A Power Generation Device Based on Spherical Gear Meshing

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Abstract: This study aims to develop an inn ovative energy conversion device based on s pherical gear design, which efficiently transf orms vibrational energy from industrial env ironments into electrical energy. The goal is to meet industrial energy recovery demands and promote sustainable energy developme nt. The research team designed a spherical g ear mechanism, taking into account mechan ical efficiency, material selection, durability, and environmental impact. A precise contr ol system was implemented to regulate the c apture and conversion of vibrational energy. To validate the feasibility of the design, a se ries of simulation experiments were conduct ed. The results demonstrate that the device operates stably under predefined simulated conditions and achieves medium-temperatu re output power, highlighting its potential in the field of energy conversion. This device p rovides an efficient solution for recovering i ndustrial vibrational energy and holds prom ise for widespread applications in industrial machinery, building structures, and other fi elds, contributing to the advancement of gre en energy technologies.

Keywords: Spherical Gear; Three Degrees of Freedom; Tooth Contact Analysis; Stress Analysis; Transmission Error; Renewable Energy; Resource Planning; Speed Matching

1. Introduction

This paper aims to elucidate how spherical gear technology can be utilized to achieve energy recovery and power generation by harnessing industrial vibrational energy while simultaneously protecting the environment[1]. Aligned with national policies promoting the development of renewable energy, this project focuses on the development of a spherical gear power generation system specifically designed to efficiently convert irregular mechanical vibrational energy from industrial environments into electrical energy. Leveraging innovative spherical gear technology, this system is capable of capturing and converting energy that is typically difficult to harness using traditional energy recovery methods, thereby enabling continuous and efficient energy utilization[2].

The unique design of spherical gears allows them to receive vibrational forces from multiple directions and, through a precise mechanical conversion mechanism, effectively transform this kinetic energy into electrical energy. The application of this technology not only responds to national policy requirements for renewable energy development but also provides an innovative solution to global energy crises and environmental protection. Spherical gear power generation technology demonstrates the critical role of technological innovation in advancing green development and achieving industrial sustainability.

Through this project, we aim to provide a new pathway for energy recovery in the industrial sector, converting previously discarded vibrational energy into usable electrical energy, reducing energy waste, and contributing to the reduction of operational costs for industrial equipment[3]. Furthermore, the widespread adoption of spherical gear power generation systems will promote the development of related industrial chains, inject new momentum into economic growth, and drive the global application and popularization of environmentally friendly technologies.

2. Research Background and Significance

With the growing global awareness of sustainable development and environmental protection, the Chinese government has been actively promoting the development of renewable energy to reduce reliance on fossil fuels and mitigate environmental pollution. In this context, a series of policies and regulations, such as the Renewable Energy Law and the Medium- and Long-Term Development Plan for Renewable Energy, have been formulated and implemented to accelerate the research[2], promotion, and application of renewable energy technologies, thereby increasing the proportion of renewable energy in the overall energy structure.

Low-carbon environmental protection has become a widely discussed topic. According to data released by the National Development and Reform Commission, during the "13th Five-Year Plan" period, electricity generated from renewable energy sources such as hydropower and wind power accounted for a certain proportion of the energy mix[3]. However, coal-fired power still dominated, indicating that the utilization of renewable energy remains insufficient. This presents significant opportunities for our product, which aims to maximize energy utilization and provide a new pathway for enterprises to embrace low-carbon and green practices.

The spherical gear power generation project represents an innovative gear-driven power generation system with unique design advantages, demonstrating strong potential for application in space-constrained environments. Spherical gears[1], characterized by their compact size, lightweight, and high transmission efficiency, are capable of operating under complex dynamic loads, making them particularly suitable for renewable energy projects such as wave and tidal energy. The application of this technology not only enhances energy conversion efficiency and reduces energy losses during transmission but also drives innovation in gear manufacturing and materials science, thereby providing momentum for advancements in other technical fields[1]. Furthermore, the promotion of spherical gear power generation projects will expand their application scope, create more business opportunities for related enterprises, and foster the growth of the entire industrial chain. Most importantly, this technology contributes to reducing dependence on fossil fuels, diversifying energy supply, improving energy stability, and ultimately enhancing national energy security.

3. Mechanical Structure Design

The spherical gear consists of two types of tooth surfaces engaged in meshing, which are composed of multiple planar involutes and spherical involutes[4]. This design inherits the advantages of involute gears:

Dual Tooth Surface Engagement: The spherical gear features two types of tooth surfaces during meshing, with tooth profiles based on planar involutes and spherical involutes, respectively. This eliminates transmission principle errors and retains the benefits of involute gears. This design overcomes potential errors that may arise in traditional discrete gears during transmission, ensuring more precise and smooth power transfer[3]. In terms of transmission performance, spherical gears exhibit high transmission efficiency and low frictional resistance, enabling them to adapt to various complex and demanding working environments.

Three-Degree-of-Freedom Motion: Spherical gears can achieve three-degree-of-freedom (3-DOF) motion, including yaw, pitch, and rotation[2]. This characteristic allows them to transmit spatial motion and power, enabling 3-DOF motion with compact mechanisms. This contributes to the lightweight design of the system, making it suitable for operation in confined spaces and precision applications[5].

The spherical gear power generation system primarily consists of three core components: the spherical gear itself, an energy converter, and a power storage unit. The spherical gear is responsible for capturing and initially converting mechanical energy, while the energy converter further transforms the mechanical energy into electrical energy. The power storage unit stores the generated electricity for on-demand supply. Additionally, the system includes a control module to monitor and regulate the power generation process, ensuring stable operation[1]. Figure 1 illustrate the product modeling, while Figure 2 provide schematic diagrams of the actual product.

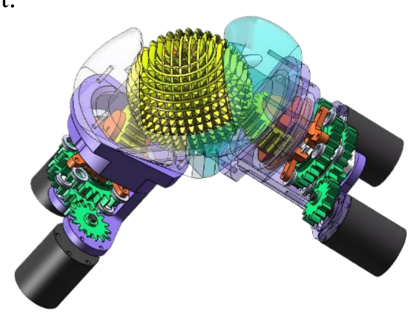

Figure 1. Modeling Diagrams

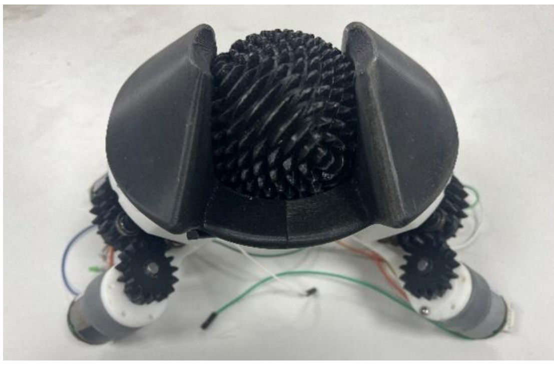

Figure 2. Physical Prototype Diagrams

3.1 Spherical Gear and Intermediate Gear

3.1.1 Formation principle and structural characteristics of spherical gears

The combination of spherical gears and two intermediate gears, through their unique geometric shapes and meshing mechanisms, enables rotation by receiving irregular forces from multiple directions. These forces are decomposed into two separate directions, achieving the initial conversion of mechanical energy. This design allows spherical gears to efficiently capture energy from multiple directions, enhancing the system's adaptability to environmental dynamic changes and improving energy capture efficiency[5]. This constitutes the core mechanism of energy conversion and is a critical step in transforming irregular motion into regular rotation[3].

The meshing motion of spherical gears can be regarded as pure rolling between two spherical segments, with a constant transmission ratio of 1:1. The two spherical segments remain in tangential contact, meaning the tooth profiles of the two spherical gears are in point contact, as shown in Figure 3 Coordinate systems S1(o1,x1,y1,z1) and S2(o2,x2,y2,z2) are fixed to the two spherical gears, respectively, where o1 and o2 are the origins of the coordinate systems and also the centers of the two spherical gears. The driving spherical gear 1 can rotate around the x1, y1, and z1 axes of coordinate system S1, enabling pitch, yaw, and rotation motions of the gear pair. The driven spherical gear 2 rotates around the x2, y2, and z2 axes of coordinate system S2, correspondingly, thereby transmitting motion between the two spherical gears.

The rotation motion of the spherical gears is the relative rolling of two spherical segments along the latitude lines. At different latitudes, this is equivalent to the pure rolling between two pitch cones of straight bevel gears with different base cone angles[6]. The pitch and yaw motions are the relative rolling of two spherical segments along the longitude lines, equivalent to the pure rolling between two pitch circles of straight cylindrical gears.

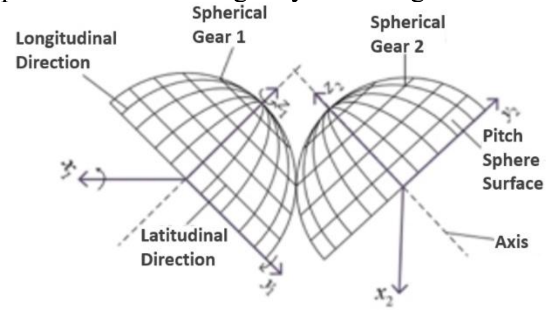

Figure 3. Diagram of Spherical Tangency

When the spherical gears perform yaw and pitch motions, the tooth profile on any cross-sectional plane passing through the polar axis (the z1 and z2 axes) of the spherical gear is identical to the tooth profile on the end face of a straight cylindrical gear. When the spherical gears perform rotation motion, the tooth profile on any cross-sectional plane perpendicular to the polar axis of the spherical gear is similar to the tooth profile on the end face of a straight bevel gear[7]. Therefore, the two spherical gears can correctly engage regardless of the shaft angle, meaning pure rolling can be achieved between the two spherical gears in any orientation.

Each single tooth of the spherical gear (excluding the convex and concave teeth at the apex of the spherical gear) is composed of a ring tooth and a spherical conical tooth. The ring teeth are distributed along the latitude lines of the base sphere, while the spherical conical teeth are distributed along the longitude lines of the base sphere, as shown in Figure 4 The base sphere is concentric with the pitch sphere of the spherical gear, and the radius of the base sphere is rb. Planar involutes are generated on different latitude lines of the base sphere, while spherical involutes are generated on different longitude lines of the base sphere, equivalent to being generated on the base cone's bottom circle[5].

For a single ring tooth, the starting points of the left and right planar involutes lie on different latitude lines of the base sphere. The planar involutes rotate around the z-axis to form the ring tooth surface of the spherical gear. For a single spherical conical tooth, the starting points of the left and right spherical involutes lie on different longitude lines of the base sphere. Multiple spherical involutes generated on the same longitude line combine to form the spherical conical tooth surface of the spherical gear.

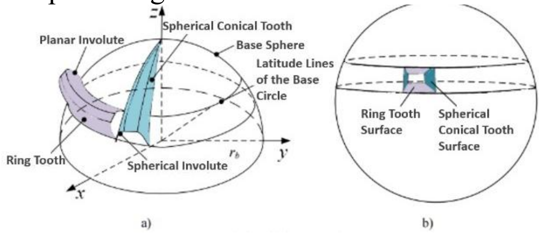

Figure 4. Schematic Diagram of Single Tooth Formation and Tooth Surface Structure on the Spherical Gear
a)Diagram of Latitude and Longitude Distribution on the Base Sphere
b) Schematic Diagram of Single Tooth Surface Formation on the Spherical Gear

Each single tooth of the spherical gear consists of two types of tooth surfaces: the ring tooth surface formed by planar involutes (hereinafter referred to as the "ring tooth surface") and the spherical conical tooth surface formed by spherical involutes (hereinafter referred to as the "spherical conical tooth surface")[6]. The tooth profile surface distributed along the latitude lines is the spherical conical tooth surface, while the tooth profile surface distributed along the longitude lines is the ring tooth surface. A schematic diagram of the formation of a single tooth surface of the spherical gear is shown in Figure 4(b).

Therefore, the three-degree-of-freedom spherical gear can achieve pitch, yaw, and rotation motions between the gear pair[3]. During meshing, two types of tooth surfaces are involved: the pitch and yaw motions correspond to the meshing motion between the ring teeth, while the rotation motion corresponds to the meshing motion between the spherical conical teeth.

3.1.2 Mathematical model of spherical gear tooth surfaces

Each single tooth of the spherical gear consists of two ring tooth surfaces and two spherical conical tooth surfaces. Based on the formation principles of planar involutes and spherical involutes, the tooth surface equations for the ring tooth surface and the spherical conical tooth surface are derived using coordinate transformation methods, ultimately yielding the tooth profile surface equation of the spherical gear.

According to the generation principle of planar involutes, coordinate systems S0(o0,x0,y0,z0) and S(o,x,y,z) are established, as shown in Figure 5, where rK is the radial vector of point K5, and αK is the pressure angle at point K on the involute[1]. Based on the properties of planar involutes, the parametric equation of the involute in coordinate system S0 is:

$$\begin{cases} x_0 = r_b(\sin u - u\cos u) \\ y_0 = 0 \\ z_0 = r_b(\cos u + u\sin u) \end{cases} \tag{1}$$

where $u=\theta_k+\alpha_k$ is the rolling angle of the involute, $inv\alpha_k=\theta_k=\tan\alpha_k-\alpha_k$ is the involute's unfolding angle (also known as the planar involute function), and rb is the base circle radius, which is also the base sphere radius of the two spherical gears.

The transformation matrix from coordinate system S0(o0,x0,y0,z0) to coordinate system S(o,x,y,z) is:

$$M = \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} \tag{2}$$

Combining Equations (1) and (2), the parametric equation of the planar involute in coordinate system S can be expressed as:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = M \cdot \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} = \begin{bmatrix} r_b[\sin(u+\beta) - u\cos(u+\beta)] \\ 0 \\ r_b[\cos(u+\beta) + u\sin(u+\beta)] \end{bmatrix} \tag{3}$$

where β is the angle between rK and the polar axis, as shown in Figure 5.

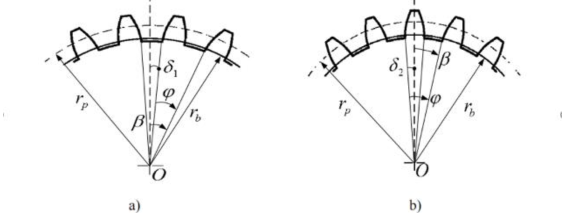

Figure 5. Planar Involute Tooth Profiles of Convex and Concave Ring Teeth on the Spherical Gear
a) Concave Ring Tooth Profile
b) Convex Ring Tooth Profile

For the concave ring tooth, as shown in Figure 5(a), β can be calculated as:

$$\beta = i \cdot \varphi + \delta_1, i = 0,1,2\ldots \tag{4}$$

where φ is the central angle between adjacent teeth, given by $E = mc^2$, and δ1δ1 is the angle between the starting point of the involute on the base circle and the polar axis, given by

$\delta_1 = \frac{\pi}{2zv_1}$.

Substituting π and δ1 into the equation yields:

$$\beta = \frac{\pi(4i+1)}{2z_{v_1}} - \theta_k, i = 0,1,2 \ldots \quad (5)$$

where δ1 is the angle between the starting point of the involute on the base circle and the polar axis, given by $\delta_2 = \frac{\pi}{z_{v1}} + \theta_k$。

Substituting π and δ2 into the equation yields:

$$\beta = \frac{\pi(2i-1)}{z_{v1}} - \theta_k, i = 0,1,2 \ldots \quad (6)$$

The ring tooth surface is formed by rotating the planar involute around the polar axis. By rotating the planar involute around the z-axis by an angle ν, the ring tooth surface is obtained. It is evident that the intersection line between the plane passing through the polar axis z and the ring tooth is a planar involute, meaning the ring tooth profile surface is composed of countless planar involutes. Therefore, the equation of the ring tooth profile surface is:

$$r^{(1)} = M \cdot \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} r_b[\sin(u+\beta) - \text{u}\cos(u+\beta)]\cos v \\ r_b[\sin(u+\beta) - \text{u}\cos(u+\beta)]\sin v \\ r_b[\cos(u+\beta) + \text{u}\sin(u+\beta)] \end{bmatrix} \quad (7)$$

where M is the transformation matrix from coordinate system S(o,x,y,z) to coordinate system S1(o1,x1,y1,z1), given by:

$$M = \begin{bmatrix} \cos v & -\sin v & 0 \\ \sin v & \cos v & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (8)$$

According to differential geometry theory, a surface is composed of countless lines, which can be divided into transverse lines and longitudinal lines, characterized by variables u and ν, respectively. The infinite density of u-lines and ν-lines forms the surface, as shown in Figure 6. By fixing either parameter u or ν, a curve parameterized by the other variable is obtained[5]. Simultaneously fixing both parameters u and ν yields two intersecting curves, and the intersection point $c(u_m,v_n)$ represents the coordinates of a point on the surface.

The ring tooth profile surfaces at different latitudes are expressed as vector equations parameterized by u and ν:

$$r = r(u,v) = x(u,y)i + y(u,v)j + z(u,v)k \quad (9)$$

At point CC, the partial derivatives of Equation (9) with respect to variables u and ν yield the tangent vectors of these two curves, respectively:

$$\mathbf{r}_u = \& \frac{\partial r}{\partial u}(u_m, v_n) = [r_b u_m \sin(u_m + \beta_i)\cos v_n]\mathbf{i} + [r_b u_m \sin(u_m + \beta_i)\sin v_n]\mathbf{j} + [r_b u_m \cos(u_m + \beta_i)]\mathbf{k} \quad (10)$$

$$\mathbf{r}_v = \frac{\partial r}{\partial v}(u_m, v_n) = \{-r_b[\cos(u_m + \beta_i) + u_m \sin(u_m + \beta_i)]\sin v_n\}\mathbf{i} + \{r_b[\cos(u_m + \beta_i) + u_m \sin(u_m + \beta_i)\cos v_n\}\mathbf{j} \quad (11)$$

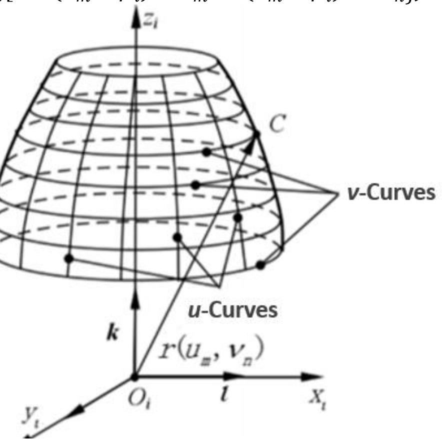

Figure 6. Coordinate Curves of the Ring Tooth Surface

In Figure6, there is a point *C* on the tooth profile surface. The plane determined by the tangent vectors $\mathbf{r}u$ and $\mathbf{r}v$ at point *C* is the tangent plane of the tooth profile surface. This tangent plane contains all tangent lines passing through point *C*. The normal direction at point *C* on the tooth profile surface is defined as the direction perpendicular to the tangent plane. Therefore, the normal line at point *C* is a straight line parallel to the normal direction. Thus, the normal vector of the ring tooth profile surface at point *C* can be expressed as:

$$\mathbf{N} = r_u \times r_v = \begin{vmatrix} i & j & k \\ \frac{\partial x}{\partial u} & \frac{\partial y}{\partial u} & \frac{\partial z}{\partial u} \\ \frac{\partial x}{\partial v} & \frac{\partial y}{\partial v} & \frac{\partial z}{\partial v} \end{vmatrix} \quad (12)$$

Consequently, the unit normal vector of the ring tooth profile surface at this point can be derived as:

$$\mathbf{n} = \frac{\mathbf{N}}{|\mathbf{N}|} \quad (13)$$

Its direction is from the solid to the space. Through calculation, we obtain:

$$\mathbf{n} = \frac{\cos(u+\beta) + \text{u}\sin(u+\beta)}{|\cos(u+\beta) + \text{u}\sin(u+\beta)|} \cdot [-\sin(u+\beta)\cos v\mathbf{i} - \sin(u+\beta)\sin v\mathbf{j} + \cos(u+\beta)\mathbf{k}] \quad (14)$$

Based on the tooth profile characteristics of the ring tooth, the directions of the unit normal vectors of the two tooth surfaces at the meshing point can be determined. Specifically, the unit normal vector direction of the convex ring tooth surface is determined by $r_u \times r_v$, while the unit normal vector direction of the concave ring tooth surface is determined by $r_v \times r_u$.

3.1.3 Mathematical model of spherical gear conical tooth surface

The spherical conical tooth surface of the spherical gear is composed of multiple spherical involutes generated on the base circles of different base cones, which is equivalent to being generated on different longitude lines of the base sphere of the spherical gear[7]. Therefore, the spherical conical tooth surface is formed by multiple spherical involutes generated on different base cones (with varying base cone angles).

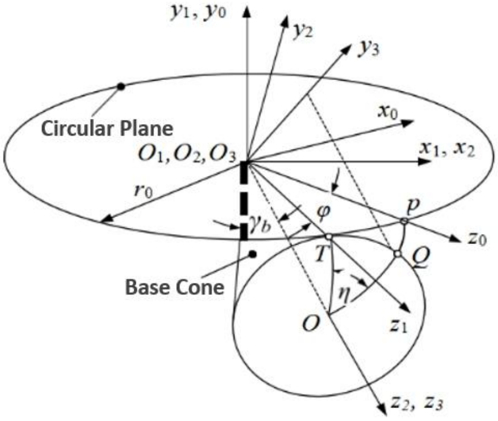

Figure 7. Formation Process of Spherical Involute

To facilitate the subsequent kinematic analysis of the spherical conical gear, the coordinate transformation method is employed to derive the equation of the spherical involute and the conical tooth surface equation. First, the equation of the spherical involute under a constant base cone angle is derived[4]. In Figure 7, a circular plane maintains tangential contact with a base cone and rolls purely on the base cone. The trajectory PQ of any point P on the circular plane is a spherical involute. Here, coordinate system S0$S0$ is fixed to the circular plane, coordinate system $S1$ is obtained by rotating $S0$ around the $y0$ -axis by an angle ϕ, coordinate system $S2$ is obtained by rotating $S1$ around the $x1$ -axis by an angle γb , and coordinate system $S3$ is fixed to the base cone.

The coordinates of point P in coordinate system $S0$ are expressed as:

$$r_0^{(p)} = \begin{bmatrix} 0 \\ 0 \\ r_0 \\ 1 \end{bmatrix} \tag{15}$$

The transformation matrices from coordinate system $S0$ to $S1$, $S1$ to $S2$, and $S2$ to $S3$ are respectively:

$$\boldsymbol{M}_{10} = \begin{bmatrix} \cos\boldsymbol{\varphi} & 0 & \sin\boldsymbol{\varphi} & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\boldsymbol{\varphi} & 0 & \cos\boldsymbol{\varphi} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{16}$$

$$\boldsymbol{M}_{21} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\gamma_b & \sin\gamma_b & 0 \\ 0 & -\sin\gamma_b & \cos\gamma_b & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{17}$$

$$\boldsymbol{M}_{32} = \begin{bmatrix} \cos\eta & -\sin\eta & 0 & 0 \\ \sin\eta & \cos\eta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{18}$$

By combining the above equations, the transformation matrix from coordinate system $S0$ to $S3$ is obtained as:

$$\boldsymbol{M}_{30} = \boldsymbol{M}_{32} \cdot \boldsymbol{M}_{21} \cdot \boldsymbol{M}_{10} = \begin{bmatrix} \cos\eta\cos\boldsymbol{\varphi} + \sin\eta\sin\boldsymbol{\varphi}\sin\gamma_b & -\sin\eta\cos\gamma_b & \cos\eta\sin\boldsymbol{\varphi} - \sin\eta\cos\boldsymbol{\varphi}\sin\gamma_b & 0 \\ \sin\eta\cos\boldsymbol{\varphi} - \cos\eta\sin\boldsymbol{\varphi}\sin\gamma_b & \cos\eta\cos\gamma_b & \sin\eta\sin\boldsymbol{\varphi} + \cos\eta\cos\boldsymbol{\varphi}\sin\gamma_b & 0 \\ -\sin\boldsymbol{\varphi}\cos\gamma_b & -\sin\gamma_b & \cos\boldsymbol{\varphi}\cos\gamma_b & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{19}$$

Thus, the coordinates of point P in coordinate system $S3$ represent the equation of the spherical involute as:

$$\boldsymbol{r}_s^{(p)} = \boldsymbol{M}_{30} \cdot \boldsymbol{r}_0^{(p)} = \begin{bmatrix} r_0(\cos\eta\sin\varphi - \sin\eta\cos\varphi\sin\gamma_b) \\ r_0(\sin\eta\sin\varphi + \cos\eta\cos\varphi\sin\gamma_b) \\ r_0\cos\varphi\cos\gamma_b \\ 1 \end{bmatrix} \tag{20}$$

In the equation, $r0$ is the radius of the circular plane, which is also the base sphere radius of the spherical gear. η is the unfolding angle of the spherical involute, where $\eta=\phi+\psi$. ϕ is defined as the rolling angle of the circular plane, and γb is the base cone angle.

An additional advantage of using the coordinate transformation method to derive the spherical involute is the ability to quickly obtain the tangent and normal vectors of the spherical involute.

The unit normal vector of the spherical involute at point P in coordinate system $S0$ can be expressed as:

$$n_0^{(P)} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \tag{21}$$

The unit tangent vector of the spherical involute at point P in coordinate system $S0$ can be expressed as:

$$t_0^{(P)} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \tag{22}$$

At point P, the unit normal vector and unit tangent vector are perpendicular to each other. In coordinate system $S3$, they can be expressed as:

$$n_3^{(P)} = L_{32}L_{21}L_{10}n_0^{(P)} = \begin{bmatrix} \cos\eta\cos\varphi + \sin\eta\sin\varphi\sin\gamma_b \\ \sin\eta\cos\varphi - \cos\eta\sin\varphi\sin\gamma_b \\ -\sin\varphi\cos\gamma_b \end{bmatrix} \quad (23)$$

$$t_3^{(P)} = L_{32}L_{21}L_{10}t_0^{(P)} = \begin{bmatrix} -\sin\eta\cos\gamma_b \\ \cos\eta\cos\gamma_b \\ -\sin\gamma_b \end{bmatrix} \quad (24)$$

Here, the coordinate transformation matrices $L32$, $L21$, and $L10$ are 3×3 matrices, which are the submatrices corresponding to the coordinate transformation matrices $M32$, $M21$, and $M10$, respectively.

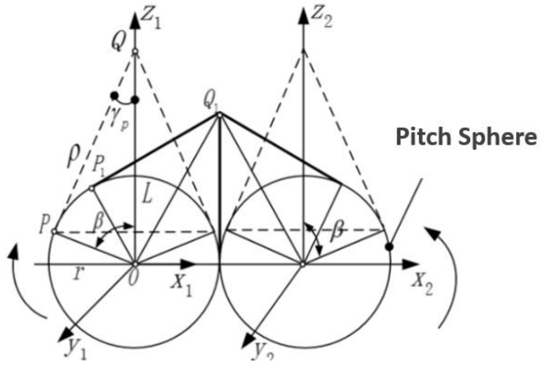

Figure 8. Generation of Spherical Conical Tooth Surface

At a specific pitch position, the meshing transmission between the spherical conical tooth surfaces is equivalent to the pure rolling between a pair of pitch cones. The spherical conical tooth surface is formed by multiple spherical involutes generated at different pitch positions (i.e., on different pitch circles). In other words, the spherical conical tooth surface is a family of spherical involute curves generated on different base cones. The figure illustrates the formation of multiple spherical involutes on the spherical conical tooth surface and the meshing motion of the spherical conical teeth. The transmission ratio of the relative motion of the pitch spheres is 1, which is both the transmission ratio of the ring teeth of the spherical gear and the transmission ratio of the spherical conical gears. The vertex and generatrix length of the base cone are identical to those of the pitch cone.

In the initial position (shown as dashed lines in the figure), the central axes of the two spherical conical gears are parallel, and the generatrix of the pitch cone of gear 1 is tangent to the pitch circle. When the pair of pitch circles rolls relative to each other, the pitch cone of gear 1 moves to the position shown in the figure, where the generatrices of the two pitch cones coincide. Here, rp is the pitch sphere radius of the ring tooth, the angle between OPi and the $z1$-axis is b (defined as the pitch angle of the spherical conical tooth), PQ is the generatrix of the base cone (also the generatrix of the pitch cone), denoted as ρ, the length of OQ is LL, and the angle between PQ and OQ is the pitch cone angle γp.

As shown in the Figure 8, in the right triangle OPQ, the following relationships hold:

$$\gamma_p + \beta = \frac{\pi}{2} \quad (25)$$

By the Pythagorean theorem, the following relationship can be derived:

$$\begin{cases} \rho(\beta) = r_p \tan\beta \\ L(\beta) = \frac{r_p}{\sin\gamma_p} = \frac{r_p}{\cos\beta} \end{cases} \quad (26)$$

Thus, the parametric equation of the spherical conical tooth surface is:

$$\boldsymbol{r}^{(s)}(\beta,\eta) = \boldsymbol{M}_{103} \cdot \boldsymbol{r}_s^{(p)} = \begin{bmatrix} \rho_{(\beta)}[\sin\eta\sin\varphi + \cos\eta\cos\varphi\sin\gamma_b] \\ \rho_{(\beta)}[\cos\eta\sin\varphi - \sin\eta\cos\varphi\sin\gamma_b] \\ -\rho_{(\beta)}\cos\varphi\cos\gamma_b + L_{(\beta)} \\ 1 \end{bmatrix} \quad (27)$$

In the equation, $M103$ is the transformation matrix from coordinate system $S3$ to the ring tooth coordinate system $S10$, given by:

$$\boldsymbol{M}_{103} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & L_{(\beta)} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (28)$$

Therefore, any spherical conical tooth profile surface can be expressed as a dual-parameter vector equation in terms of β and η:

$$\mathbf{r}^{(s)} = r^{(s)}(\beta,\eta) = x(\beta,\eta)\mathbf{i} + y(\beta,\eta)\mathbf{j} + z(\beta,\eta)\mathbf{k} \quad (29)$$

3.2 Generator Module

A Permanent Magnet Synchronous Generator (PMSG) is selected for its high energy conversion efficiency. Permanent magnet generators simplify the design by eliminating the need for additional excitation current, thereby reducing losses and improving efficiency.

Cooling System:

Depending on the generator's power rating and operating environment, a water circulation system and radiator are employed to lower the generator's temperature. The circulating coolant absorbs heat generated by the generator, ensuring it operates within an optimal temperature range.

Bearings and Lubrication:

High-quality bearings are selected, and an appropriate lubrication system is designed to ensure long-term stable operation. The bearings must withstand high-speed rotation and various load conditions, while the lubrication system should maintain effective lubrication across different environmental temperatures.

Control System:

The control system includes real-time monitoring, fault diagnosis, and automatic adjustment functions. It encompasses control algorithms, sensor selection, and real-time monitoring capabilities. The system is designed to seamlessly integrate with the turbine's control system, ensuring coordinated operation and optimizing the performance of the entire power conversion system.

Environmental Protection:

Environmental protection requirements are considered during the design process to ensure that noise and emissions during operation comply with relevant standards, minimizing environmental impact.

Engineering Calculations and Simulation Testing:

Detailed engineering calculations and simulation tests are conducted to validate the design's feasibility. Based on the test results, the parameters of the turbine and generator are adjusted to ensure system stability and economic efficiency under various operating conditions.

3.3 Power Storage Unit

Battery Selection:

We have chosen solid-state lithium-ion batteries, renowned for their slim design, high energy density, lightweight, and excellent waterproof performance[8]. These batteries are well-suited to the compact structure of the spherical gear and can maintain stable performance at various orientations and angles. The Jackery Explorer 240 features a 240Wh battery capacity and a maximum continuous output power of 200W, sufficient to meet the power demands of small appliances and tools in daily use[9]. The design ensures that the battery capacity and output power align with actual user requirements. With a specification of 240Wh (equivalent to 16.8Ah@14.4V), it is suitable for extended off-grid use.

Charging Methods:

The power station supports charging via an included AC adapter, car charger, or solar panels, making it an ideal choice for renewable energy applications. For output interfaces, the Jackery Explorer 240 provides USB-A, USB-C, DC, and AC outputs[8], capable of powering various devices. Weighing only 6.6 pounds, the Jackery Explorer 240 is highly portable. Therefore, the newly designed power station should retain this lightweight and portable characteristic, allowing users to easily carry it to any location.

Battery Management System (BMS):

An advanced BMS is integrated to monitor battery status, control charging and discharging processes, and optimize battery performance and lifespan. The BMS will monitor the battery's voltage, current, and temperature in real time, ensuring the battery system operates optimally during power generation and preventing overheating, overcharging, or over-discharging.

Sealed Design:

The battery casing adopts a high-sealing design and is made of materials with superior water resistance to prevent moisture ingress. The casing may be covered with special waterproof seals or coatings, achieving an IP67 waterproof rating to ensure reliable operation in humid environments.

Energy Management:

The BMS will manage the battery's energy, including balancing the state of charge among battery cells to prevent performance degradation caused by inconsistent charging and discharging. Additionally, the BMS will optimize the charging and discharging processes to extend battery life[10].

Fault Diagnosis and Alarm:

The BMS includes fault diagnosis capabilities, enabling rapid identification of battery system issues and issuing alerts for timely intervention. It also records operational data to support performance optimization and lifespan prediction.

Communication Interface:

The BMS will exchange data with other systems, monitoring devices, or upper-level control systems through a communication interface, enabling remote monitoring and control to enhance the efficiency and reliability of the entire power generation system.

Through the above design, the power storage unit of the spherical gear power generation project will effectively store and manage the electricity generated by the energy converter, ensuring a stable power supply when needed. With the BMS's managemen t[7], the battery's lifespan will be extended, improving the performance and safety of the entire power generation system.

4. Basic Performance and Application Prospects

4.1 Vibration Energy Transmission Testing

4.1.1 Experimental setup and equipment design

(1) Vibration Simulation Device

Function: Simulates vibration conditions in industrial environments, including adjustable vibration amplitude and frequency.

Components:

Adjustable-amplitude exciter to provide stable vibration input.

Vibration control unit for adjusting vibration intensity and characteristics.

Accelerometers and displacement sensors for real-time monitoring of vibration amplitude and frequency.

Vibration isolation platform to contain and isolate the vibration source, ensuring test safety.

(2) Spherical Gear Transmission Device

Function: Ensures optimal operation of spherical gears under various vibration conditions, improving vibration energy capture efficiency and transmission stability.

Components:

Spherical gear assembly, including the main gear and driven gear.

Brackets and fixtures for stable installation of spherical gears.

Bearings and lubrication system to ensure smooth operation and reduce wear.

(3) Energy Conversion and Power Generation Unit

Function: Converts captured mechanical vibration energy into electrical energy.

Components:

Electromagnetic induction coils or piezoelectric elements for converting mechanical vibration into electricity.

Voltage stabilizers and rectifiers for stabilizing and adjusting electrical output.

Power quality analyzer for monitoring the stability and quality of electrical energy.

(4) Measurement and Monitoring Equipment

Function: Measures and records key parameters during experiments, such as vibration intensity, output power, and system stability.

Components:

Accelerometers for measuring vibration acceleration.

Power meters for measuring output power.

Data loggers for recording parameter changes during experiments.

(5) Data Acquisition System

Function: Collects and stores experimental data in real time for subsequent analysis and optimization.

Components:

Data acquisition cards and corresponding software for collecting data from sensors.

Computers or controllers for running data acquisition software and storing data.

Displays or chart recorders for real-time visualization of experimental data and trends.

The measured data is collected, processed, and averaged to obtain the results shown in the table below.

4.1.2 Experimental observations and analysis

In this experiment, we aimed to evaluate the performance of the vibration energy transmission system, particularly its efficiency in capturing industrial vibration energy and converting it into electrical energy[3]. The following are the observations and analysis:

(1) Performance of the Vibration Simulation Device

Exciter Stability: The exciter successfully provided stable vibration input, simulating industrial vibration conditions.

Vibration Control Unit: The vibration control unit performed well, precisely adjusting vibration intensity and frequency to meet different testing requirements.

(2) Efficiency of the Spherical Gear Transmission Device

Gear Operation: The spherical gears operated stably under various vibration conditions, demonstrating excellent adaptability and stability.

Bearings and Lubrication: The bearings and lubrication system effectively reduced wear during gear operation, ensuring transmission efficiency.

(3) Performance of the Energy Conversion and Power Generation Unit

Electromagnetic Induction and Piezoelectric Elements: The electromagnetic induction coils and piezoelectric elements efficiently converted mechanical vibration into electrical energy.

Power Stability: The voltage stabilizers and rectifiers ensured stable electrical output, and the power quality analyzer confirmed that the power quality met expected standards.

(4) Accuracy of Measurement and Monitoring Equipment

Accelerometers: The accelerometers accurately measured vibration acceleration, providing critical data for system performance evaluation.

Power Meters: The power meters consistently recorded output power, reflecting the system's energy conversion efficiency.

(5) Reliability of the Data Acquisition System

Data Acquisition Cards: The data acquisition cards and software successfully collected data from sensors without technical failures.

Computers or Controllers: The computers or controllers ran the data acquisition software stably and stored experimental data accurately.

Real-Time Data Display: The displays or chart recorders effectively visualized experimental data and trends in real time, facilitating monitoring and analysis.

The experimental results indicate that the vibration energy transmission test system performed well overall, with all components working synergistically to achieve the intended testing objectives. The vibration simulation device successfully replicated industrial vibration environments, and the spherical gear transmission device demonstrated efficient vibration energy capture[5]. The energy conversion and power generation unit effectively converted the captured energy and provided stable electrical output. The measurement and monitoring equipment, as well as the data acquisition system, exhibited high accuracy and reliability.

Future work will focus on further optimizing system performance, improving energy conversion efficiency, and exploring additional industrial application scenarios to enable broader vibration energy recovery and utilization.

4.2 Innovative Aspects of Gear Design

(1) Involute Gear Design

The spherical gear design breaks through traditional limitations, enabling free rotation in three-dimensional space. This characteristic enhances its efficiency and adaptability in capturing industrial vibration energy. Compared to conventional cylindrical gears, the spherical gear design significantly improves energy conversion efficiency and enhances responsiveness to vibrations from different directions.

(2) Unique Energy Capture Mechanism

In industrial environments, vibration energy is transmitted to the spherical gear device through a turbine. The unique shape and structure of the spherical gear allow it to decompose complex multi-dimensional vibration motions and convert them into unidirectional transmission energy. This process not only improves energy capture efficiency but also effectively transmits rotational motion to the generator through the gear transmission mechanism[9], converting mechanical energy into electrical energy for industrial facilities.

(3) Maintenance and Sustainability

The spherical gear power generation system is designed for long-term efficient and stable operation. Regular professional maintenance plans help extend equipment lifespan, reduce failure risks, and ensure continuous power supply. The project employs eco-friendly materials and energy-saving technologies[7], aiming to minimize resource consumption and waste generation. By recycling old components and optimizing production processes, the project significantly reduces carbon emissions, aligning with international environmental standards.

4.3 Future Prospects

The spherical gear power generation project demonstrates significant potential and promising development prospects in capturing and converting industrial vibration energy. As global demand for sustainable energy solutions grows, industrial vibration energy, previously an underutilized energy source, is gaining attention. Spherical gears, as the core component of this power generation system, effectively convert irregular vibration energy into useful electrical energy, providing additional power supply for industrial facilities. Continuous technological advancements will further optimize the design and manufacturing processes of spherical gears, enhancing their transmission efficiency and durability. This will not only reduce the operational and maintenance costs of the entire power generation system but also improve energy conversion efficiency[5], making industrial vibration energy recovery economically viable. Compared to traditional fossil fuel-based power generation methods, projects utilizing industrial vibration energy have a smaller environmental impact, significantly reducing greenhouse gas emissions and other environmental pollution issues. This aligns with global efforts to promote environmental protection and sustainable development.

In terms of policy support, many governments have introduced various incentives, such as financial subsidies, tax reductions, and priority grid access, to promote the development of renewable energy technologies, including industrial vibration energy[2]. These policies provide a favorable environment for the commercialization and scaling of spherical gear power generation technology, encouraging further investment and innovation.

In summary, the spherical gear power generation project has broad application prospects and significant market potential in industrial vibration energy recovery and utilization[9]. As the technology matures and policies advance, spherical gear power generation technology is expected to play an increasingly important role in industrial energy recovery, contributing significantly to the global energy transition and sustainable development.

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