Agronomy Research Biosystem Engineering Special Issue 1, 49-54, 2012

Performance optimization of a rotary mower using Taguchi method

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Abstract. Optimum energy consumption and prevention of energy losses are important issues in various fields including agricultural engineering. Mower is one of the agricultural machineries that can waste too much energy if does not function properly. In this study, the performance of a single disc rotary mower was studied and optimized by measurement of cutting quality of the stem cross section (cutting quality) as a criterion. Taguchi L9 orthogonal arrays table was used to find the optimum combination of parameters to reach the best cutting quality. The selected factors are: mower forward velocity, disc rotational speed, number of disc blades and shape of the blade, each one at 3 different levels. To measure the quality of the cut hay, ENVI image processing software was used. This software has been developed for texture qualification of image processing studies. The texture of the images captured from the cross section of cut stems by the mower is analyzed according to the reflected wavelength from the surface. ENVI software assigns a number to the cutting quality of each stem, which is called eigenvalue. The results then were imported to the orthogonal arrays table of the Taguchi method. Minitab software was used to calculate the optimal level of the studied variables. Analysis of the results show that 886 rpm of the disc rotational speed, 1m s^{-1} of the forward speed, four symmetrical triangular serrated blades on the mower disc are the optimal values of the factors and offer the highest cutting quality. The optimum value predicted by the Taguchi method was approved by an experimental method.

Keywords: rotary mower, cutting quality, Taguchi method, image processing, ENVI software.

Introduction

Since hay is one of the main foods for cattle, every year many of agricultural lands are allocated to the cultivation of this product. The cutting quality is important because it reflects the levels of machine adjustment, blade sharpness and energy consumption. In this research the cutting quality of a disc mower was measured by analysis of the pictures taken from the cross section of cut stems. The image processing technique and Taguchi design of experiment method were used to define and find the optimum mower parameters setting for best cutting quality. According to the smoothness of the cut section of the hay stem, the operator can estimate the sharpness of the blade. Agricultural machineries are going to be intelligent in the future, in further developments of this project, when the machine is not adjusted and does not cut plants well, the image processing system displays the fault on a monitor in front of the operator or buzz an alarm or turns on a light to hint him. An onboard computer or a micro controller and actuators can be used to adjust automatically the mower forward velocity, disc rotational speed, number and shape of the blades to an optimal level.

Tuck et al. (1991) studied the performance of toothed disc mowing mechanisms. Mowing performance was studied over a range of forward speeds from 2 to 12 km h^{-1} and at tooth tip speeds up to 80 m s^{-1}. He found that sharp-toothed discs required 65% of the total power of sharp conventional blades and 50% of that with blunt conventional blades. O'Dogherty et al. (1991) studied the effect of blade parameters and stem configuration on the dynamics of cutting grass. He found that the bluntest blade (0.15 mm edge radius) required three times the specific cutting energy and twice the specific peak force as a sharp blade (0.325 mm edge radius).

Oztop et al. (2007) studied effects of microwaves on quality of fried potatoes and optimized the process by using Taguchi technique. Hwang et al. (2009) Evaluated machinability according to the changes in machine tools and cooling lubrication environments and optimization of cutting conditions using Taguchi method. Wu et al. (2003) applied the Taguchi method to optimize the process parameters for the die casting of thin-walled magnesium alloy parts in computer, communications and consumer electronics (3C) Industries. He investigated the effects of various die casting control parameters, including the temperature, injection velocity, and cooling time upon the surface warping of magnesium alloy die cast components.

Image processing

One of the latest software's of image processing based on the analysis of surface texture is ENVI[1]. The software works based on the value of the reflected wavelengths from various surfaces. The principal component analysis (PCA) is one of the commands of ENVI. PCA is a statistical method for data reduction. Levels of the PCA process are:

1. Calculation of the variance and covariance matrix (or correlation) of the image
2. Eigenvector and the eigenvalue matrix extraction.

The software default setting is to calculate the eigenvalue of good pixels for images by PCA method. As much as the image of the plant section is smoother and more uniform in color, its eigenvalue is higher. This number is known as PC1 (Alavipanah, 2009).

Taguchi optimization method (signal to noise ratio analysis)

Most of Taguchi attention is the philosophy of design of experiments, not in the mathematical formulation of it. His method is the concept of regular, strong and uniform laws to improve the quality that is different from traditional methods. Taguchi designed tables known as 'orthogonal arrays' are standard arrays that make design of experiment very simple and efficient. In the standard arrays table, number of rows show number of tests and number of columns indicate the number of factors and interactions.

The heart of Taguchi optimization method is analyzing the signal to noise ratio or S/N ratio. Generally there are two categories factors for a test:

- Manageable factors (signals): are said to the factors that can be adjusted by the user;
- Uncontrollable factors (noise): refers to the factors that are not adjustable by the user.

1 - The Environment For Visualizing Images (ENVI)

A test is in optimum condition when changes in output are affected by signal values not noise values. It means that highest S/N ratio determines the optimum condition. Since this ratio is proportional to the inverse of the variation's coefficient, increasing the signal to noise ratio leads to reduction in errors or changes. Commonly there are three indicators of the optimum quality in this analysis: the higher the better, the lower the better and much closer to nominal value the better. Since in this paper the higher output value of the PC1 (eigenvalue) of the image shows the higher cutting quality of the mower, therefore, the higher the better indicator must be used and the proper S/N ratio can be calculated from equation (1) (Roy, 1990):

$$S/N = -10 \log [(1/y_1^2+1/y_2^2+\ldots+1/y_n^2)/n] \quad (1)$$

In this equation, y is the value of measured response for each test, and n is the number of repetitions of each test (in this study was 3). S/N Ratio from eq. (1) only can be used when the test has more than one replication, if n=1 the average data analysis which is a different method should be used (Roy, 1990; Roy, 2000).

The value of output in optimum level is calculated from equation (2) (Roy, 1990):

$$Y_{Optimum} = \bar{T} + (\bar{A}_{Opt} - \bar{T}) + (\bar{B}_{Opt} - \bar{T}) + (\bar{C}_{Opt} - \bar{T}) + \ldots \quad (2)$$

T is average of total data and $\overline{A}_{Opt}$, $\overline{B}_{Opt}$, etc. are average of optimum levels values of A, B, etc. factors.

Material and methods

As the hay during the growing period (early spring to mid-autumn) may have several harvests, the mowers are particularly important to farmers. The purpose of this study was to optimize the performance of a single circular disc mower. The output is the stem cross section cutting quality. To evaluate the stem cutting quality of the mower blade, an alfalfa stem was cut by a very tiny and sharp shaving blade. This blade produces a very smooth and uniform cross section surface. An image was taken from this cross section and the PC1 eigenvalue of this image was defined as the ideal 'cutting quality'. The PC1 eigenvalues of the pictures taken from alfalfa stem cross sections cut by real mower blades in the farm were compared to the ideal cutting quality eigenvalue. The Taguchi design of experiment method was used to study the effect of different cutting variables on the 'cutting quality'. Mower forward speed, disc rotational speed, number of blades on the disc and the shape of the blades were defined as main effective variables on cutting quality. Each variable was studied at three different levels. Three images from each test set up were taken by an sx210 canon camera and were imported to the ENVI image processing software. This software processes the light wavelengths which are reflected from the stem cross section pictures and links it to the surfaces texture and smoothness.

The machine that was used in this study is a single-disc two wheels rotary mower. The disc rotates clockwise and is powered by a 6.5 hp gasoline engine. The mower was made at the Department of Mechanics of Agricultural Machinery in Shahid Bahonar University of Kerman by the authors.

a)  b) 

Fig. 1. Single-disc rotary mower (a) and 9 cut experimental treatments (b).

The operator walks behind the mower. According to an operator walking speed, three levels of the mower speed were considered as 1, 1.25 and 1.5 meter per second (table 1). Rotational motion of the disc was set on three levels, slow, medium and high speed. Theses speeds are accordingly 535, 886 and 1,210 rpm. The rotational speeds of the disc were measured by a L200 model Shimpo light tachometer. The numbers of the blades on the disc are 1, 2 and 4.

Table 1. Factors and levels

Row	Factor	Unit	Level 1	Level 2	Level 3
1	Mower forward speed	m s^{-1}	1	1.25	1.50
2	Disc rotary speed	rpm	535	886	1,210
3	Number of blades	number	1	2	4
4	Shape of blades	–	smooth-edge triangular	serrated-edge triangular	serrated-edge rectangular

The selected shapes of the blades are: smooth-edge triangular, serrated-edge triangular and rectangular serrated-edge. Each blade is fixed on the disc by two bolts. Considering the number of variables and their levels, Taguchi L9 orthogonal arrays table was used. Considering a normal statistical method for these design 81 tests must be conducted, but using the Taguchi method the design reduces to 9 tests. According to the Taguchi proposed table, the test were carried out in the field. 3 stems in each treatment were randomly selected and photographed (3 replications). The images were imported to image processing software. The software calculates an eigenvalue for each treatment and replication. It is called the eigenvalue of good pixels. These are unitless numbers and are tabulated as: R1, R2, and R3 in table 2. These numbers were imported to Minitab14 software to be used for analysis by Taguchi design of experiments program.

Results and discussions

The program calculates the S/N ratio for each level of each variable by using eq. (1). The results are shown in Fig. 2. The program also predicts the optimum level and approximate number of PC1 eigenvalue for that level, using eq. (2). R1 to R3 are values for the variable *y* in formula (1).

Table 2. Taguchi l9 orthogonal arrays and numbers of each treatment with 3 repetitions

Factor / Test	Mower forward speed (A)	Disc rotary speed (B)	Number of blades (C)	Shape of blade (D)	R1	R2	R3	S/N
1	1	1	1	1	519	417	579	53.82
2	1	2	2	2	1,793	1,969	1,963	65.59
3	1	3	3	3	1,105	1,182	1,144	61.16
4	2	1	2	3	1,032	1,118	1,080	60.63
5	2	2	3	1	1,323	1,420	1,164	62.21
6	2	3	1	2	816	659	757	57.33
7	3	1	3	2	1,597	1,608	1,789	64.39
8	3	2	1	3	587	645	544	55.38
9	3	3	2	1	820	857	951	58.80

According to the Fig. 2, first level of mower forward speed (A), second level of disc rotation speed (B), third level of blade numbers (C) and second level of blades shape (D) are optimal levels in this test. They have highest S/N ratios. Graphical form of the optimum conditions is shown in Fig 2.

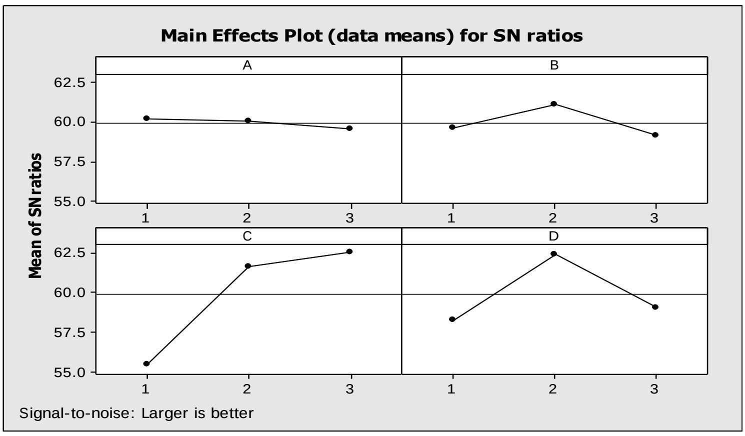

Fig. 2. The S/N ratio for each level of each variable.

According to the calculations of S/N ratio, the proposed optimum level for the variables is as follows: (table3).

As it is clear from Fig. 2 the optimum level predicted by Taguchi method for forward speed- rotational speed- number of blades and shape of blade is respectively 1-2-3-2 levels in table3. Putting values of these levels in eq.2 gives eigenvalue (PC1) of 1,991.5 for this optimum combination. To confirm this predicted value a confirmation test with the optimum setting predicted by Taguchi method was conducted at real field condition and the cross section images were analyzed. The average number of PC1 eigenvalue was measured as 2,062.67. It shows that the difference between the predicted and real number is very low (3.42%), this difference is due to the uncontrollable factors. The PC1 value of ideal 'cutting quality' that was cut by a very tiny and sharp shaving blade is 6,912. This value is much higher than the real value got from the blade in the field test. It is because the real knives of a mower are blunter than a sharp shaving blade.

Table 3. Optimum levels of each variable

Variable	Var. name	Optimum level	Condition	Average of optimum levels value
A	Mower for. speed	1	1 m s^{-1}	1,185.7
B	Disc rot. speed	2	886 rpm	1,267.6
C	Number Of Blades	3	4	1,370.2
D	Shape of Blades	2	serrated-edge triangular	1,439

Conclusion

Taguchi method showed to be a fast and cost effective technique for the design of experiments (DOE) to evaluate a machine performance. In this research it reduced the number of test from 81 to 9. It showed that 1 m s^{-1} mower forward speed, 886 rpm disc rotation speed, 4 blade numbers and serrated-edge triangular blade is optimum set up for the experimental mower. Taguchi method predicted the eigenvalue of 1,991.5 for this optimum set up.

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