Original Research Article

A leaf shredding and collecting machine based on counter-Rotating blade technology

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Abstract: This study presents the design of a leaf shredding and collecting machine based on counter-rotating blade technology, aimed at addressing the inefficiencies in urban green waste management. The machine integrates a rotary rake mechanism for leaf collection and a counter-rotating blade system for shredding, ensuring efficient processing of fallen leaves. Key components, including the rotary rake, shredding unit, and power transmission system, were optimized through mechanical calculations and 3D modeling using Unigraphics NX software. The design achieves high shredding efficiency with reduced motor power consumption and includes a height-adaptive mechanism for terrain adaptability. The results demonstrate the machine's capability to automatically collect, shred, and store green waste, offering a practical solution for urban green waste utilization and contributing to the sustainable development of green energy.

Keywords: Leaf shredder; Leaf-to-energy conversion; Unigraphics NX

1. Introduction

Many developing countries around the world face the dual challenges of limited energy reserves and large population bases, with China being a prominent example. In order to meet the enormous energy demands of industrial production and societal needs, it is essential not only to utilize conventional energy sources such as petroleum and coal more efficiently, but also to vigorously develop alternative green energies such as solar, nuclear, and wind power. This transition toward new energy sources to gradually replace conventional ones represents the prevailing trend in the current energy sector[1,2] . Among these alternatives, biomass energy has attracted considerable attention due to its natural abundance, renewability, and environmentally friendly characteristics. Through processes such as degradation, liquefaction, and gasification of green waste residues, biomass can be converted into fuels such as syngas and vegetable oils. At present, as an important supplement to the new energy industry, biomass energy is the focus of extensive research and growing interest[3,4].

With the rapid advancement of urbanization and industrialization in China, forestry resources have shown a gradual decline, while urban greening resources have exhibited a sharp increase. Consequently, there is an abundant availability of urban green waste in China. This is particularly evident during urban greening activities such as pruning, felling operations, and the seasonal leaf shedding of deciduous trees in northern regions during the autumn and winter transition, which collectively generate large quantities of green waste, including branches, grass clippings, sapwood, and leaves[5]. Efficient collection of green waste, followed by its conversion into green energy through physical processing, chemical transformation, or biological degradation, offers an effective pathway to transform renewable green resources into energy products that can be directly utilized in industrial production and daily life. This strategy represents a practical and promising solution to alleviate the current energy shortage in China[6,7]. However, due to the lack of effective collection methods for materials such as fallen leaves and grass residues, a large portion of urban green waste remains underutilized. Therefore, the deployment of specialized equipment capable of efficiently collecting, crushing, and storing urban green waste is of critical importance. Such technology would greatly promote the sustainable development of both China's urban greening industry and its ecological energy sector[8] .

At present, there are shredding machines available that are suitable for processing large branches and leaves. However, due to their substantial weight, these machines are typically installed in fixed locations and require manual operation, with workers using feeding tools to deliver raw materials to the inlets. As a result, they are incapable of automatically collecting and shredding fallen leaves[9]. In addition, a small number of mobile roadside leaf collectors, towed by tractors, have been developed. However, these systems generally rely on suction-based mechanisms for collection, which makes it difficult to simultaneously achieve effective material shredding[10] .

To address these limitations, this study proposes a raking-suction type leaf shredder capable of efficiently collecting, shredding, and storing urban green waste. First, the overall technical route of the machine was determined, and the geometric dimensions of the key components were designed. Subsequently, the reliability of the mechanical structure was evaluated through calculation and verification, with iterative optimization of the geometric parameters.

2. Working principle and main technical parameters of the leaf shredder

2.1. Principles of leaf collection, shredding, and discharge

In this type of leaf shredder, power from the electric motor is transmitted via a coupling and output shaft to the primary multi-ribbed pulley mounted on the main shaft. The main shaft pulley drives two subsystems: forward transmission occurs through a 10-ribbed belt to a secondary multi-ribbed pulley (with two ribs) connected to the rotating rake shaft. This pulley drives the rotation of the rake shaft, transferring kinetic energy to another multi-ribbed pulley (with four ribs) at the opposite end of the rake shaft. This secondary pulley then drives the stiff brush shaft to rotate in the same direction via another multi-ribbed belt.

Thirty-three bundles of symmetrically staggered rotating rakes are mounted on the rake shaft, effectively clawing fallen leaves of specified sizes from the ground and conveying them toward the stiff brush region. The multi-ribbed pulley mounted on the opposite side of the rake shaft further drives the stiff brushes to rotate in the same direction, thereby sweeping the collected leaves into the feed inlet.

The rotating rakes and stiff brushes serve as a pre-shredding mechanism, effectively reducing the strength and size of the collected leaves to a certain extent. The shredding unit consists of four blades rotating in alternating directions. An interlocking mechanism based on a fixed-axis gear system is employed between adjacent blades, ensuring that neighboring blades rotate in opposite directions. This configuration generates a high relative velocity between the blades, allowing the shredder to achieve a significantly enhanced shearing effect. As a result, even under relatively low motor power and main shaft rotational speed, the blades can attain a high relative rotational speed, thereby ensuring more thorough and efficient leaf shredding.

This device adopts a multifunctional single-shaft mechanical optimization design. Curved blades with alternating rotational directions are arranged along the midsection of the shredding shaft. In addition to performing the shredding operation, these blades also facilitate air guidance within the chamber. At the end of the shaft, a lightweight metal fan blade is mounted in series. As the shaft rotates, the fan generates a significant pressure differential along the axial direction within the shredding chamber, promoting the directed movement of shredded leaves. Ultimately, the shredded material is discharged through the outlet and collected in a collection bag positioned at the rear of the machine.

2.2. Main technical parameters of the leaf shredder

2.2.1. Determination of the diameter, shape, and arrangement of the rotating rakes

In the leaf hooking mechanism, the rotating rake is positioned at the end of the transmission chain. The determination of the rake's dimensions and technical parameters is a primary prerequisite for the reverse design of the entire machine[11]. The design requirement for this shredder is to operate under a working speed of 0.5–1.1 m/s, targeting leaves with a minimum internal diameter greater than 30 mm. Considering that an excessively large rake diameter would result in an excessively high linear velocity at the same rotational speed — and given the approximately linear relationship between air resistance and velocity — there is a heightened risk of leaves breaking during the hooking process. Moreover, an increase in rake diameter is directly proportional to an increase in the required driving power. Taking all factors into account, a rake diameter of approximately 300 mm is considered optimal.

As shown in Figure 1, the geometry of a single rake tine is depicted. For optimal performance when hooking leaves, the rake teeth should penetrate at a vertical angle. The required sliding distance from the hooking side to the side that leaves the ground is given by:

$$\mathrm{L} = \frac{\mathrm{R}}{2} \times \sin\alpha \times 2 \tag{1}$$

Where: L is the sliding distance of the leaf along the ground; R is the radius of a single rake tine; α is the angle between the rake teeth and the tine.

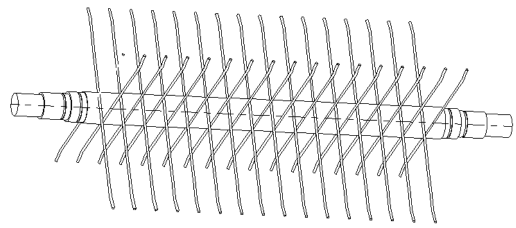

Figure 1. Geometrical shape of the rake tine in the rotary rake.

To ensure an optimal leaf pickup rate, the pickup rate increases as the axial distance *l* between the rake tines decreases. Therefore, when the relative overlap of the rake tines ε_α=2, the axial distance between the rake tines is set to 15 mm.

$$\varepsilon_\alpha = l/c \tag{2}$$

Where: *l* is the axial distance between the rake tines; c is the minimum inner diameter of the leaves.

2.2.2. Determination of the rotary rake shaft drive power

The rotational speed of the rotary rake shaft is related to the working speed V of the crusher and the distribution of leaves on the ground. For modeling convenience, the working speed is set to 0.5 m/s, and the leaves are assumed to be distributed in a single-layer full-cover pattern. It is determined that, for every 0.5 m of working distance, 17 leaves are distributed per unit width. Therefore, the rake will encounter 17 leaves per second, meaning the rake must rotate 4.25 times per second to collect all the leaves. With a safety factor of 1.4, the rotational speed is set to 6 r/s. Using the relation ω=2πn, the angular velocity ω=12π/s. The formula for calculating the required driving power of the rotary rake shaft is as follows[12] :

$$\mathrm{P} = (\varpi_1 * R_1 * F_1 + \varpi_2 * R_2 * F_2) \tag{3}$$

Where, ϖ_1 is the angular velocity of the rotary rake; R_1 is the rotational radius of the rotary rake;
F_1 is the force required for the rake to collect leaves; ϖ_2 is the angular velocity of the steel brush;
R_2 is the rotational radius of the steel brush; F_2 is the force required for the steel brush to brush the leaves; P is the transmission efficiency. With values ϖ_1=47.12r/s, R_1=0.15m, F_1=20N, ϖ_2=31.4r/s, R_2=0.06m, F_2=10N, the driving power is calculated as P=160.2 W, rounded to P=160.2W.

2.2.3. Determination of the rotational speed of the shredder blade spindle

The rotational speed of the shredder blade spindle determines the crushing effectiveness of the collected fallen leaves. Based on parameters from domestic leaf shredders, the spindle speed is typically set between 500 and 3000 rpm. Given the counter-rotational motion between adjacent blades, which significantly increases the relative speed between the blades, as well as the pre-crushing and directional debris removal effect of the steel brush, a lower rotational speed is sufficient to meet the operational requirements. The initial speed is set to 1200 rpm, with experimental data to be collected after the prototype is fabricated. The formula for calculating the power of the shredder blade spindle is as follows [13]:

$$P=Z\times\omega\times R\times F/K \quad (4)$$

Where, Z is the number of shredder blades; ω is the angular velocity of the spindle; R is the rotational radius of the steel brush; F is the force required for the steel brush to brush the leaves; K is the transmission efficiency, where $K=\beta_1\beta_2\beta_3\beta_4$; $\beta_1=0.96$ is the efficiency of the V-belt transmission; ; $\beta_2=0.98$ is the efficiency of the rolling bearing transmission; $\beta_3=0.97$ is the efficiency of the closed gear transmission; $\beta_4=0.99$ is the efficiency of the coupling; ; The calculated power is P=2.2kw.

3. Design of key components for the leaf shredder

3.1. Design of rotary rake transmission and component design

The power input to the rotary rake is transmitted from the electric motor to the main spindle of the rake via a coupling and a multi-V-belt. The power for the leaf brush is transferred from the input side of the rotary rake shaft to the power output side, and then, through the output side of the rake shaft, the power is transmitted to the leaf brush shaft via the multi-V-belt, driving the leaf brush in the same rotational direction. This design simplifies the power transmission system with multiple power inputs. The schematic diagram of the transmission is shown in Figure 2.

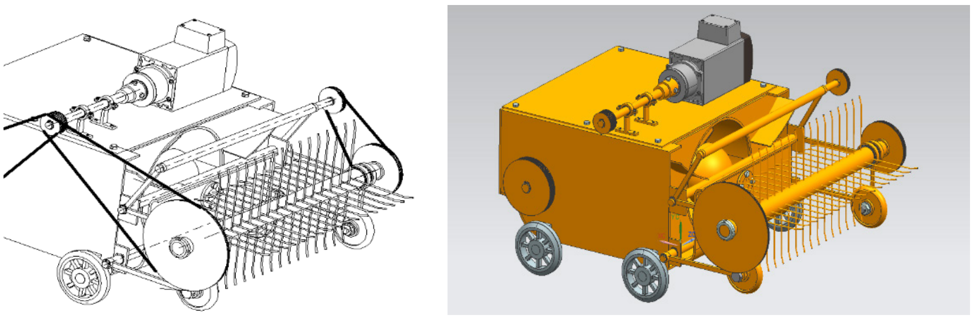

Figure 2. Transmission design of the rotary rake and leaf brush device and rotary rake air-intake leaf shredder model.

Due to the use of a height-adaptive device at the front end of this machine, if the leaf brush is fixed in position, the rotary rake will experience fluctuations in working height during operation, which will continuously alter the center distance and overlap between the rake and the leaf brush, resulting in alternating stresses. This can significantly reduce the mechanical lifespan. Therefore, a triangular retaining arm hinged to the housing is used to maintain a constant center distance between the rotary rake and the leaf brush, as shown in Figure 3.

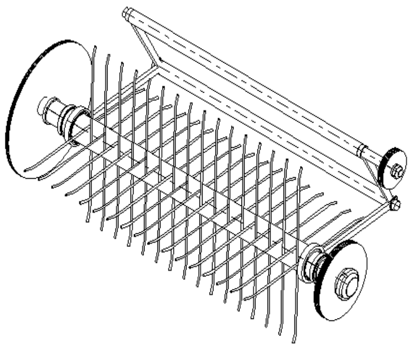

Figure 3. Rotary rake and leaf brush device with fixed center distance.

The height of the rotary rake must be maintained at a constant value relative to the ground to prevent contact between the rake and the ground in areas with pits or protrusions, which could damage the rake and reduce its lifespan. Therefore, by connecting the front wheel frame to the lower part of the housing via a transmission pair, and linking the rake shaft to the upper part of the housing through another transmission pair, a four-bar mechanism is formed. This design ensures that the rotary rake maintains a constant distance from the ground. As shown in Figure 4.

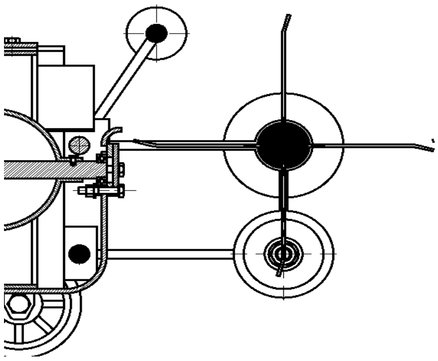

Figure 4. Rotary rake height adaptive device with four-bar mechanism.

3.2. Design of the rotary rake spindle

The rotary rake spindle is a critical component for the installation and fixation of several major parts, including the spindle gear, planetary carrier, reversing wheel, and internal gears of the triple-blade system. This spindle integrates the height-adjustable front wheel assembly, the fixed center distance triangular arm, input pulley, output pulley, and the rotary rake's multi-position rotation into a single unit, using a symmetrical arrangement of four bearings and dual pulleys. The design of the spindle must take into account the assembly relationships between the components and the values of the transmitted torque. Based on the torsional strength of the minimum shaft diameter as the design criterion, the minimum diameter at the spindle neck can be calculated. The detailed calculation formula is as follows:

$$d \geq 17.2\sqrt[3]{\mathrm{T}/\tau_{\mathrm{P}}} = A\sqrt[3]{P/n} \tag{5}$$

Where, T is the torque applied to the shaft, in N·mm; τ_p is the allowable torsional shear stress, in MPa; P is the power transmitted by the shaft, in kW; n is the rotational speed of the shaft, in r/min; d is the diameter of the shaft at the minimum cross-section, in mm.

The design material for the spindle is typically 45 steel, following the shaft and connection verification steps outlined in section 6-1-18 of the Mechanical Design Handbook [14]. Based on the torsional strength and stiffness calculations for the spindle neck, the value of AAA is taken to be between 103 and 126, with a value of 120 selected for this case. The peak power of the rotary rake spindle in the leaf shredder is 0.245 kW, and the spindle speed is set to 540 r/min. Substituting these values into the formula, the minimum diameter of the spindle at its narrowest point should not be less than 9.22 mm. Considering the fit with other components, interference prevention requirements, and manufacturing process constraints, the minimum diameter of the rotary rake spindle is set to 33 mm. The design of the rotary rake spindle is shown in Figure 5.

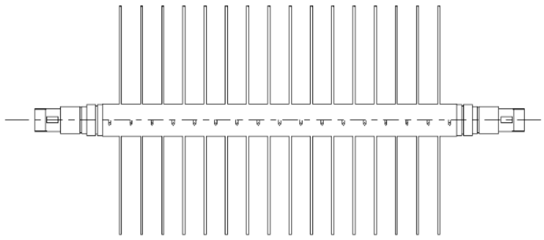

Figure 5. Rotary rake spindle.

3.3. Leaf shredding device with four-level counter-rotating blades based on a fixed shaft gear system

The arrangement and parameters of the counter-rotating blades are shown in Figure 6. Based on the mechanical characteristics where two external meshing gears rotate in opposite directions and two internal meshing gears rotate in the same direction, the direction of the sleeve gear can be reversed relative to the internal gear by meshing the sleeve gear with a fixed idler gear, which then meshes with the fixed internal gear. This configuration allows the direction of rotation of the sleeve gear to oppose that of the internal gear. The triple-blade system fixed to the outer circumference of the internal gear can then rotate in the opposite direction to the sleeve blade, enabling the low-speed rotation of the shaft to achieve a higher relative speed between adjacent blades. This reduces the load on the shaft, lowers the required motor power, and decreases manufacturing costs.

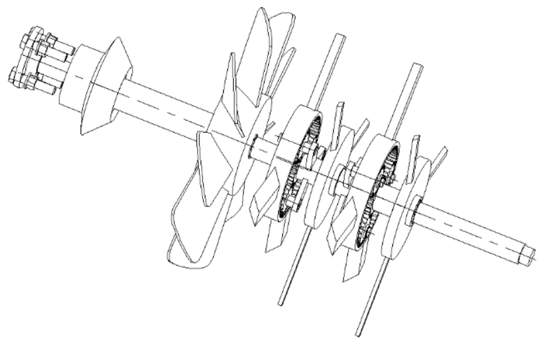

Figure 6. Leaf shredding device with four-level counter-rotating blades based on a fixed shaft gear system.

The geometric parameters of the shredding spindle are shown in Figure 7. Following the principles of mechanical design optimization, this spindle achieves a multi-functional design with a single shaft. It integrates the forward and reverse rotation design and arrangement of the blades, the series connection of the debris removal fan, and the transmission of input power into one unit. This not only optimizes the structure rationally but also significantly reduces the risks associated with work fatigue and the manufacturing costs. Based on the torsional strength of the minimum shaft diameter as the reference for verification, the minimum diameter at the spindle neck can be calculated. The detailed verification formula is as follows:

$$d \geq 17.2\sqrt[3]{\mathrm{T}/\tau_{\mathrm{P}}} = A\sqrt[3]{P/n} \tag{6}$$

T is the torque applied to the shaft, in N·mm; τ_p is the allowable torsional shear stress, in MPa; P is the power transmitted by the shaft, in kW; n is the rotational speed of the shaft, in r/min; d is the diameter of the shaft at the minimum cross-section, in mm.

The material of the shaft is 45 steel. According to the verification steps for shafts and their connections in section 6-1-18 of the Mechanical Design Handbook, the value range for Acalculated based on torsional strength and stiffness is between 103 and 126, with 120 selected for this case. The peak power required for the main spindle of the leaf shredder is 2.2 kW, and the initial spindle speed is set to 1200 rpm. By substituting the above data into the formula, the minimum diameter of the shredding spindle is calculated to be 14.68 mm. Considering the fit with other components, interference prevention requirements, and manufacturing process constraints, the minimum diameter of the shredding spindle should not be less than 17 mm.

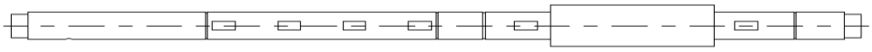

Figure 7. Shredding spindle.

4. Conclusion

The proposed leaf shredding and collecting machine effectively addresses the challenges in urban green waste management by combining a rotary rake collection mechanism with a counter-rotating blade shredding system. The design ensures efficient leaf collection, thorough shredding, and rapid discharge of shredded material. Key innovations include the height-adaptive rotary rake and the fixed-shaft gear system, which enhance performance while reducing power consumption. 3D modeling and assembly confirm the design's feasibility and manufacturability. This machine provides a practical solution for urban green waste utilization, supporting the development of sustainable green energy. Future work will focus on prototype testing and performance optimization for broader application.

About the author

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References

[1] Dong, S., Xu, J., & Wang, X. H. (2000). Utilization methods and technologies of residual materials in foreign logging areas. Forest Engineering, 16(1), 57-58.

[2] Qiao, Y. J., Xia, Y., & Fang, Y. (2004). Utilization and development prospects of tree leaves. Protective Forest Science and Technology, 60(3), 33-35.

[3] Li, J., & Wang, Z. J. (2010). Research on the utilization of forest harvesting residues in China. Anhui Agricultural Science, 38(7), 3787-3789.

[4] Chen, Y. X., Xiao, S., & Wang, Q. (2007). Research on the rational utilization of woody residues in forest areas. Forest Engineering, 23(6), 1-5.

[5] Liu, M. H. (2010). Overview of the current situation and prospects for the development and utilization of "three residuals" in forestry. Forest Survey and Planning, 35(3), 62-67.

[6] Dong, S., Xu, J., & Wang, X. H. (2000). Utilization methods and technologies of residual materials in foreign logging areas. Forest Engineering, 16(1), 57-58.

[7] Xiao, S. L. (2001). A comparison of different production processes for harvesting residues chip production. Journal of Northeast Forestry University, 29(1), 90-92.

[8] Li, S. L. (1999). On the comprehensive, rational, and economical utilization of forest resources. Forest Engineering, 15(3), 16-17.

[9] Tang, S. (2011). Design and research of a mobile branch shredder (Master's thesis). Beijing Forestry University.

[10] Andersson, G. (1999). New technique for forest residue handling. Presented at the Forest Engineering for Tomorrow Conference (June 28-30), Edinburgh, Scotland.

[11] Cheng, D. X. (2007). Mechanical Design Handbook (5th ed.). Beijing: Higher Education Press.

[12] Pu, L. G., Chen, G. D., & Wu, L. Y. (2013). Mechanical Design (9th ed.). Higher Education Press.

[13] Liu, X. L., & Cui, J. L. (2017). Mechanical Design Course Design Based on CDIO. Tsinghua University Press.