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A Review of Local Manufacturing of Borehole Windmill Gear Trains Using Reverse Engineering and Integrated Braking Systems

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Abstract
Many local windmill water pumping systems can suffer maintenance and repairs due to a lack of readily available indigenous spare parts and a dearth of appropriate repair tools and equipment, thereby degrading system performance, efficiency and longevity and sustainability. This suggests the development of localizable solutions. This review aims to evaluate the application of reverse engineering technology in facilitating the manufacturing of wind-mill gear trains designed for local environmental conditions and to identify gaps in knowledge in the literature in the application of reverse engineering for local manufacturing of windmill gear trains. A systematic literature review was conducted, which encompassed several related fields such as reverse engineering, wind energy systems, windmill gearbox systems, gear mechanisms, braking systems, modern manufacturing techniques, and computer-based tools such as CAM, CAD, CAE, CAM and simulation software. These individual areas are combined to offer a complete view of their use in the development of wind mill gear trains. This study concludes that the application of modern manufacturing techniques with the use of reverse engineering concepts can offer an efficient method of replica and further improve the windmill gear mechanisms for remote location use. Furthermore, the literature has identified the gaps and potential of reverse applications for application with specific local conditions. The systematic review and analysis contribute by proposing an application strategy of reverse engineering for local manufacturing of wind-mill gear pumping or water pumping applications, which can significantly improve their performance, reliability and longevity, and provide locally viable solutions. Hence a method for the indigenous production of windmill gear trains for water pumping systems, to improve performance, reliability and maintainability of windmill systems is proposed, for more efficient and sustainable utilization. It is also hoped to increase the system life by using cost-effective and sustainable local solutions, which will improve rural water supply development.

Keywords: *Reverse engineering, windmill gear trains, water pumping applications, for local manufacturing, braking systems.*

1.0 Introduction
Access to reliable water supply is a major constraint in the lives of many rural and semi-arid communities, especially in developing countries where access to electricity and conventional pumping systems may be expensive and limited. Wind-powered water pumping systems are continually gaining interest as a reliable, affordable, and sustainable option for pumping borehole water, especially in off-grid rural water supply and irrigation, because they are environmentally friendly and can be easily run with very little maintenance cost. Several studies have shown that, for areas with sufficient wind resources, windmill-powered water pumps can serve domestic needs, irrigate crops, and water livestock. However, efficient operation of the windmill depends on the reliability of mechanical systems like the gear train, which is the main link that transmits power from the wind rotor to the pump mechanism. Windmill gear system maintenance is always a problem in rural areas because wear and tear of components, scarcity of spare parts, and lack of original design data are the common features in rural windmill systems. Often, only components imported from abroad are usable, which causes prolonged delays and increased maintenance costs, thus reducing the sustainability of the windmill system. This issue has attracted many local manufacturers towards manufacturing components using local materials and technology. Reverse engineering is one such technology that has shown significant promise in recovering the design of any component, even when there is no original design specification available. Methods like geometrical reconstruction, element detection, measurement, CAD/CAE tools, etc. are employed in reverse engineering processes and can reconstruct the component designs, which can further be manufactured and improved using the available resources and technology. Many researchers have applied reverse engineering for the redesign of gears and mechanical drive systems; however, specific literature on reverse engineering for borehole windmill gear train manufacturing with locally available materials is rather scant. Operational safety of windmill systems is another significant issue in these rural setups. Mechanical failure might result when the gear system is subjected to high rotational speeds and torque because of over speed due to high winds. Brake systems have been recognized as the important safety

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mechanism for avoiding over speed and mechanical overload, reducing damage to gears and other transmission parts of a windmill. However, studies related to brake systems used in small-scale borehole windmill systems have not been focused on in literature as much as those concerning large-scale wind turbines and also the local manufacture of the brake system itself. Current technological trends and facilities like computer-aided design and computer-aided engineering (CAD/CAE), finite element analysis (FEA), and advanced manufacturing technology (AMT) may greatly contribute towards an improved design and higher performance efficiency of a locally manufactured gear system. CAD/CAE may be employed for the detailed design, stress analysis, and performance simulation of gears. FEA provides a virtual testing environment to evaluate the design before any component is actually manufactured. However, to date, limited works could be identified that combine local manufacturing and reverse engineering of the gear train and braking systems using integrated CAD/CAE tools for borehole windmill systems. In the light of the above, this paper reviewed literature and developments in local manufacture of borehole windmill gear trains by applying reverse engineering principles, incorporating integrated brake systems, and utilizing CAD/CAE. The review has covered wind-powered water pumping systems, gear train design, reverse engineering techniques, braking system requirements, manufacturing technologies, and usage of CAD/CAE. Existing gaps were also highlighted to provide direction for future development of locally manufactured windmill systems.

2.0 Reverse Engineering in Mechanical Product Development

It can be concluded that reverse engineering has become a vital and fundamental tool in mechanical product development, especially in mechanical systems where design data are lost, obsolete, or not available. Instead of only focusing on merely replication of existing products, it has emerged as an engineering technique that serves various purposes, like re-design of products, performance enhancement of products, maintenance of parts, and localized manufacturing of products. In rural engineering, particularly with imported mechanical parts that can't be easily replaced, it is crucial as a methodology that offers a way of sustaining mechanical systems, especially a windmill gear train. The use of reverse engineering to extract geometric, material, and functional characteristics of existing components represents one prevalent theme within the literature of reverse engineering [1] His research colleagues illustrated that product design parameters could be obtained from an existing product even in the absence of original drawings, thereby leading to redesign and replication of components. This feature of reverse engineering has relevance in windmill gear mechanisms because failure and subsequent lack of the manufacturer's drawing and design parameters of gear teeth in rural windmills used in water pumping applications necessitate reverse engineering to facilitate replacement and repairs. Another recurring theme is the integration of reverse engineering with different digital manufacturing technologies like CAD modeling, rapid prototyping, laser scanning, and coordinate measuring machines. This integration, according to [2] enhances the dimensional accuracy of the components and reduces the time for producing the components to a great extent. This approach of linking reverse engineering with digital manufacturing tools could be applicable to rural windmill gear systems in creating accurate 3D models of gears, shafts, and transmissions that can be readily analyzed, modified, and reproduced using local technology. Reverse engineering is also being developed as an improvement tool in addition to just duplication. Research has revealed the potential to improve the designs of systems rather than simply mimicking existing designs [3]. That is, to identify weaknesses in an existing product and, thereby, produce an improved design alternative. This aspect of reverse engineering is a major component in windmill gear systems because reverse engineering will not just focus on replicating the worn-out gears but also help in developing better designs of tooth forms, optimal material composition, reduction in gear wear, and possibly include other components that can enhance system efficiency and protective braking mechanisms for safe operation under fluctuating wind speed conditions. A recurring theme in literature reviews concerning reverse engineering is its role in making product manufacturing less reliant on the original equipment manufacturer (OEM) [4] In rural areas, particularly developing countries where expensive parts from overseas may not be accessible, this factor promotes local production of components and builds local capacity for repair, which strengthens overall sustainability. In the case of windmill-driven water-pumping systems, this is particularly applicable to community-based production of windmill components. There is still an apparent deficiency in applying reverse engineering to renewable energy transmission systems, especially in the development of the rural windmill gear trains, as most of the literature available in the area deals with standard industrial parts, automotive products, and tooling systems. The unique functional requirements of a windmill water-pumping system (low-speed torque, variable wind load, ruggedness in rural applications, incorporation of braking systems) have only been superficially examined in comparison to other systems. The present work thus tries to contribute by applying reverse engineering to develop a rural borehole windmill gear system.

3.0 Wind Energy Systems and Small-Scale Mechanical Windmill Technology

For hundreds of years, wind energy has been utilized for a variety of applications besides the generation of electricity, such as pumping water where mechanical wind energy is employed by rural and off-grid locations. In the scope of this study, emphasis is placed on a small mechanical windmill that uses wind energy for a variety of operations (e.g., pumping water), where wind energy is converted into rotational energy, which through a gear train mechanism is used to drive a water pump. The gear train within this type of system plays a vital role, since it transmits mechanical energy from the rotor to the water pump and has an impact on the overall windmill's efficiency and reliability. .In general, one theme that recurs in the literature is the fact that the extraction of wind power must occur through the transmission of mechanical power. [5] discussed the Betz limit, which establishes the maximum power that can be captured from wind, providing theoretical evidence when analyzing windmill performance. The performance of a windmill, however, is determined not by how much energy is harvested by the rotor but by how efficiently the mechanical power transmission system transmits the harvested energy. [6] stresses that rotor design, aerodynamic performance, and power transmission system effectiveness influence turbine performance. When it comes to windmills used for pumping water, the gear train becomes critical as it couples the slow-speed, high-torque wind rotor to the required motion that drives the water pump. Another factor that repeats throughout the literature is the interrelation of windmill components for a reliable performance. Studies carried out on components like the rotor, drive train, gearbox, and output mechanism show the importance of proper coordination of windmill parts to attain success. [7] listed the gearbox as an indispensable part for speed regulation and torque transmission between the rotor and the driven equipment. In the case of small wind turbines for pumping water, the gear ratio used, the torque transferred, and efficiency are key elements for effective water pumping under varying wind speeds. The literature has also emphasized the advantages of small wind energy for rural and off-grid areas. In [8] listed that the development of decentralized renewable energy resources, including small wind turbine systems, can enhance access to water and can promote agricultural productivity for the rural communities. Mechanical windmills seem to be most advantageous in those remote locations where electrical supply is either absent or unstable, as direct pumping is obtained without the necessity of electric power generation. The gear transmission in the long run is what needs to be reliable and effective even under different wind conditions and constant wear. Another key subject mentioned by previous studies is the need to develop windmill designs based on specific working conditions. [9] demonstrated that different designs of wind turbine configurations can be developed based on the required characteristics. This also applies for small mechanical windmills for water pumping, and the choice of gear trains is of great importance depending on the conditions: speed of the rotor, working load, and application as well as gear tooth dimensions, distribution of stress across the gear teeth, and existence of braking devices. These studies contribute valuable information in general terms of wind energy and windmill technology; nevertheless, there are not enough studies pertaining to gear trains in small mechanical windmills for pumping water compared to those on aerodynamics and electricity generation wind turbines; the use of reverse engineering on used parts, gear train design optimization for water pumping, or integration of braking devices has not yet been sufficiently investigated. The absence of this research is the reason behind this study, which is geared towards designing and manufacturing a gear mechanism for rural borehole windmills based on reverse engineering.

4.0 Wind Turbine Gearboxes and Gear Train System

The function of a gearbox in a wind energy system is to transfer mechanical energy from the rotor to the driven element. While a good number of literature addresses the issues associated with electric generating wind turbine gearboxes, many principles of such studies can be of use in designing and manufacturing, at local levels, gear trains for rural water pumping applications. This involves the problems associated with variable loads, choice of material, and failure analysis. Load variations and their effect on gearbox failure have been investigated by several researchers. [10] indicate that premature bearing failure in wind turbine gearboxes is caused by such factors, among others, as mechanical overloads, lack of lubrication, and manufacturing error. The same is true of water pumping windmills operated in rural environments, as the variation of wind intensity can induce variable torques and consequently cyclic stresses on the gears. This would then lead to wear, bending fatigue, and ultimately failure if this variation is not taken into account during the design stage of the gear.. [11] shows how dynamic torque imposed by varying wind speeds affects the drivetrain. For locally manufactured gears, this may call for a design capable of resisting shocks and dynamic stresses commonly experienced. Material performance is another domain that seems to hold some insights into water pumping gear design, as [12] state that durability depends on correct material choice. This suggests that for locally manufactured gears, the chosen material must offer a compromise between performance, availability, machinability, and cost. It should provide an acceptable level of wear and bending resistance at reasonable operating loads encountered by a water-pumping windmill, and it should be machined at a local facility at minimal costs. For example, the decision to use low-carbon steel is justifiable because it is easily available and easy to machine while still providing moderate stress resistance suitable for water pumping applications. It is also cheap, especially, compared to some of the materials for wind power applications. Lastly, lessons derived from failures of electric-generating windmill gearboxes are applicable to rural windmills. The influence of gear geometry and dynamic loads on the performance and reliability of gearboxes has been shown by [13] The Former highlights the need for dynamics analysis and the latter shows effect of gear form and load distribution on gearbox fatigue and efficiency. Lessons are useful to water pumping gear trains where failure of gear tooth via wear and pitting and fatigue cracking is primary problem, which is avoidable with the correct geometry of gear and load sharing between gears with sensible design. In one word while research was done for electric generating windmills, lessons of load variability, good material performance and sources of failure can be applied to the water pumping windmills and these be incorporated into design considerations in local manufacturing of windmill gears by back-extracting of gears or from those similar.

5.0 Gear Design Principles

Gear systems are key components of mechanical power transmission systems and play an important role in wind-powered water pumping systems. Their primary function is to transmit power from the wind rotor to the pump assembly and control the speed, torque, and motion so as to perform work efficiently. Basic principles like gear ratio, torque transmission, and mechanical efficiency are the foundations of the gear trains' design and performance evaluation [14]. These principles are very significant in wind-powered water pumping because of the fact that wind speeds are highly variable, requiring the gear train to translate variable rotational input to controlled and useful mechanical output. The advances in gear system design are tremendous and have improved the efficiency and reliability of transmission systems. Such factors as the gear geometry, tooth profile, selection of materials, and manufacturing methods are responsible for improvements of gear systems [15]. In reverse engineering, which is the topic focused on in this research (because in this project an existing component will be reverse engineered and reproduced as it is not available with its manufacturing documentation or a replacement), these issues are quite relevant. Based on an understanding of the established procedures for the design of gear teeth, including their geometry and contact behavior, the design and evaluation of gears under loads is carried out [16]. The behavior of gears at high speeds or under heavy loads causes a number of considerations important in the design of windmill gears, as the transmitted loads are cyclical, varying with wind speed and direction. The objective here is to examine how to produce a working gear system with good transmission and strength, as well as how to analyze, determine, and then produce the appropriate geometry to ensure good contact with minimal wear and efficient power transfer. The transmission of motion should be smooth. The proper meshing and alignment between the gears leads to minimized vibration, fewer energy losses, and a more stable performance [17]. This feature is important, as in the windmills, any inefficiency in transmission and bad gear meshing can decrease the power transferred from the wind rotor to the pump and cause greater wear as less maintenance might be provided. Deformation of the gear tooth under load still causes a lot of concern regarding the gear's performance. The research in spur gear tooth deformation has revealed that the tooth deflection may not only decrease efficiency but can also lead to an error in the gear meshing and, consequently, to damage [18]. These results are very useful for the windmill gear train since it experiences varying and cyclical loading caused by varying wind speeds. The issue of stresses on gears and the material of their teeth will be a concern in the production phase when the teeth are produced from a relatively local and low-cost material such as low-carbon steel, and that is another issue the researcher will consider in the design of the gear train through the proper application of the standard analysis and design of gear teeth. Depending on the magnitude of reduction and torque needed in the particular windmill gear train, the arrangement of gears will be either a simple or compound gear train However, this choice must be adapted to the requirements and constraints for a specific windmill, taking into account aspects such as manufacturability, ease of maintenance, cost, and simplicity. The studies mentioned have provided a good general understanding of the gears and gear trains' design; nevertheless, the conventional, industrial type of gear trains is mostly the subject of the studies. The characteristics of a windmill gear train for rural water pumping like variable wind speed input, the necessity of reverse engineering and adaptation for local production of components, and the integration of additional functions like braking) are less covered. Hence, the research aims to fill this gap by integrating the existing gear design methods with reverse engineering processes to produce a reliable windmill gear train suitable for rural application.

6.0 Braking Systems in Wind Turbines

Braking systems serve an important role as safety and control devices for wind energy conversion systems, controlling over speed, mechanical overload, and structural damage during periods of high winds. In general wind turbines, braking systems are primarily used to control the rotor speed within limits, protecting the gearbox and other downstream mechanics from severe loads. For windmills powering water pumps, a precise and accurate braking system becomes even more critical as speed variations can affect the pump output and life of the machine and lead to inconsistent water delivery in rural applications. Current sophisticated mechatronic approaches are often utilized to improve braking responsiveness and accuracy in mechanical systems [19], but due to complexity, these high-performance, electronically actuated braking systems may not be suitable or affordable for rural water pumps or the gap that exists to provide the needed simple, reliable, and locally repairable mechanical braking system for reverse-engineered windmill gear trains in water pumping applications. While condition monitoring methods for braking systems are being developed to allow early fault detection and to prevent critical failures for large wind turbines [20], such an approach is often not viable for windmills in remote applications due to the lack of appropriate sensors, diagnostic equipment, and technical experts, thereby emphasizing the need for mechanical solutions in this application. Optimization of materials for increased surface wear properties of brake discs for improved braking performance in high-performance braking systems, such as those for industrial machines or large wind turbines, may not be economically viable for small water pumping systems, thereby requiring a different material selection strategy and design emphasis on the braking system to be readily fabricated, maintained, and repaired by local technicians. The reviewed studies are indeed contributing significantly towards more sophisticated braking system technologies; however, they mostly deal with the context of industrial-level wind energy generation rather than with the specificity of small wind turbines for rural water pumping, where conditions are less controlled, maintenance is challenging, and affordability is the key design consideration. In particular, little has been documented about how braking systems are integrated within reverse-engineered windmill gear trains for rural water pumping applications. Considering this context, a braking system should be understood not as an independent industrial component but rather as a part of an integrated safety system within a reverse-engineered windmill gear train. [21].

7.0 Gear Manufacturing Technologies

Several processes affect the gear's quality and durability. [22] studied the effect of laser cutting on the accuracy of spur gear cutting. [23] suggested an optimization approach for the power skiving of spur face gears and established that the precision can be upgraded by enhancing the gear-cutting procedure. and future [24] studied the process of gear grinding to improve the precision of the gear. [25] discussed the gear cutting tools and the existing process of gear manufacturing. [26] studied the technological process of gear manufacturing, which highlights the importance of inspection to improve the quality. Though the process of gear manufacturing has improved the precision of the gear, the tools used may not be readily available in rural areas.

8.0 Computer-Aided Design and Engineering

Computer-aided engineering has led a revolution on mechanical design approach. In their study in 2025, [27] and colleagues employed ANSYS simulations to investigate how stresses are distributed within meshing gear teeth. In the same year, [28] sought to evaluate the possibility of the application of three-dimensional computer-aided design technology in machine design, citing the improved precision as a significant advantage. [29] developed a knowledge-driven parametric CAD system to design spur gear mechanisms, where the gear parts could be directly created from parameters. Thereafter, Khan et al. discussed the role of computer-aided engineering in the Fourth Industrial Revolution, which includes the integration of CAE with CAD/CAM technologies. These CAE tools can significantly simplify the design of the windmill gear.

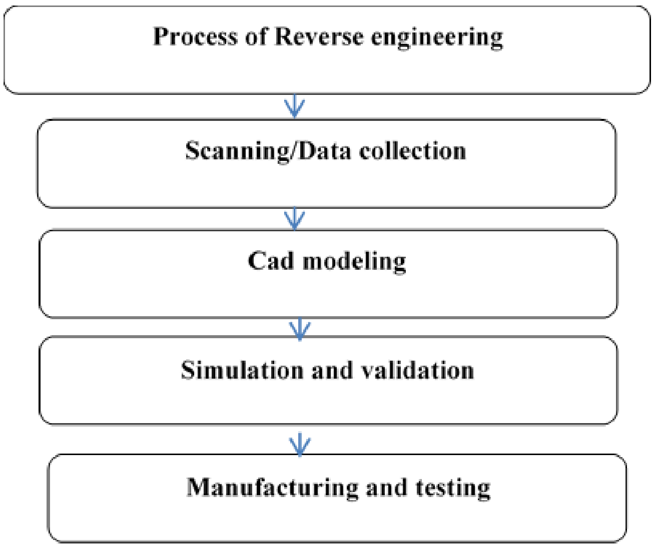

Figure 1: Process of reverse engineering

Reverse engineering (RE) is an accepted method for rebuilding and upgrading previously made mechanical parts, as evidenced in Figure1. The RE process typically starts with data collection or scanning (i.e., the physical dimensions of a part collected using measuring or digitization processes such as laser scanning and coordinate measuring technology), which provides highly precise dimensions of the part [30].After this process, CAD modeling will begin with the development of a digital model or representation of the part, which is utilized to modify the design, optimize it, and incorporate functional aspects into the design [31].The third component of

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the RE process is simulating and validating the design. At this point, engineers will utilize various analytical and numerical methods to evaluate critical performance characteristics of the part, including stress distribution, deformation of the part, and load capacity. This step in the entire RE process is crucial for validating the integrity of the design and preventing potential failure before there is any physical production of the [32]. Finally, the RE process is completed when the validated design is manufactured and tested [1]. [2]. Once the design has been manufactured, it is tested under actual conditions to ascertain its ability to function as designed or not. Collectively, all of the above is part of an integrated RE framework used to accurately reproduce a product.

9.0 Research Gap

From the reviewed literature, some important gaps were identified. First and foremost, while reverse engineering has been widely used in various industrial manufacturing processes, only a few studies have focused on its use in the reproduction and redesign of windmill gear trains for use in rural water-pumping schemes. Secondly, the majority of the reviewed literature on wind energy focused on the use of large-scale mechanical wind turbines designed for electricity generation, as opposed to small mechanical windmills used for other purposes in rural regions. Thirdly, while a great deal of theoretical work on gear train design and analysis has been carried out in the field of mechanical engineering, few studies have focused on the use of such principles in the design and analysis of windmill gear trains for use in borehole water-pumping schemes. Finally, few studies have integrated reverse engineering concepts, gear train design and analysis concepts, braking concepts, and manufacturing concepts within a framework. Renewable energy (RE), therefore, is vital in the local production of the gear train of the windmill, which can offer a sustainable solution to the water-pumping needs of the rural areas. Literature has proven the potential of the application of RE to the performance, replication of legacy systems, and integration with CAD/CAM and simulation tools. However, there is a significant research gap identified in the local production of the gear systems of RE, especially with regard to the integration of the braking systems.

10.0 Recommendation

In order to encourage the adoption of sustainable and cost-effective water pumping systems, the present study recommends that windmill gear trains should be locally produced through the application of reverse engineering (RE). The application of RE in the development of wind-powered water pumping systems is likely to minimize the importation of foreign gear trains while considering the environmental factors in the host community. There is also a need to develop and validate braking systems for small windmills. The experimental validation of the locally produced gear trains is crucial in assessing their performance and sustainability. Finally, there is a need to develop the capacity of local engineers and technicians in the application of RE and modern manufacturing techniques in support of sustainable development and long-term viability of wind energy in the host community.

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