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Soil-cutting simulation and parameter optimization of handheld tiller's rotary blade by Smoothed Particle Hydrodynamics modelling and Taguchi method

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ABSTRACT

Reduction of power consumption of mechanical tilling operation benefits the environment and sustainability of a farming system. Rotary blade is the main tilling part of a handheld tiller, and its shape and parameters directly affect power consumption and performance of a handheld tiller. For purpose of optimization of rotary blade and energy saving for the tilling operation, soil-cutting simulation was performed by means of Smoothed Particle Hydrodynamics (SPH) modelling in this study. Taking cornerite of bending point (X_1), alpha angle (X_2) and bending angle (X_3) as control factors and power consumption (Y) as evaluation index, soil-cutting experiments by simulation were conducted according to Taguchi method, and correctness of the simulation was validated by soil bin test. The effects of those control factors on power consumption were investigated. A regression equation of power consumption in terms of control factors and their interactions was obtained. The response surfaces to power consumption as functions of X_1, X_2 and X_1, X_3 were plotted. Results showed that: control factors of X_1, X_2 and X_3 are significant at 0.1% probability level by F test of analysis of variance (ANOVA), with orders of importance as X_1, X_2 and X_3; optimized parameters of the rotary blade are X_1 30°, X_2 52°, and X_3 120°; power consumption of the optimized rotary blade is 0.161 kW, with a 12.40% of power consumption reduction compared with the traditional design.

1. Introduction

Reduction of both pollutant emission and fossil fuel dependency is an objective of energy policies worldwide (Moreda et al., 2016; Varga et al., 2016). Agricultural machinery releases significant amount of exhaust gas, much higher than that from on-road vehicles, which exacerbates environment (Xu, 2017; Nabavi-Pelesaraei et al., 2017). The environmental burden could be decreased by using clean energy or optimizing power consumption of agricultural machinery (Borgui et al., 2014; Liu et al., 2017). Nowadays, electricity is the most frequently adopted cleaner energy, and many scholars and agricultural machinery companies employ it as a substitution of traditional energy (Azwan et al., 2017; Pali et al., 2015). There are barriers for electricity use in agricultural machines such as low energy density and high price of the battery, and strong vibration of the agricultural machines degrading performance and lifetime of the battery. Traditional energy is still the most widely practiced form of energy to drive agricultural machines (Karner et al., 2013; Li et al., 2016a; Ludin et al., 2014). Therefore, optimizing power consumption of the agricultural machines, driven by electricity or traditional energy, is of realistic significance to the environmental impact (Chen et al., 2017).

Handheld tillers are indispensable agricultural machines that are broadly used worldwide, especially in Asia, where 75% of the arable land is located in regions of hills, mountains and plateaus (Lu

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and Liao, 2017; Yang et al., 2004). The handheld tillers are easy to transfer from one land to another, and to make turns in any land of different scales in the mentioned regions (Chen et al., 2014; Hao et al., 2014; Luo, 2011). The rotavator is the tilling part of a handheld tiller, and it consists of many rotary blades. The shapes and parameters of the rotary blades directly affect the performance of a rotavator and the corresponding handheld tiller (Niu et al., 2015). The functions of tilling and moving are both achieved by interaction between rotavator and soil, and the tilling function includes soil-cutting, pulverization, soil-turning, soil-throwing, and soil-levelling.

The power consumption of a handheld tiller essentially depends on the geometric parameters of rotary blades from a theoretical point of view (Jafar and Surendra, 2009). Saimbhi et al. (2004) studied the power consumption difference for rotary blades of C style, L style and C-L style, and results showed that C style was better than others; Sakurai and Sakai (2010) studied the effect of scoop angle of the sidelong edge of a rotary blade on the soil-cutting performance; Yang et al. (2014) studied the effect of forward speed and tilling depth on the soil-cutting power, and results showed that tillage depth had the greatest influence on the soil-cutting power; Matin et al. (2014, 2015; 2016) studied the effect of 3 blade geometries at 4 rotary speeds and cutting edge geometry on the furrow parameters toward strip-tillage seedbed preparation. These published studies were mainly focused on design of shapes and parameters of rotary blades, and on relationship between power consumption and tilling parameters. But as to optimization of shapes and geometric parameters of rotary blades and the resulting effect on performance of a handheld tiller, few studies have been reported.

The objectives of this study are to quantitatively investigate effect of shapes and geometric parameters of rotary blades on soil-cutting performance, especially on power consumption, by the SPH based simulation and soil bin test, and to effectively optimize the rotary blades according to Taguchi method (Taguchi, 1993).

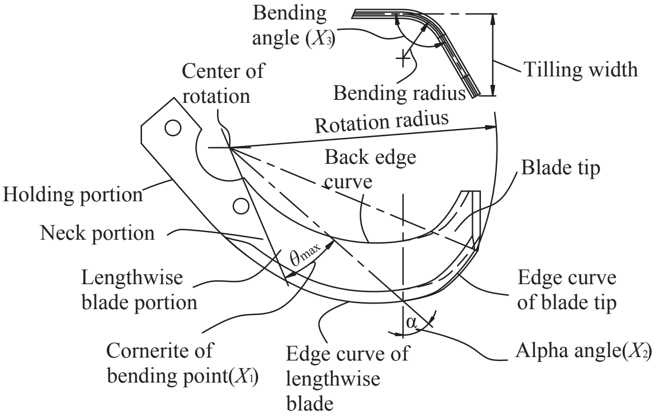

Fig. 1. Structure and composition of the rotary blade.

2. Material and methods

2.1. Material

2.1.1. Rotary blade

The rotary blade, adaptable for wetland sticky paddy field tillage, was employed for this study, as shown in Fig. 1. Since radius of the rotary blade was small for a handheld tiller, a circular back edge curve was adopted for simplicity. A spiral of Archimedes was adopted for edge curve of the blade, and the detailed design process of the edge curve was available in the previous study (Li et al., 2016b). According to standards of GB/T 5669-2008 (Chinese Standard Committee, 2008), DB50/T 277-2008 (Chongqing Bureau of Quality and Technology Supervision (2008)) and JIS B 9210-1988 (Japanese Industrial Standards Committee, 2008 confirmed), some parameters of the rotary blade were defined, as shown in Table 1.

2.1.2. Soil

Considering the climate, geological conditions and soil characteristics in Chongqing, China, soil model MAT147 by LS-DYNA was adopted in the present study (Lewis, 2004). Parameters of soil were defined for the SPH based simulation, as shown in Table 1 (Ding et al., 2007; Gao, 2017).

2.2. Methods

2.2.1. SPH based soil-cutting model

Smoothed Particle Hydrodynamics was adopted for the soil-cutting simulation. The grid size of the FEM model of rotary blade was set as 5 mm. Space among particles of the SPH model of soil was set as one tenth of the minimum side length of soil dimensions. Sliding interface penalty factor, and coefficients of dynamic and static friction were set as 0.20, 0.18 and 0.20, respectively (Jiang et al., 2012; Xue et al., 2011). The FEM model of rotary blade and the SPH based soil-cutting model were shown in Figs. 2 and 3, respectively.

2.2.2. Power consumption of soil-cutting

The motion of a rotary blade combines two parts: a forward move with the handheld tiller and the rotation around axis of the rotavator. The coordinate system of soil-cutting is defined, as shown in Fig. 4 (Li et al., 2003). Then, position of the blade tip is expressed as:

$$\begin{cases} x = R\cos(wt) + v_{\mathrm{m}}t \\ y = R\sin(wt) \end{cases} \tag{1}$$

where, R is rotary radius of the blade (mm); w is rotation speed of the blade (r/s); v_{m} is forward speed of the handheld tiller (m/s); t is

Table 1
Parameters of rotary blade and soil.

Rotary blade	Value	Soil	Value
Rotary radius [mm]	180.00	Cohesion [Pa]	4.20e+4
Material	65Mn	Bulk density [kg·mm^{-3}]	2.65e-6
Density [kg·mm^{-3}]	7.83e+3	Porosity [%]	39.20
Elastics modulus [Pa]	2.07e+11	Specific gravity	2.79
Poisson's ratio	0.35	Bulk modulus [Pa]	4.65e+7
Forward velocity [m·s^{-1}]	0.30	Moisture [%]	30.00
Velocity of rotation [r·s^{-1}]	2.20	Shear modulus [Pa]	1.86e+7
–	–	Angle of internal friction [radian]	1.10