APPLICATION OF REVERSE ENGINEERING IN MANUFACTURING A PROTOTYPE MECHANICAL WATER-PUMPING WINDMILL ROTOR

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الملخص

تركز هذه الدراسة (البحث) على تطبيق عملية الهندسة العكسية (RE) في تصميم، وتصنيع، وتركيب، واختبار النموذج الأولي لدوار الطاحونة الهوائية الميكانيكية التي تعمل بضخ المياه. يعتمد تصميم الدوار المختار على نموذج تجاري يبلغ قطره 4.88 متراً (16 قدمًا) وارتفاع البرج 12 متراً. تتضمن عملية الهندسة العكسية ثلاث خطوات رئيسية: رقمنة المكون ومعالجة البيانات المقاسة وإنشاء نموذج التصميم بمساعدة الحاسوب (CAD). يتم استخدام برنامج تطبيق تفاعلي ثلاثي الأبعاد بمساعدة الحاسب (CATIA V5) لتحليل الانحراف، والذي يتحقق من صحة النماذج ثلاثية الأبعاد للدوار من خلال مقارنتها بالبيانات الأصلية الممسوحة ضوئيًا. تعمل النماذج التي تم التحقق من صحتها كأساس لإنشاء نموذج تجميع ثلاثي الأبعاد نهائي، مما يضمن جدوى تجميع المكونات والموافقة على التصميم. كانت النماذج ثلاثية الأبعاد هي الأساس لتصنيع النموذج الأولي لأجزاء دوار الطاحونة الهوائية الذي تم تركيبه في موقع تجريبي في إحدى ضواحي تاجوراء، ليبيا. تم اختبار دوار الطاحونة الهوائية كجزء داخل نظام استخراج المياه الجوفية لنظام الطاحونة الهوائية من البئر بمتوسط سرعة رياح 2.7 متر/ثانية، مقاسة على ارتفاع 2 متر من الأرض. تم تقييم متوسط معدل تدفق المياه المقدر بنحو 1 لتر/10 ثوانٍ. خلال عملية التصميم والتطوير، تم استخدام برنامج كاتيا في (CATIA V5) كنظام متكامل، يجسر (يربط)، أنشطة الهندسة العكسية وأنشطة CAD. إن التنفيذ الناجح للهندسة العكسية في تصنيع دوار طاحونة هوائية لضخ المياه بنتائج واعدة هو في الواقع إنجاز جدير بالملاحظة، يمكن أن يكون له تأثيرات إيجابية كبيرة للحصول على المياه النظيفة والطاقة المتجددة في مناطق مختلفة من ليبيا، وخاصة في المناطق المعزولة عن شبكة الكهرباء.

ABSTRACT

This study (research) focuses on applying the reverse engineering (RE) process (approach) to design, manufacture, install, and test a mechanical water-pumping windmill rotor prototype. The selected rotor design is based on a commercial model with a height of 12 meters and a diameter of 4.88 meters. The reverse engineering process involves three key steps: digitizing the components (parts), evaluating the measured data, and generating the CAD (computer-aided design) model. CATIA (computer-aided three-dimensional interactive application) V5 is employed for deviation analysis, which validates the 3D models of the rotor by comparing them with the original scanned data. The validated models serve as the basis for creating a final 3D assembly model, ensuring the feasibility of component assembly and design approval. The 3D models, serving as the foundation for fabricating the prototype components of the rotor, were subsequently installed at a pilot location in a suburban area of Tajoura, Libya.

The windmill's rotor underwent testing as part of a groundwater extraction system, drawing water from a Well. The testing occurred under an average wind speed of 2.7 meters per second, measured at a height of 2 meters above the ground. The assessed average water flow rate was 1 liter every 10 seconds.

CATIA V5 is utilized as an integrated system throughout the design and development process, bridging reverse engineering and CAD activities. The successful

implementation of reverse engineering in manufacturing the water-pumping windmill rotor components with promising results is indeed a noteworthy achievement, which can significantly positively impact access to clean water and renewable energy in various regions of Libya, particularly in areas isolated from the electricity grid.

KEYWORDS: Windmill; Rotor; CATIA; Reverse Engineering; Point Cloud.

INTRODUCTION

Reverse engineering is an invaluable approach to creating a component or product, especially when critical technical information like blueprints, a bill of materials (BOM), or engineering data is inaccessible.

RE involves replicating an existing part without the original documentation or computer model while capturing its physical dimensions [1,2]. Nowadays, reverse engineering is widely spread in various manufacturing industries. RE can be described as "the approach that initiates the design process, wherein a product is predicted, observed, disassembled, analyzed, tested, and documented in terms of its functionality, form, physical principles, manufacturability, and assemblability" [3]. RE is a rigorous approach that enables designers to capture intents and integrate digital data from prior products into the lifecycle of a new product [4]. RE has emerged as a practical approach for generating a 3D virtual representation of an existing physical component, applicable for integration into various software applications such as 3D computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided engineering (CAE), and more [5].

The traditional mechanical windmill continues to be manufactured in industrialized countries like the USA, Argentina, Australia, South Africa, and many others [6,7]. The most essential element of the windmill is the rotor, often referred to as the "Rotor Rosette" due to its structural configuration. The windmill typically has a diameter ranging from 3m to 5m and can feature over 18 metal sheet sails. Hence, these windmills remain "modern" machines with hundreds of thousands of installations in these countries, all employing designs that have remained unchanged.

Numerous research studies have established the economic viability of utilizing mechanical windmills for water pumping. Badran [8] indicates that classical windmills are noteworthy for their cost-effectiveness, simplicity of design, and potential for local manufacturing in many third-world countries. Moreover, these systems significantly enhance social and economic development in remote areas, offering a more economical option than other alternative systems, such as conventional electric or diesel-powered pumps. In a study conducted by Elamouri, the potential of mechanical wind pumping was investigated at eight different synoptic locations in southern Tunisia. By analyzing meteorological data collected over five years, the research unveiled that the Southern part of the country possesses a promising wind resource, indicating its suitability for implementing mechanical wind pump systems [9]. In their study, Odesola and Adinoyi [10] developed and put into operation a water-pumping model using a rotor with a diameter of 2.14 meters. This model underwent testing in an area where the wind velocity was measured at 2.5 meters per second, with the windmill positioned at a height of 16 meters above the ground. The evaluation of the windmill's performance indicated that it could pump water for irrigation at a rate ranging from 3.4 to 6.44 liters per minute. It is important to emphasize that successful electricity generation from wind energy typically necessitates an average wind speed exceeding 2.5 meters per second. Furthermore, the time-tested reliability of the classical mechanical windmill water-pumping systems remains significant, particularly for extracting water from deep Wells [11].

The final ultimate objective of this study entails implementing the RE approach and methodology in the development, production, installation, and testing of a water-pumping windmill, as previously mentioned. The testing of a water-pumping windmill aims to validate the success of reverse engineering in manufacturing the rotor for extracting groundwater from a designated Well in the context of this research experiment. The outcomes of this system will contribute to future studies focused on improving cost and efficiency within extensive research aimed at manufacturing a complete model for water pumping in the state of Libya countryside (i.e., Tajoura) based on local manufacturing capabilities.

The selected components for RE in this study are considered crucial to the windmill. Digitization or scanning is vital to obtain the essential dimensional data for generating a design drawing or computer-aided (CAD) model. The degree of accuracy and tolerance needed for reverse engineering a part is frequently dictated by its criticality level. Thanks to advanced software, precise measurement instruments, and contemporary reverse engineering (RE) technologies, it has become possible to replicate mechanical parts with stringent tolerances and remarkable fidelity [2].

RESEARCH METHODOLOGY

The methodology involves applying the RE process to acquire a 3D CAD model of the rotor and manufacturing a prototype for water-pumping windmill rotor components, encompassing all the steps involved in the RE process of an existing mechanical windmill and manufacturing the prototype.

The steps involve (i) Employing the Baces3D portable laser scanning system to digitize the rotor parts and acquire dimensional data, (ii) Processing the collected data and generating the final surfaces by overlaying the point cloud with the mesh through various operations performed using CATIA's DSE (digitized shape editor), (iii) Formulating surface models of the scanned parts using CATIA's QSR (quick surface reconstruction) workbench; and, (iv) Constructing solid 3D models of the rotor parts via CATIA's part design workbench (PD) and assembling the rotor within the CATIA assembly design workbench, in addition to (i) Manufacturing the rotor components (using inexpensive galvanized ASTM-36 steel available in the Libyan market) and assembling the rotor, and (ii) Installing and testing the rotor on a tower of a height of 12m on the Well dedicated primarily for this research.

Several engineering applications, including structure analysis and airflow, can be carried out using CAE software. In contrast, CAM software can be employed to manufacture the dies (molds) of the parts or create prototypes. This paper only refers briefly to the manufacture of sail bending die using CAD/CAM as an example of applications of the three-dimensional models obtained from reverse engineering. In reference [12], an integrated practical illustration is presented, demonstrating the design of a bending die for shaping water-pumping windmill sails. This design process utilizes simulation programming and computer numerical control (CNC) machines, making full use of (CAD/CAM). Manufacturing for all remaining prototype components of the rotor is completed per the established working schedule and documented in reference [13].

By following this methodology, the study aims to comprehensively understand the reverse engineering process and successfully manufacture and test the rotor prototype for a water-pumping windmill.

WINDMILLS ROTOR COMPONENTS

In this research, significant focus was placed on implementing the adopted approach of reverse engineering for manufacturing the windmill rotor and its key components, the target for the application of RE, except for the Hub (Win008), which the Al-Enma for Engineering Industries Company (AEEI Company) provided. These components are:

- **Rotor or Wheel**: This component converts the power of the wind into rotary motion.
- **(Win 001) Outer and (Win 002) Inner Rotor Bands:** These metallic sheets form the outer and inner circles for securely attaching the sails.
- **(Win 003) Sail Ties**: The sail ties serve two functions: (i) Controlling the attack angle of the sails and (ii) Fixing the sails to the inner bands.
- **(Win 004) Sails or Blades**: **These components extract power from the wind by slowing it down, yet there exists a limit to** the maximum power achievable from the wind.
- **(Win 005) Sail Ribs**: These ribs are responsible for attaching the sails onto the outer bands, which will help maintain the desired attack angle.
- **(Win 006) Cross Ties**: These ties are attached to the rotor arms to fasten the inner bands to these arms.
- **(Win 007) Rotor Arms**: These rods with a circular cross-section play a crucial role in attaching (fixing) the sections of the sails on the hub. The rotor assembly is connected to the hub assembly by these long arms.

  Table (1) describes the rotor's main components, as shown in Figure (1). These are the targeted components for applying reverse engineering and manufacturing.

Table 1: Rotor components description and number (No).

Component No.	Description	Component No.	Description
Win 001	Outer Rotor Bands	Win 005	Sail Ribs
Win 002	Inner Rotor Bands	Win 006	Cross Ties
Win 003	Sail Ties	Win 007	Rotor Arms
Win 004	Sails (Blades)	Win 008	The Hub

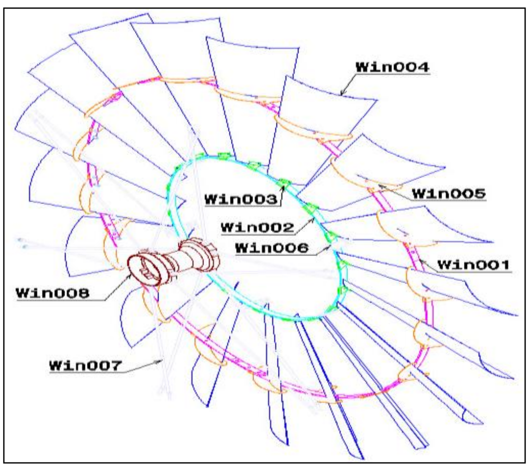

Figure 1: The mechanical windmill rotor parts understudy.

CHOOSING THE RIGHT SITE AND ROTOR SIZE

The selection of the optimal size for the windmill understudy, particularly tailored to the chosen location (site) designated for reverse engineering, was based on the analysis of eleven years' worth of wind profile data, taking into account the site's water demand.

The appropriate rotor size at this site was determined and reported in a previously published paper to be 4.88 meters. The rotor's height must be high enough to be far above the obstacles [7,14].

The findings from the analysis of the wind energy profile are as follows:

- The average annual wind speed for eleven years was calculated to be 3.24 meters/sec.
- The installation windmill's site was carefully selected to be far from tall buildings and trees. A tower with a height of 12 meters was chosen to adequately elevate the rotor above the surrounding isolated trees and wind turbulence.

The appropriate rotor size and site placement were determined to optimize the performance and efficiency of the water-pumping windmill. During the windmill design process, specific calculations were conducted to evaluate the appropriateness of the rotor size for the site.

The equations used for these calculations can be found in various published papers, including [15,16]. The hydraulic power needed (P_{hyd}) for lifting water from its source to the storage tank is determined using equation (1):

$$\mathbf{P_{hyd}} = Q_p . \rho_w . g . H \tag{1}$$

Where: Q_p= water requirement (m³/sec); ρ_w= water density (1000Kg/m³); g = gravity (9.81m/sec²); and H = total discharge head (m).

The wind power potential, denoted as (P_{wind}), is expressed as the specific wind power per unit area, and the following equation determines its calculation:

$$P_{wind} = \frac{1}{2} . \rho_a . V^3 . C_p \tag{2}$$

Where: $\boldsymbol{\rho_a}$= air density ($\mathrm{kg/m^3}$); and V = wind velocity (meters/sec).

The dimension of the area, known as the reference area (R_a), is obtained by dividing the hydraulic power of each month by the specific wind power potential for that same month:

$$\boldsymbol{R_a} = \frac{\boldsymbol{P_{hyd}}}{\boldsymbol{P_{wind}}} \tag{3}$$

The design month is determined by computing the ratio of the hydraulic power requirement to the available wind power resource for each month and identifying the month in which this ratio reaches its peak. The rotor diameter is given in the equation:

$$(\boldsymbol{D_r}) = \sqrt{\frac{\boldsymbol{4R_a}}{\boldsymbol{\pi}}} \tag{4}$$

In equation (4), (R_a) represents the reference area for the design month, while equation (5) can be employed to determine the geometric volume displaced by the piston (V_S) during each stroke (s) in a piston pump with a diameter of (D_p).

$$\text{V Stroke} = V_S = \frac{1}{4} . \pi . D_p{}^2 . s \tag{5}$$

Due to the intermittent nature of wind-generated flow rates, there is typically a need for higher water flow rates during brief periods of the day. Managing the storage and distribution of water plays a crucial role in pumping systems. Reference [14] contains an in-depth discussion covering a wide range of topics such as wind energy, wind resource analysis, site and windmill size selection, water demand assessment, hydraulic and wind power potential determination, as well as reference area and windmill size specifications.

REVERSE ENGINEERING PROCESS

Acquisition Tools and Equipment

This research marks a significant milestone, as it is the first known instance in Libya, as far as the researchers' knowledge, where wind power is utilized to extract groundwater using a locally manufactured mechanical windmill.

The process begins with implementing 3D scanning techniques, explicitly focusing on selecting the most suitable scanning technique for capturing the dimensions of all rotor components. In this case, a non-contact scanning technique using the 3D BacesSCAN portable laser scanning device was chosen, as shown in Figure (2). The scanning operation yielded scanned data in the form of a 3D visual sketch, commonly referred to as a (point cloud or mesh). However, additional scanned data processing is required before creating a CAD model.

Figure 2: Baces SCAN portable laser scanning system.

Reverse Engineering Software

To facilitate additional alterations to the scanned surfaces and to create a 3D CAD model, it is necessary to transform the point cloud data from the Baces3D software into a 3D software using IGES (Initial Graphics Exchange Specification) file format, which serves as a universal format for data transfer. The final surface creation, achieved by overlaying the point cloud with a mesh, requires several operations within CATIA's Digitized Shape Editor (DSE).

Reverse Engineering Procedure and Analysis

The initial step in the reverse engineering process involves digitization, which entails capturing the coordinates of points on the component surfaces [17]. It is crucial to acquire the point cloud to initiate the geometric modeling of the rotor parts for reverse engineering. This point cloud serves as a three-dimensional depiction of digitized points within geometric space. Subsequently, the data collected from the scanning device can be transformed into a neutral format like IGES or directly integrated into the modelling software [18]. Figure (3) depicts the general process flow diagram of the operations undertaken within the scope of this work and is represented by the solid lines; however, the dotted lines show additional potential operations beyond the scope of this work. In simpler terms, the result of digitizing the components in this study is a geometric model of the rotor parts. This model can be created in CATMODEL or one of the exclusive formats like IGES. Once these 3D models are employed to produce manufacturing drawings, they serve as the foundation for different engineering analyses. These analyses can be carried out using CAE software such as ANSYS for structural analysis or computational fluid dynamics (CFD) for airflow analysis. Moreover, they can be utilized in industrial applications by employing CAM in CATIA to manufacture prototypes or molds (dies) through NC machines or rapid prototyping technology. For this study, the choice was to utilize CAM.

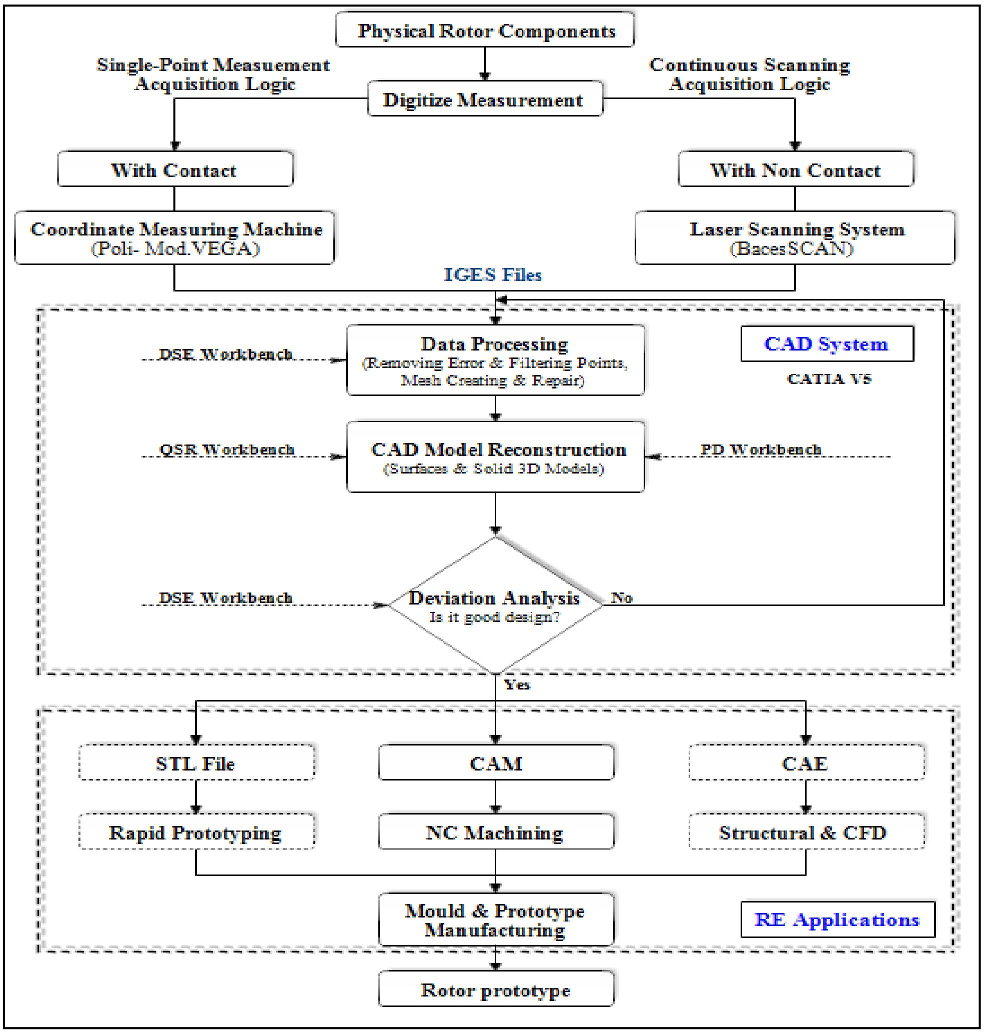

Figure 3: RE process flow diagram.

The Reverse Engineering process can be explained as follows:

Scanning the physical rotor components

To ensure accurate scanning of the rotor components results and to prevent incorrect CAD modification points, all components were carefully painted white as a precautionary measure. The painting process prevents errors arising from unadjusted surfaces and uncontrolled scattering of laser rays [19,20]. These errors can pose significant challenges in CAD modification, particularly in the context of rapid prototyping processes and manufacturing involving NC machining.

To ensure stability during the scanning process and to prevent the movement of the measured pieces, each component was securely fixed one after another on a specially prepared measuring Table. Additionally, the examination room was dimmed to minimize errors that could arise from external lighting [19].

The scanning process was carried out for all components without fragmentation, meaning each part was scanned as a single unit or patch. Figure (4) illustrates the BacesSCAN device in operation as it scans the rib. The IGES format was used to facilitate the transfer of point cloud files from the Baces3D software digitizing machine to CATIA. This choice ensured the efficient transfer of data for subsequent point processing tasks and CAD model reconstruction.

Figure 4. Baces3D arm during scanning of the rib.

Processing the measured data

During the 3D rendering of a scanned physical object on CAD system software, two critical issues arise: (i) A large number of digitized points and (ii) Errors introduced during the scanning process. So, it is crucial to correct measurement errors to the best extent possible and discard points that exceed a predetermined error threshold. Upon obtaining the detailed dimensions of the rotor components from the scan files, further refinement is needed to transform the data into an accurate, final representation; this involves cleaning up, smoothing, and sculpting the measured data to ensure it retains the desired shape and accuracy [21].

Several steps were taken to achieve the refinement, including (i) Removing error points: The remove Command in CATIA DSE was employed to eliminate points with errors; (ii) Filtering points: The filter Command in CATIA DSE was applied to refine the point cloud data; (iii) Creating the mesh: The mesh creation Command in CATIA DSE facilitated the generation of a mesh representation of the scanned data, (iv) Mesh repair: Any holes in the mesh were repaired using Commands such as fill holes, mesh smoothing, and mesh cleaning within the DSE workbench in CATIA. By executing these processing steps, the measured data of the rotor parts was enhanced, ensuring the necessary shape and accuracy for subsequent stages of the reverse engineering process.

The CAD model construction

Once digitized points have been repaired, the subsequent step involves creating the curves that will form the geometric model of the part [20]. Planar curves were produced by the "planar sections" command within the CATIA DSE workbench. Figure (5) provides a visual representation of these planar curves, which function as the foundational support for the mended mesh. At this stage, the primary task involves carefully selecting the most appropriate surfaces for interpolating the acquired curves, with the objective of closely mirroring (reproducing) the physical geometry of the component [13].

All surfaces were created using the QSR tool in CATIA for the rotor parts. As an example, Figure (6a) illustrates the obtained surfaces of the sail ribs, one of the rotor parts produced in this study. These surfaces were utilized to construct a solid model with a thickness of 1.5mm, employing the Part Design feature in CATIA, as shown in Figure (6b).

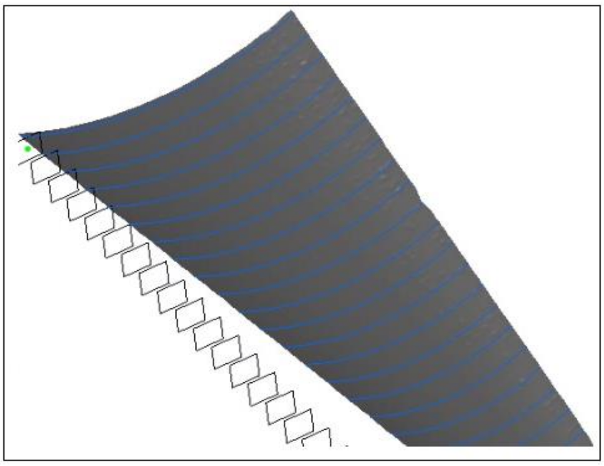

Figure 5. Planar curves on the repaired mesh.

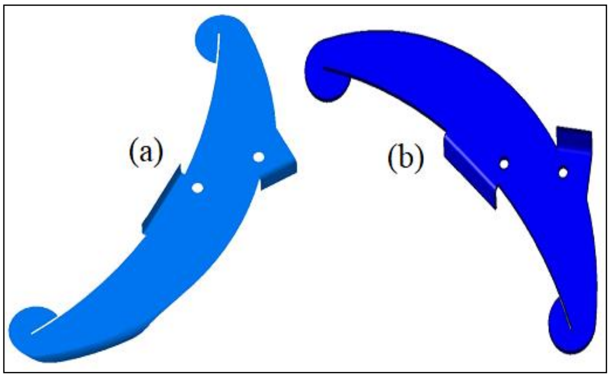

Figure 6. (a) Final obtained surfaces, and (b) Three-dimensional solid rib model.

The Rotor Hub

The rotor hub is integral to the physical powertrain and brakes group within the water-pumping windmill. It's important to mention that all the components making up the power train and brakes group were provided by the AEEI Company. The hub is an essential component included in this group. It contributes to the overall functionality and operation of the windmill.

Deviation analysis results

A comparison between the point cloud data acquired through 3D scanning of each component and its final CAD model was carried out as part of a deviation analysis to evaluate the accuracy of the reverse engineering process. This involved utilizing the deviation analysis Command within DSE and was performed for all the rotor parts, as explained for the sail tie. Table (2) depicts the input parameters, while Table (3) presents results suggesting that nearly 100% of the data points adhere to the specified tolerance limits of ±1mm. The mean and standard deviation values are 0.01mm and 0.03mm, respectively. These findings demonstrate that the design meets the required standards and is considered satisfactory and appropriate for adoption.

Table 2: Test input parameters of the tie deviation analysis.

Reference data	**Surface.1**
Data to measure	Mesh creation.1
Accuracy	0.010
Only orthogonal	0
Absolute	0

Table 3: Statistical results of the sail tie deviation analysis.

Total points	3704
Points used in the computation	3704
Points with positive deviation	614
Points with negative deviation	397
Maximum deviation value (positive)	0.15mm
Maximum deviation value (negative)	-0.12mm
Mean deviation	0.01mm
Standard deviation	0.03mm
Positive mean deviation	0.05mm
Negative mean deviation	-0.02mm
Positive tolerance	1.00mm
Negative tolerance	-1.00mm
Percentage in tolerance	100.00

Among the valuable outputs of the analysis is a graphical colored map shown in Figure (7). This map serves the purpose of visualizing the data from the deviation analysis and various annotations related to the sail tie. It also shows a histogram representing the distribution of the deviation values between the CAD model surface points and the original point cloud data. Remarkably, around 81.75% of the deviation values lie between 0 and - 0.04mm. As a result, all the parts are prepared for assembly operations utilizing the assembly design feature Command in CATIA. They are ready to undergo testing for their assembly capability before commencing the prototype manufacturing phase.

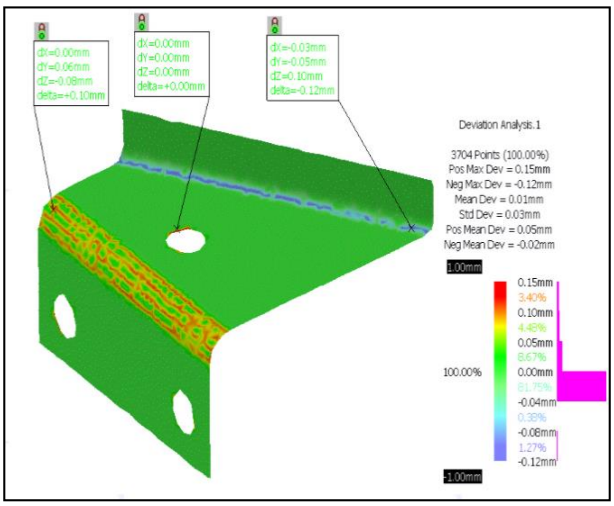

Figure 7: An image captured of sail tie deviation analysis.

Rotor components 3D CAD models

An assembly model of the components in 3D-CAD was generated using the existing physical windmill, as illustrated in Figure (8). The CATIA assembly design workbench was employed to verify the rotor's assembly feasibility and eliminate any possible issues in the overall dimensions, such as fouling or interference. This verification step was undertaken to confirm the precision and functionality of the 3D assembly model before manufacturing the rotor prototype [13,22].

Due to the previously identified deviations, adopting 3D models for the rotor components became essential. Consequently, the generation of two-dimensional manufacturing drawings emerged as one of the most critical outputs derived from applying reverse engineering to the rotor components. These drawings played a vital role in ensuring the precise manufacturing of the rotor prototype.

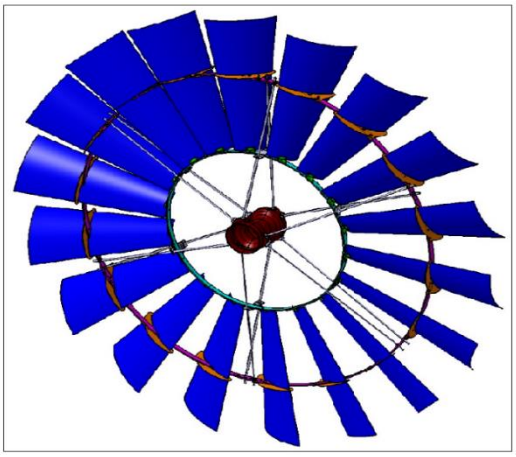

Figure 8: The 3D assembly model of the windmill rotor.

MANUFACTURING AND PERFORMANCE TESTING

Designing and Manufacturing Die for Curving the Rotor Sails

The researchers employed various CAD/CAM modules integrated into CATIA to design and develop the die. They also simulated its operation using 3D graphic models and meticulously followed CNC machine programming. A compound die's design and development phases are critical in sheet metalworking. Even minor design errors can result in significant manufacturing losses due to die failures, part geometry distortion, and heightened production risks [23]. When designing a die, several factors must always be considered. Selecting potential solutions to production-related issues for a specific part requires considering the object's characteristics (such as shape, size, and material), the available machine specifications (including stroke, size, and load), and the number of parts to be manufactured [24].

Economic and technical factors motivated the decision to create a single-operation die for designing and producing windmill sails. These factors included (i) The challenge of manually crafting curved sails with the existing labor force, (ii) The number of sails needed to construct a single windmill unit, and (iii) The significance of sails in enhancing the windmill's overall efficiency.

Based on the CAD model of the sail obtained from the RE application, the CAD model was realized in CATIA software design for the die parts responsible for curving the sails of the water-pumping windmill rotor. Subsequently, an attempt was initiated to generate the CAM model required to manufacture the die components using a CNC machine. Figure (9) illustrates the workflow diagram commencing with the approved 3D design of the sail die, progressing through the CAM processes, simulation, and the physical production of the die parts on the CNC machine, culminating in die testing and the commencement of the production stage.

The appropriate planning and machining strategies were selected to achieve the final geometric product shape, starting with a roughing operation to eliminate excess metal quickly, bringing the product closer to its final form. Then, the contour is achieved using the Z-level finishing function in CATIA. Finally, the required finishing of the surface of the die is obtained using a two-level sweeping function. A CAM model has been prepared for each part of the sail die, applying the selected strategies, setting all machining parameters in the advanced machining workbench of CATIA software, and conducting machining and tool paths simulations to ensure it works well during the actual machining process on the CNC machine.

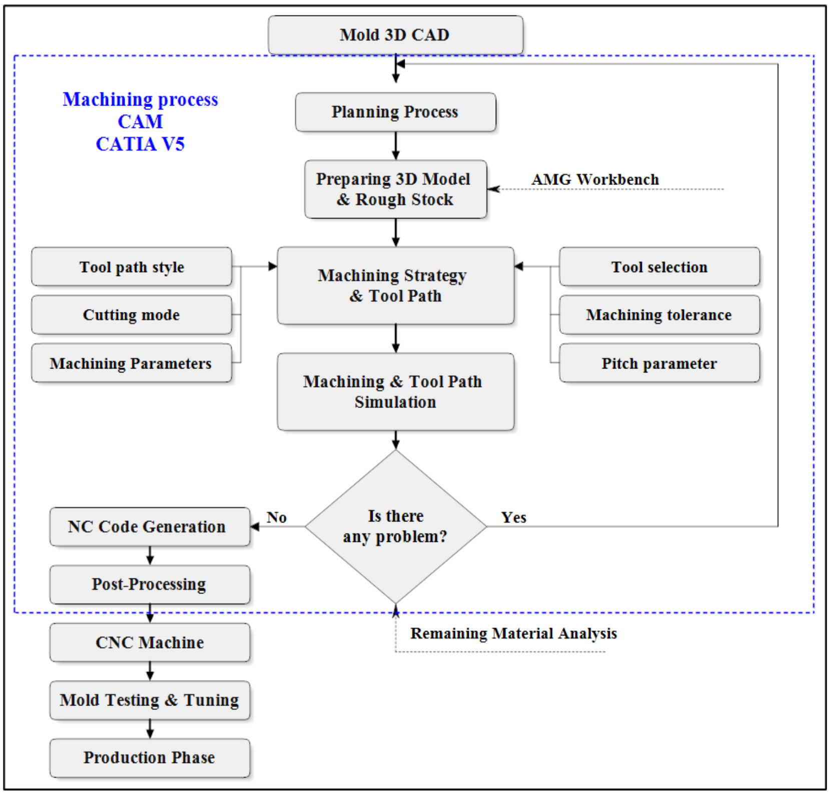

Figure 9: The CAM process workflow diagram.

CATIA has the capability to exhibit a video that simulates the three operations, as depicted in Figure (10). This simulation lets users easily observe the tool's movement and pinpoint any operational inefficiencies in the machinery. Should any inefficiencies be identified, adjustments are made to the existing settings to achieve optimal results. Subsequently, NC programs are generated for each component of the die, and these programs are then transferred to the CNC machine. Finally, a dimensional scanning system is employed to execute Reverse Engineering (RE) inspections and simulate machining processes within an integrated CAD/CAM system, all in a virtual environment. This integrated approach reduces design time, prevents costly errors or modifications, and minimizes the duration of the CNC machining process.

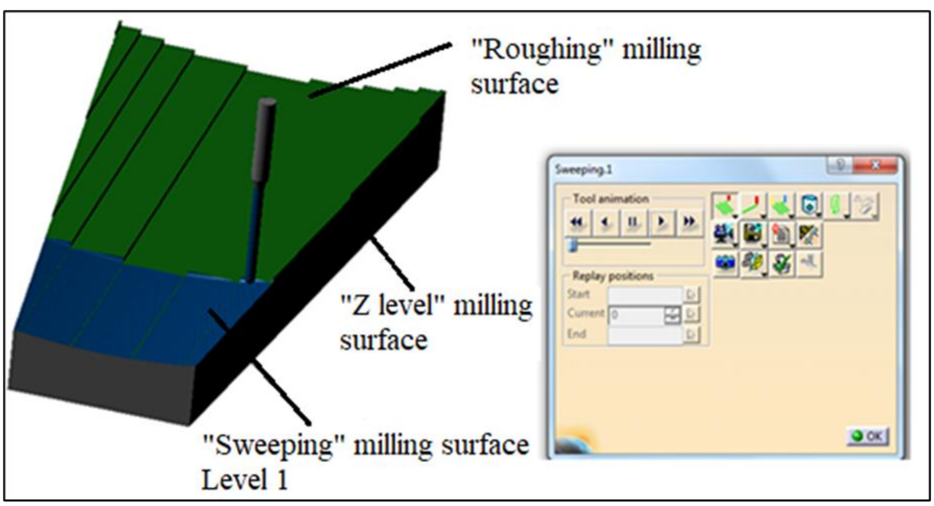

Figure 10: An image captured during "Sweeping" Level 1 in the simulation.

On the contrary, Figure (11) illustrates the "Roughing" and "Sweeping" operations serving as the finishing steps while machining one of the lower sail's die components on the CNC machine.

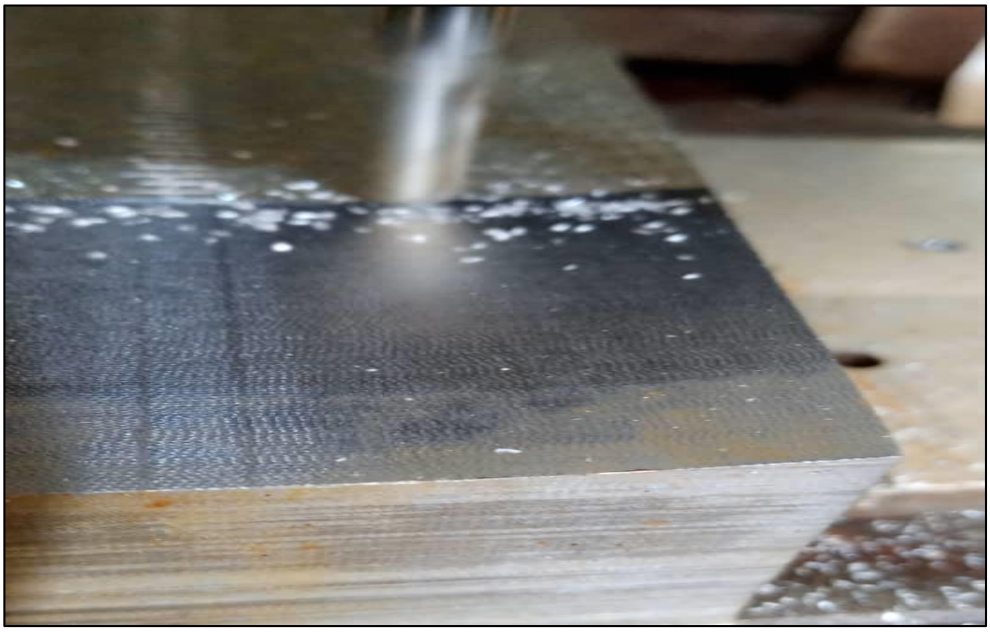

Figure 11: "Roughing" and "Sweeping" operations of lower sail die.

The die was successfully produced and set up on the appropriate hydraulic press bending machine, as demonstrated in Figure 12, as an integral step in the prototype manufacturing process. Subsequently, the sail prototypes were produced, and significant modifications were made to refine the die.

Manufacturing the Prototype Components for the Rotor

Manufacturing of all prototype components of the rotor is completed according to the established working schedule requirement and is documented in reference (7). Examples of various stages of the manufacturing processes for rotor components are shown in (Figures 13-15). Figure (13) demonstrates the operation of the rotor sail-cutting

Figure 12: Installing the sail curving die onto the bending machine

through the CNC plasma cutting machine. Figure (14) clearly depicts the sail tie bending procedure executed using the bending press machine.at the Truck-Bus Company. Figure (15) displays the bending operation of the outer band, accomplished through the utilization of the CNC Rolling machine.

Figure 13: Sails cutting with a CNC plasma machine.

Figure 14: Bending the sail tie with the press machine.

Figure 15: Using a CNC rolling machine to bend the outer band

Sails Section and Complete Rotor Assembly

The windmill rotor's assembly process involves preparing six sub-assemblies, known as the (sails section), as illustrated in Figure (16). Figure (17) depicts photographs detailing the sequential steps of the entire windmill rotor assembly procedure onto the hub; Figure (17a) illustrates explicitly the insertion of the rotor arms into the hub, and Figure (17b) displays the installation of the 6th sails section.

Figure 16 illustrates the fully assembled rotor sails section.

Performance Testing of the RE Rotor Components

The windmill rotor assembly underwent testing to validate the successful manufacturing of its components and ensure they functioned as intended. This rotor assembly was mounted on a dedicated tower, standing at a height of 12 meters, specifically for the purpose of this experimental study. Figure (18) depicts two photographs capturing the installation procedure of both the rotor and the tower at the designated Well situated within the premises of AEEI Company.

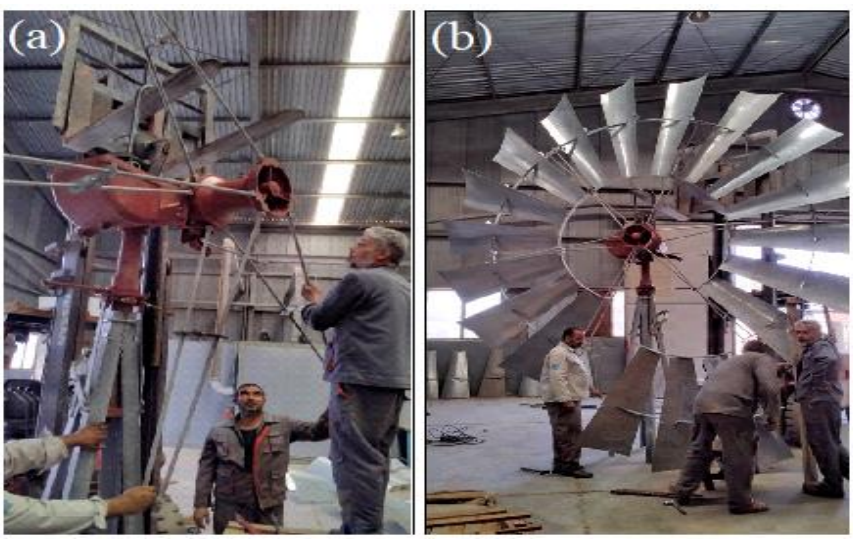

Figure 17. (a) Installing rotor arms into hub; (b) Assembly of the 6th sails section.


Figure 18. Rotor and tower installation.

Figure 19 depicts extracting groundwater from the Well using a windmill system. This illustration was taken when the wind speed was 2.7 meters per second and measured at a height of 2 meters above the ground. This attempt proved successful, with an estimated water flow rate of 1 liter per 10 seconds.


Figure 19. Water is extracted from the Well by the windmill system.

CONCLUSIONS AND RECOMMENDATIONS

The researchers have reached several significant conclusions by using digitized dimensional scanning systems for RE in creating CAD models of the windmill rotor. Firstly, RE effectively reduced design time and prevented point errors or modifications. Secondly, all targeted components were successfully manufactured during the course of this study, and the complete assembly of the windmill rotor components was accomplished without encountering any issues. Furthermore, the rotor was subjected to testing within a windmill setup, where it extracted groundwater from a specified Well. This testing occurred under an average wind speed of 2.7 meters per second, as measured at a height of 2 meters above the ground. The estimated average water flow rate achieved during these tests was found to be 1 liter every 10 seconds.

In fact, the rotor prototype was designed, manufactured, and installed on the tower prepared for this mechanical water-pumping windmill and tested in May 2022. ASTM-A36 0.25 wt.% steel coated using the galvanizing tub available at Al-Inma Company for all components of the rotor prototype.

Remarkably, the windmill has operated at peak efficiency since its installation without encountering any operational interruptions or malfunctions. The researchers considered choosing this type of steel with a galvanized coating was probably the most favorable decision. It is worth noting that this study represents a pioneering and comprehensive initiative in Libya, being the first of its kind to cover the design, production, installation, and testing of rotor components for mechanical water-pumping windmills through a reverse engineering process. Building upon this study's achievements and the recommendations the researchers put forth, AEEI Company decided to adopt the reverse engineering process to design and produce all the remaining parts of the windmill locally.

Please be aware that the understudy has undergone revisions and incorporated additional content compared to the version originally presented at the ICMIE2022 conference on November 15-17, 2022, held at the University of Tripoli, Tripoli-Libya, and published in the conference proceedings (reference 25).

REFERENCES

[1] V. Raja, "Introduction to Reverse Engineering," Chap 1, "Reverse Engineering: An Industrial perspective," Springer Series in Advanced Manufacturing, V. Raja and K. J. Fernandes (Eds.), Springer, London, 2008, pp. 1-9.

[2] T. Varady, R. Martin, and J. Cox, "Reverse Engineering of geometric models- An introduction," CAD Computer Aided Design, vol. 29, no. 4, 1997, pp. 255-268.

[3] K. Otto and K. Wood, "Product evolution: A Reverse Engineering and redesign methodology," Research in Engineering Design, vol. 10, no. 4, 1998, pp. 226-243.

[4] S. Motavalli and R. Shamsaasef, "Object-oriented modeling of a feature-based Reverse Engineering system," International Journal of Computer Integrated Manufacturing, vol. 9, 1996, pp. 354-368.

[5] E. Chikofsky and J. Cross II, "Reverse Engineering and Design Recovery- A Taxonomy in IEEE Software," IEEE Computer Society, January 1990, pp. 13–17.

[6] R. Gasch and J. Twele, "Wind power plants: Fundamentals, design, construction and operation," Springer, Heidelberg-Germany, second edition, 2012.

[7] S. Saravanan, D. Anbazahan, G. Manikandan, M. Mathavan, A. Mohamed Afrith, and K. Prakash, "Design and fabrication of wind energy water pump," International Journal of Engineering Research & Technology, vol. 6, no. 4, 2018, pp. 1-4.

[8]. O. Badran, "Wind turbine utilization for water pumping in Jordan," Journal of Wind Engineering and Industrial Aerodynamics, vol. 91, 2003, pp. 1203–1214.

[9]. M. Elamouri and F. Ben Amar, "Wind pumping assessment as source of renewable energy," Leonardo Journal of Sciences, vol. 29, 2016, pp. 55-74.

[10]. I. Odesola and L. Adinoyi, "Development of wind powered water pump," international Journal of Engineering Science and Computing, vol. 7, no. 4, 2017, pp. 10341-10345.

[11]. J. Van Meel and P. Smulders, "Wind pumping: A Handbook," Washington: The International Bank for Reconstruction and Development, The World Bank, 1987.

[12] I. Belal and A. Frefer, "Reverse engineering of a physical windmill sail and manufacturing the curving sail die in CAD/CAM system," Libyan Journal of Applied Science and Technology, vol. 10, no. 01, June 2022, pp. 58-76.

[13] I. Belal, "Applying RE in manufacturing prototype of rotor components for water-pumping windmill," MSc Thesis, Supervised by Dr. A. Frefer, Mechanical and Industrial Engineering, University of Tripoli, Libya, Spring 2021-2022.

[14] I. Belal and A. Frefer, "Reverse Engineering and design of a windmill pumping system suitable for wind conditions: A case research in a Suburb of Tajoura, Libya," Journal of Solar Energy and Sustainable Development, vol. 10, no. 2, 2021, pp. 21-40.

[15] M. Borok, Z. Johnson, and J. Agandu, "Design and simulation of wind pump system for ban village," Innovative Systems Design and Engineering, vol. 35, no. 2, 2016, pp. 80–84.

[16] A. Manyonge, R. Ochieng, F. Onyango, and J. Shichikha, "Mathematical modelling of wind turbine in a wind energy conversion system: Power coefficient analysis," Applied Mathematical Sciences, vol. 6, no. 91, 2012, pp. 4527–4536.

[17] S. Motavalli, "Review of Reverse Engineering approaches," Computers and Industrial Engineering, vol. 35, nos. 1-2, 1998, pp. 25-28.

[18] J. Keast, "Selecting a Reverse Engineering System," Chap 4, Reverse engineering: an industrial perspective Springer Series in Advanced Manufacturing, V. Raja and K. J. Fernandes (Eds.), Springer, London, 2008, pp 71–98.

[19] M. Dubravcik and S. Kender, "Application of reverse engineering techniques in mechanics' system services," Procedia Engineering, vol. 48, 2012, pp. 96-104.

[20] K. Lee and H. Woo, "Direct integration of reverse engineering and rapid prototyping," Computers and Industrial Engineering, vol. 38, 2000, pp. 21-38.

[21] Z. Bi and L. Wang, "Advances in 3D data acquisition and processing for industrial applications," Robotics and Computer-Integrated Manufacturing, vol. 26, 2010, pp. 403–413.

[22] A. Afeez and A. Kumar, "Application of CAD and reverse engineering methodology for the development of complex assemblies," Journal of Engineering Design, and Technology, vol. 11, no. 3, 2013, pp. 375-390.

[23] N. Jyothirmayi and B. Rao, "The design and fabrication of a compound die to make hexagonal washer," International Journal of Mechanical and Production Engineering Research Development, vol. 9, no. 4, 2019, pp. 517–528.

[24] V. Reddy, K. Mutyalu, S. Reddy, and M. Nayak, "Modelling and manufacturing of progressive die for mechanical press operations," Turkish Journal of Computer and Mathematics Education, vol. 12, no. 3, 2021, pp. 3662–3671.

[25] A. Frefer, I. Belal, and Y. Arebi,"Applying reverse engineering in the manufacture of water pumping windmill rotor prototype," International Conference on Mechanical and Industrial Engineering ICMIE2022 November 15-17, 2022 Tripoli-Libya.