in a new era where locally manufactured cycloidal gear mechanisms become integral components in the manufacturing and robotics landscape of India. This comprehensive exploration sets the stage for the project's objective of bringing innovation to cycloidal gearboxes, aligning with the nation's industrial growth and innovation aspirations.

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