DESIGN, ANALYSIS AND TEST OF SMALL ROTARY LAWN MOWER OF SINGLE-DISC TYPE
/
小型单元盘割草机设计、分析与试验

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ABSTRACT

Machine quality, mowing efficiency and work reliability of lawn mowers are main issues concerned in hilly and mountainous regions. Taking a rotary lawn mower of single-disc type as research object, structure and parameter design of the mower was defined according to empirical formula, performance of grass cutting and modal analysis of the cutting blades were conducted by means of EDEM and Creo, and field test was conducted to verify the overall performance of the machine. Results showed that symmetrically installed 2 cutting blades with revolution speed 3500 r/min and forward speed 1.4 m/s showed good performance of grass cutting and stability. The velocity of grass particles of cut grass was mostly in the range of 1.1-1.5 m/s, and the velocity of broken grass was stable, which proved good harvest and gathering of grass. The height of remained stubbles was about 50 mm, and the length of cut grass was distributed in the range of 30-60 mm, which met requirements of forage production.

摘要

丘陵山地割草机的机器质量、割草效率和工作可靠性广受关注。本研究以小型单圆盘式旋转割草机为研究对象，根据经验公式对其进行了结构和参数设计，基于 EDEM 和 Creo 对割草性能和切割刀片振动模态进行了分析，并割草机的整机性能进行了田间试验。结果表明，对称布置 2 把切割刀片，在旋转速度 3500r/min，前进速度 1.4m/s 的条件下，切草性能和稳定性俱佳。被切草粒子的速度值主要范围为 1.1-1.5m/s，且速度稳定，有利于牧草收割和拢草。割后草茬高度约为 50mm，割后草段长度范围 30-60mm，能满足牧草生产要求。

INTRODUCTION

China is rich in grass resource and ranks the 2nd largest country of grassland area after Australia, having nearly 4 million km^2 of natural grasslands (*Yang L., 2019*). Especially in the southwest of China, there are plentiful of rainfall and heat that benefit the growth of grass, which results in 4-6 times of natural grassland area higher than that in the north. However, the grasslands in the southwest are mostly distributed in hilly and mountainous regions, particularly in the range of 800 to 2000m above sea level, and they mainly consist of sparsely dispersed forest grassland and shrub grassland. As a result, the harvest and utilization of the grass are difficult by means of large lawn mower in these regions, with the effective utilization rate less than 50% (*Fu M.Z., 2009*). Therefore, it is necessary to develop small lawn mowers suitable for the mowing in these regions with good quality, high efficiency, and low cost (*Yang H.W. and Zhang Y.H., 2016*).

According to the working principle of cutters, lawn mowers can be divided into reciprocating lawn mowers and rotary ones (*He Z.Q. et al, 2020; Fu M.Z. et al, 2018*). As cutters of the rotary lawn mowers rotate with high revolution speed, they are suitable for grass harvest of high-yield forage with fast forward speed, and they show high reliability under harsh conditions, such as high humidity, high density, and severe lodging (*Zhang N., 2014; Yang S.K. and Su Z.F., 2009*). At present, the applicability of lawn mowers cannot fully meet the requirements of grass harvest in the southwest of China, especially in the hilly and mountainous regions. The main obstacles to the applicability are failures during mowing because of unreasonable design and unqualified manufacturing. With the advance of rectification of rural industrial structure, reforestation of

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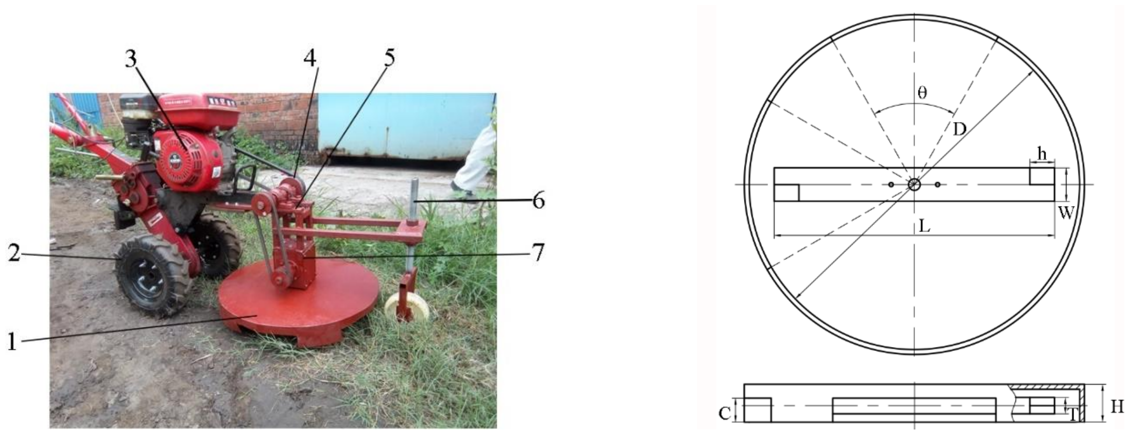
countryside, and agricultural mechanization of weak links in the hilly and mountainous regions of China, farmers' desires to purchase lawn mowers increased substantially (*Xie Y.F. et al, 2020*).

This study focused on development, analysis, and test of a small rotary lawn mower of single-disc, including explanation of working principle, design of main parameters, analysis of cutting process and vibration, performance evaluation by field test. The results could provide basis for the development and optimization of lawn mowers suitable for hilly and mountainous regions.

MATERIALS AND METHODS

Materials

A small rotary lawn mower of single-disc type was developed, as shown in Fig.1 (a). Configuration of grass box and cutting blade was shown in Fig. 1 (b). The external diameter of grass box *D* was 0.6 m. The dimensions of the cutting blade were length *L* 0.5 m, width *W* 0.08 m, thickness *T* 0.05 m, and cutting-edge height *h* 0.056m. There were 2 openings at the bottom edge of the grass box, one as entrance of growing grass, and the other as exit of cut grass. Both openings had opening angle θ 60^{o} . The entrance was forward faced, and the exit was right-sided along forward direction of the mower. The cutting blade and grass box were made of carbon steel. Field test was conducted in a grassland in Beibei, Chongqing, China. Tape measure with precision of 1 mm was used to measure dimensions of growing grass, cut grass and stubble left.



(a) (b)

Fig. 1 - Lawn mower: (a) outlook; (b) dimensions of grass box and cutting blades

1- Grass box; 2- Walking wheels; 3- Diesel engine; 4- Pulley; 5- Frame; 6- Adjusting lever; 7- Gearbox

Methods

Cutting velocity

A coordinate system was defined as *X* along the right side, and *Y* along the forward speed, and the trajectories of end points a and b of cutting-edge of the cutting blade and composition of cutting velocity were plotted, as shown in Fig. 2. The move of the cutting blade was the combination of lawn mower walking and rotation of the blade, then a trochoid was formed for the blade (*Ma X.C. 2005; Dong D.J. and Chen H. X., 2002*). For the end points of the cutting-edge, their positions were expressed as (*Fu, M. Z. et al, 2018*):

$$\begin{cases} X_{\mathrm{a}} = r\cos(\omega t + \beta) \\ Y_{\mathrm{a}} = V_{\mathrm{m}} t + r\sin(\omega t + \beta) \end{cases}, \text{[m]} \tag{1}$$

$$\begin{cases} X_{\mathrm{b}} = R\cos(\omega t + \alpha) \\ Y_{\mathrm{b}} = V_{\mathrm{m}} t + R\sin(\omega t + \alpha) \end{cases}, \text{[m]} \tag{2}$$

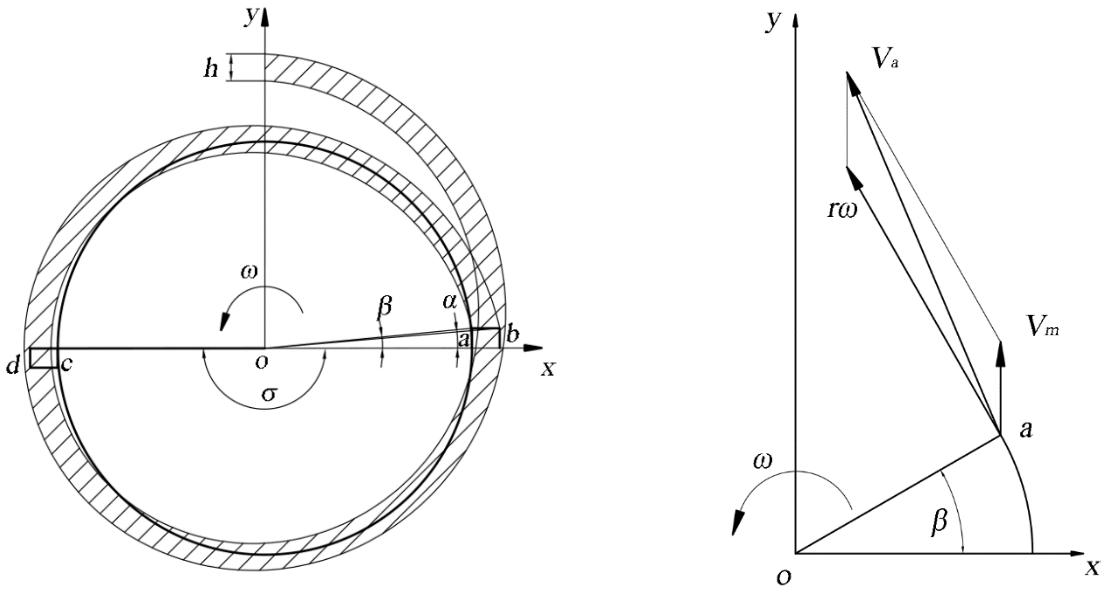
Where

(X_a, Y_a) – position of point a [m]; (X_b, Y_b) – position of point b [m]; ω – angular velocity, [rad/s];

r– radius of point a, [m]; R– radius of point b, [m]; t – time, [s]; V_m – forward speed of lawn mower, [s];

β – rotation angle of point a at time t, [rad]; α – rotation angle of point b at time t, [rad].

By applying differentiation to Eqs. (1) and (2), the cutting velocity of points a and b could be obtained. The cutting velocity can also be schematically plotted as combination of forward speed and rotational speed, and the velocity of point a, namely V_a was shown in Fig. 2 (b).



(a) (b)

Fig. 2 – Trajectories of end points of cutting-edge and cutting velocity: (a) trajectory; (b) cutting velocity

For each cutting-edge with height *h*, there was a cutting width *h* along the forward direction, as shown in Fig. 2 (a). In order to cut grass without missing, the following requirement should be met:

$$\frac{V_\mathrm{a}}{V_\mathrm{m}} \geq \frac{2\pi r}{mh}, \text{[dimensionless]} \tag{3}$$

Where *m*–number of cutting blades, [pieces].

Power consumption

The walking wheels and cutting blades of the lawn mower were driven by the same diesel engine while with different transmission paths. As for the cutting blades, power of engine was transmitted to a gear box through belts. There was a vertical output via transmission of bevel gears. Then, the cutting blades in the grass box was driven by the vertical output. Therefore, the total power consumption of the lawn mower was expressed as (*Stone and Gulvin, 2007*):

$$P = P_1 + P_2 + P_3, \text{[kW]} \tag{4}$$

Where P – total power consumption, [kW]; P_1 – power consumption in transmission, [kW];

P_2 – power consumption in grass cutting, [kW]; P_3 – power consumption for forward move, [KW].

The power consumption in transmission was expressed as:

$$P_1 = P_\mathrm{u} B, \text{[kW]} \tag{5}$$

Where P_u – power consumption for unit cutting width, [kW/m]; B – cutting width of lawn mower, [m].

For flat grassland, the power consumption in grass cutting was expressed as (*Chinese Academy of Agricultural Mechanization Sciences*, 2007):

$$P_2 = \frac{V_\mathrm{m} B W_0}{102}, \text{[kW]} \tag{6}$$

Where W_0 – work for unit area of grass cutting, [J/m^2].

Numerical method

For forage grass cutting, stalks of the grass are regarded as structure of slender pipes. The contact, collision between stalks and other motions of the stalks can be treated as function by particles with corresponding parameters. Then, stems and leaves of the forage grass can be filled in the grass box and bonded each other as particles in discrete element method analysis. Software of EDEM was employed in the numerical analysis. As there was cohesion force while grass cutting, Hertz-Mindlin adhesive contact model was selected.

Particles became bonded at a certain time t_{BOND}, namely bond time. Before t_{BOND}, particles interacted through default Hertz-Mindlin contact model. The adhesive normal and tangential forces F_n, F_t and torques T_n, T_t increased from zero with time (*Wang G.Q. et al, 2010*). For bonded particles, when normal and tangential stresses exceed a certain value, the bond was destroyed. Therefore, the maximum values of normal and tangential stresses were defined as:

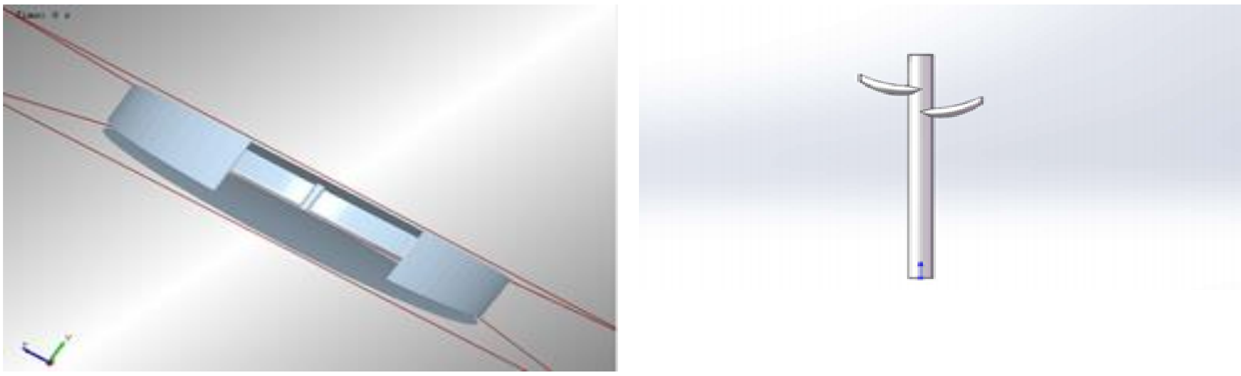
$$\sigma_{\max} < \frac{-F_n}{A} + \frac{2T_t}{J} R_B,\ [\text{N}] \tag{7}$$

$$\tau_{\max} < \frac{-F_t}{A} + \frac{T_n}{J} R_B,\ [\text{N}] \tag{8}$$

Where R_B – bond radius, [m]; A – contact area, [m^2], and $A = \pi R_B^2$; J – parameter, [m^4], and $J = \frac{1}{2}\pi R_B^4$.

The standard Hertz-Mindlin forces increased with the process of bonding, and bonding forces and moments increased as well. When bonding forces were introduced into the contact model, particles were no longer in natural contact. Then the contact radius should be set larger than actual contact radius of the spherical particles (*Yao Y.P. et al, 2015; Shimizu and Cundall, 2001*).

Simplified model of grass box with cutting blades and forage grass was created in Creo software, as shown in Fig. 3. According to the actual situation, the height of the forage grass was set to 60 mm, and diameter 10 mm. Some suitable amount of grass was added into the model during simulation.



(a) (b)

Fig. 3 – Geometric model: (a) Grass box and cutting blades; (b) Grass

Forage grass was automatically meshed in software of Gambit with minimum mesh size 0.26 mm. According to real problem of forage grass cutting, the minimum mesh size was manually set as 10.4 mm, 40 times of original 0.26 mm, in order to reduce computing time and save computing resources. 9555 particles were created to form a stalk of forage grass, as could be extracted in the file of API (Application Programming Interface). Similarly, only a small amount of grass stalks was considered in this study, as treated by a previous work (*Moysey and Thompson, 2005*). There were 2 types of particles for the grass, namely fraction particles and whole particles. A grass stalk was filled with fraction particles, and fraction particles combined as whole particle subsequently. Particle replacement method was adopted in the simulation. The material of cutting blades and grass box is defined as steel. The basic parameters for the DEM simulation were adopted, as shown in Tab. 1.

Table 1

Basic parameters of material and contact

Items	Material		Contact	
	Grass	45 steel	Grass-grass	Steel-grass
Poisson's ratio	0.4	0.3	/	/
Shear modulus [MPa]	1	10000	/	/
Density [kg/m^3]	100	7800	/	/
Restitution coefficient	/	/	0.2	0.5
Static friction coefficient	/	/	0.5	0.01
Dynamic friction coefficient	/	/	0.5	0.01

The grass cutting plane was a circular plane, with the same diameter as rotation diameter of the cutting blades. When grass particles of a stalk were replaced, grass model was re-generated at centre of whole particle of the stalk. The lower plane of grass cutting machine was defined as 150 mm, equal to the radius of whole particle of a stalk.

The total number of whole particles was 15, equal to the number of the grass stalks (*Chen, J. et al, 2011*). The Rayleigh time-step was determined by Rayleigh's method (*Owen and Cleary, 2010*):

$$T=\frac{\pi R_{\mathrm{p}}(\frac{\rho}{G})^{\frac{1}{2}}}{(0.1631v+0.8766)},\ [\mathrm{s}] \tag{9}$$

Where *v*– Poisson's ratio, [dimensionless]; R_p– radius of fraction particles, [m];
G– shear modulus, [MPa]*; ρ*– particle density, [kg/m^3].

Rayleigh time-step was set as 0.01 s, 0.02% of the fixed time-step. Particles were replaced at 0.01 s. The maximum velocity of particles flying out were limited to 0.5 m/s, which was better to bonded particles. After running for a period, the limitation was removed. The rotation of the cutting blades was set as 3500 r/min, which was consistent with field test.

RESULTS AND DISCUSSIONS

Machine design

For forage grass, the work for unit area of grass cutting was W_0 = 200-300 J/m^2. While cutting width of the lawn mower B = 0.5 m and forward speed V_m = 1.4 m/s. The minimum power consumption in grass cutting should be P_2 = 2.06 kW. For small lawn mowers, power consumption for unit cutting width was P_b = 0.44-1 kW, then the minimum power consumption in transmission should be P_1 = 0.5 kW. When the lawn mower moved forward with speed 1.4 m/s, about 5 km/h, power consumption for the unit mass of machine was 1-2.3 kW/1000kg. The mass of lawn mower was 350 kg, then the minimum power consumption for forward move should be P_3 = 0.805 KW. Therefore, without considering power consumption in transmission, the minimum total power consumption of lawn mower P should be the sum of P_1, P_2, and P_3, namely 3.365kW.

The revolution speed of cutting blades *n* were calculated as:

$$n=\frac{30(V_{\mathrm{m}}+V_{\mathrm{b}})}{\pi R},\ [\mathrm{r/min}] \tag{10}$$

Where V_b – linear velocity of point b, [m/s], and V_b = 90 m/s.

While forward speed V_m = 1.4 m/s, linear velocity of point b, V_b = 90 m/s, and radius of point b, R = 0.25 m, the revolution speed of cutting blades was calculated as 3491 r/min. For practical application, the revolution speed of cutting blades was defined as 3500 r/min.

For grass cutting without stalk support, the limited velocity should be higher than 30 m/s (*Wang et al, 2003*). As for the grass cutting in the present study, the lowest velocity occurs at point a of the cutting-edge. The velocity of point a was expressed as:

$$V_{\mathrm{a}}=\sqrt{r^2\omega^2+2r\omega V_{\mathrm{m}}\cos(\omega t+r)+V_{\mathrm{m}}{}^2},\ [\mathrm{m/s}] \tag{11}$$

When $\omega t+r=\pi+2k\pi\ \ (k=0,1,2...,i)$, the lowest velocity of point a was obtained as $V_{\mathrm{amin}}=r\omega-V_{\mathrm{m}}$, and it was 69.7 m/s, which met the limited velocity of 30 m/s, then the transmission scheme of the lawn mower was rational.

To meet the requirement of no-missing grass cutting, the number of cutting blades *m* should be larger than $60\,V_{\mathrm{m}}/(hn)$, namely 1.58 in the present case. Considering stability of blade move and production feasibility, the number of cutting blades was defined as 2.

Numerical analysis

Cutting process analysis by means of EDEM

The grass cutting process was simulated by means of EDEM, and the contour of velocity of typical particles was obtained and plotted, as shown in Fig. 4. Particles were in state of grass after being cut and broken by cutting blades. The velocity of particles after being cut and broken was between 0.3-3.75 m/s.

The bottom and top of the grass stalk had the slowest velocity, and the cutting parts had the fastest velocity. In addition, the grass stalks could be cut multiply, which resulted in the great change of particle velocity.

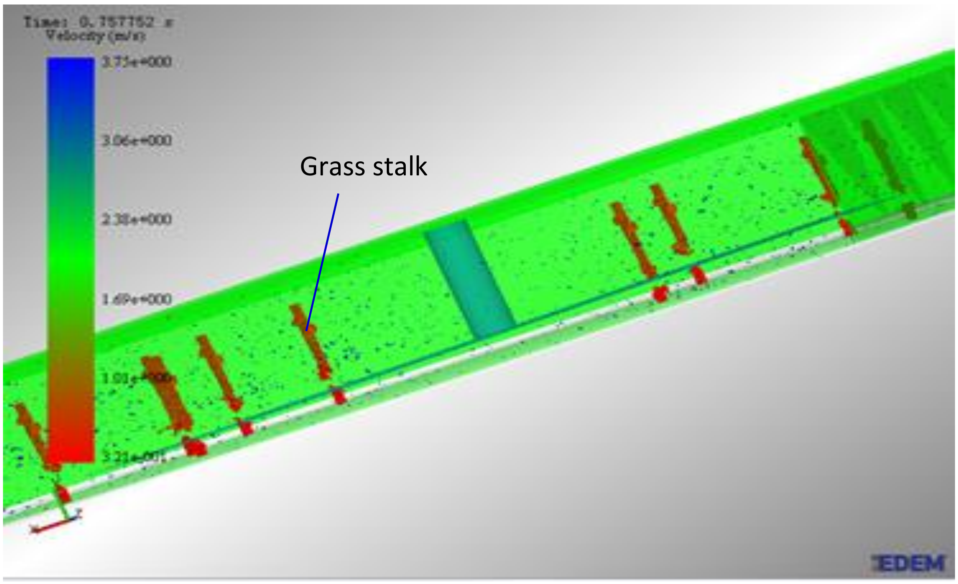
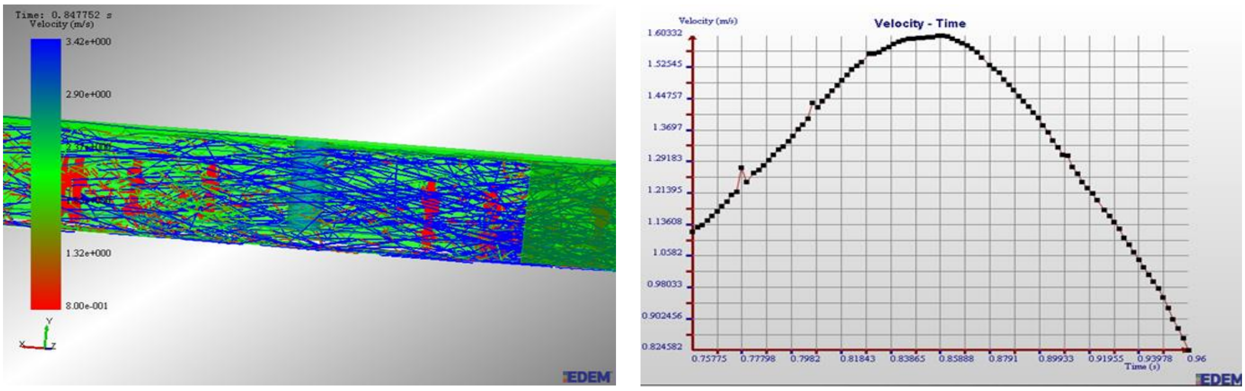


Fig. 4 – Contour of velocity of typical particles of grass

The broken grass moved in the grass box in all directions. The trajectory of grass particles was plotted by means of streamline, as shown in Fig. 5 (a). The relative move of grass and cutting blades formed circulating particle flow in the grass box. The distribution of grass particles revealed relatively uniform and lots of grass particles located in cutting zone, which showed the structure design and parameters defined were reasonable for the forage grass cutting. On conditions of revolution speed of cutting blades 3500 r/min and forward speed of lawn mower 1.4 m/s, the velocity of grass particles was mostly in the range of 1.1-1.5 m/s, and the velocity of broken grass was stable, which proved good harvest and gathering effect for the lawn mower. Fig. 5 (b) showed the typical curve of velocity of a grass particle vs. time in the *Y* direction. The grass particles obtained acceleration after being cut, and their velocity peaked afterwards, which agreed with real application.



(a) (b)

Fig. 5 – Typical particle move: (a) Grass trajectory; (b) Velocity vs. time

Modal analysis of vibration of cutting blades

Cutting blades are important for a lawn mower, and their vibration performance have a great influence on safety, reliability and efficiency of the grass cutting work. The modal analysis of vibration of cutting blades was conducted by Creo Simulate. The 3-D model of the cutting blade was built in Creo, as shown in Fig. 6. The material of the cutting blade was 45 steel, with elastic modulus 210 GPa, density 7800 kg/m^3 and Poisson's ratio 0.3. The vibration mode and natural frequency at different orders of the cutting blades could be obtained.

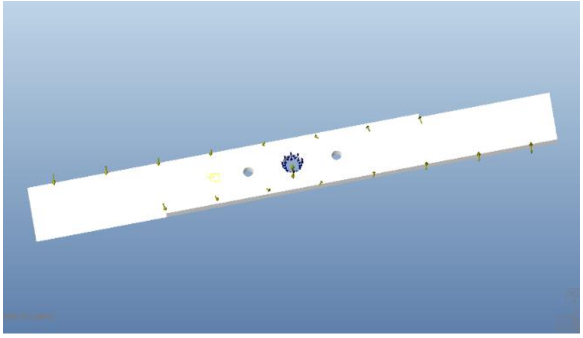


Fig. 6 – 3-D model of the cutting blades

The vibration patterns of cutting blades were shown in Fig. 7. According to vibration patterns of the first six orders, the vibration mainly occurred at locations of cutting edge of the blades. In the first-order and second-order modals of vibration, the cutting blades swung up and down in the vertical direction. In the third-order and fourth-order modals, the vibration was further strengthened, and a concave curved surface appeared between blade edges and the centre of rotation. And in the fifth-order and sixth-order vibration modals, the vibration was transmitted to the entire blade. The blade twisted back and forth along the *X* direction, and swung up and down along the vertical direction.

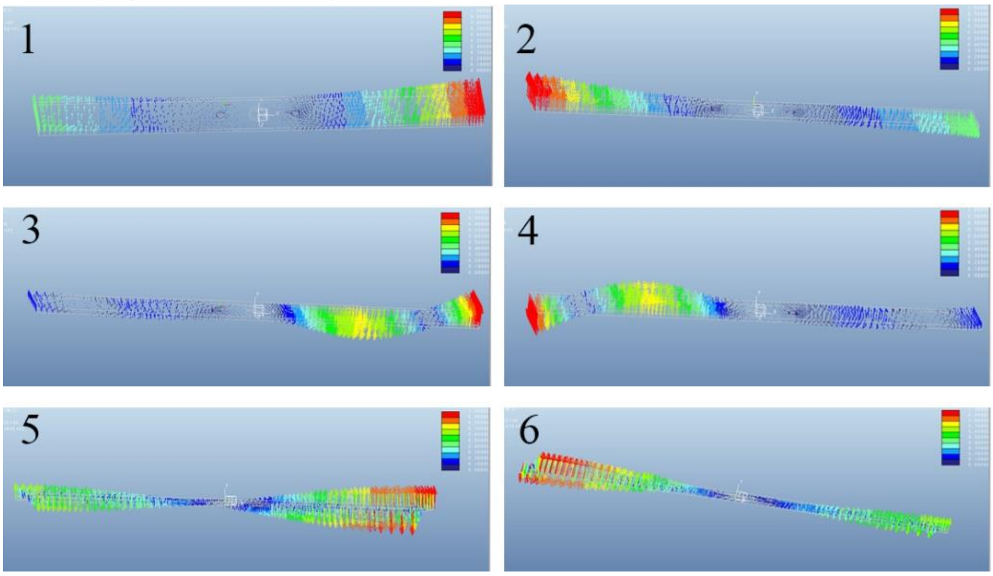


Fig. 7 – Vibreation patterns of cutting blades

Since the main shaft that fixed the cutting blades was well installed with gearbox, the vibration increased gradually with the radius of the cutting blades. Therefore, the cutting edges of the blades were susceptible to damage of bending due to vibration, and the natural frequency and limited velocity of the first six orders were obtained by the modal analysis, as shown in Tab. 2. The minimum limited velocity of cutting blades among these orders was 5506.566 r/min, which corresponded to natural frequency of the first order. As for the present study, revolution speed of cutting blades was 3500 r/min, and it was far below the minimum limited velocity. Therefore, no resonation would occur during the grass cutting with the parameter design, and the safety and reliability of lawn mower could be guaranteed.

Table 2

Natural frequency and limited velocity of cutting blades

Vibration modal orders	Frequency [HZ]	Limited velocity [r/min]
1	91.7761	5506.566
2	92.1708	5530.248
3	322.952	19377.12
4	324.990	19499.40
5	463.691	27821.46
6	466.466	27897.96

Field test

A small rotary lawn mower was developed according to the structure and parameter design. The field test was conducted in a grassland near Southwest University. The outlook of grassland for test was shown in Fig. 8, and the quality of the grass cutting was shown in Fig. 9. The height of grass stalks was about 200 mm, the height of remained stubbles was about 50 mm, and the length of cut grass was distributed in the range of 30-60 mm. The performance of the grass cutting met the requirements of forage production. At the same time, the small rotary lawn mower showed good passing ability and adaptability in the test grassland.

(a) (b)

Fig.8 – Grassland for test: (a) before mowing; (b) after mowing

Fig. 9 – Measurement of grass stalk, stubble and cut grass

CONCLUSIONS

In this study, the structure and parameter design of a small rotary lawn mower single-disc type was defined according to empirical formula, performance of grass cutting and modal analysis of the cutting blades were conducted by means of EDEM and Creo, and field test was conducted to verify the overall performance of the rotary lawn mower. Main conclusions were drawn as follows:

- Rotary lawn mower single-disc type is suitable for forage grass cutting in hilly land areas. Two cutting blades with revolution speed 3500 r/min and forward speed 1.4 m/s showed good performance of grass cutting and stability of the mower.
- The distribution of grass particles revealed to be uniform that proved good harvest and gathering effect of the lawn mower. The move of grass particles agreed with real application. The revolution speed of 3500 r/min was far below the limited velocity from modal analysis, and resonation could be avoided for the lawn mower.
- Field test of the rotary lawn mower showed good performance of grass cutting, good passing ability and adaptability. The height of remained stubbles was about 50 mm, and the length of cut grass was distributed in the range of 30-60 mm, which met requirements of forage production.

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