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Structural Design of a cone clutch for walking-Type tractors using FEA, RSM and ANN

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Abstract

The majority of farms in developing countries are small plots of less than two hectares. Most agricultural activities are done using walking-Type tractors (tillers) known as tillers. In our previous study, we designed and fabricated a cone clutch for the rotary axle of tillers was performed. Since tillers are guided by humans, a lightweight design is one of the most important factors for the comfort and safety of the user. Therefore, in this paper, the structural design of the proposed cone clutch was carried out based on Finite Element Analysis (FEA), Response Surface Methodology (RSM) and Artificial Neural Network (ANN) to reduce the weight. This study has shown that a combination of RSM and ANN techniques with FEA enables the structural design and low weight of the desired cone clutch on the rotary axle of rotary tillers.

Keywords

lightweight design, walking-Type tractor, Tiller, FEA, RSM

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1. Introduction

The configuration of tillers, mainly due to their single-axle design. The driver therefore has to use a lot of energy to guide and steer the soil tillage implements. For this reason, working with them is an arduous task [1 and 2]. Due to the shortage of labor and the need to complete various agricultural operations on time, their demand is increasing rapidly [3]. Despite this increasing demand, the use of walking tractors still lags behind tractors. This is evident from the fact that the annual use of walking tractors is only 300 hours compared to 1000 hours for tractors [4 and 5]. In the literature, FEA has been performed by some researchers. For example, in research, the transmission of a power tiller was simplified using FEA and the load on the gears was calculated using FEA to determine the overall robustness of the transmission system [6 and 7]. Therefore, it is necessary to investigate the design and analysis of a cone clutch on the rotary axle of tillers used in gardens and agricultural land in field operations. The cone clutch transmits a higher torque than disc clutches of the same size. As the rotary tillers work at low speed when weeding and ploughing, the use of a cone clutch was investigated. In particular, a FEA of the cone clutch is required in order to optimize and develop the steering of the rotary tillers. It is also expected that the steering and guidance of tillage machines can be useful to improve the mechanization level of small farms.

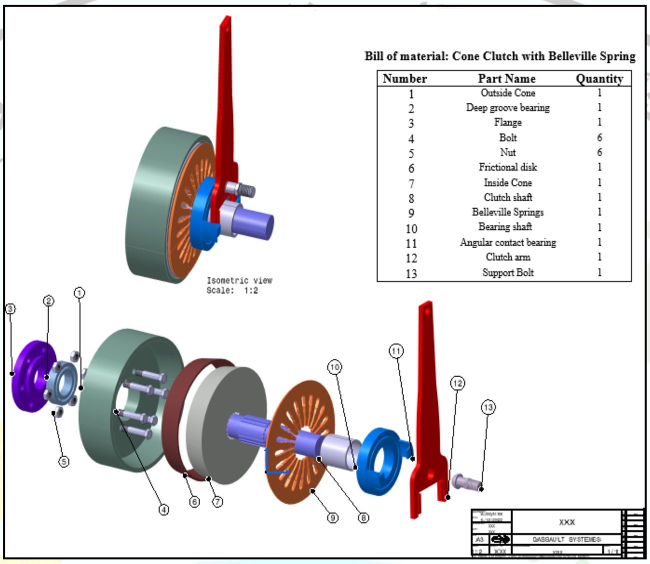
2. Material and Methods

2.1. WEIMA 1100 AE tiller

The WEIMA 1100 AE tiller, manufactured in Korea, was used in this study. The various parts considered and analyzed in this study are shown in Fig. 1. The rated power of the tiller was 6.6 kW at an engine speed of 3,600 rpm. The travelling speed during tillage (i.e. weeding) is 1-4 km/h.

Fig. 1. The two-wheel tractor, i engine, ii gearbox, iii umbrella gear shafts, iv umbrella gear (cone gear), v rotary output shaft, vi left rotary axle, vii right rotary axle

A 3D view of the designed clutch components with their parts table is shown in Fig. 2 [7]. As can be seen in Fig. 2, the outer cone, the inner cone and the clutch arm, parts number 1 and 7 of the 12 clutches, respectively, have the most weight. Therefore, our aim in this study is to reduce the weight of these three parts by numerical and computer-aided methods (FEA, RSM and ANN).



Bill of material: Cone Clutch with Belleville Spring

Number	Part Name	Quantity
1	Outside Cone	1
2	Deep groove bearing	1
3	Flange	1
4	Bolt	6
5	Nut	6
6	Frictional disk	1
7	Inside Cone	1
8	Clutch shaft	1
9	Belleville Springs	1
10	Bearing shaft	1
11	Angular contact bearing	1
12	Clutch arm	1
13	Support Bolt	1

Fig.2. Exploded view of the cone clutch components with the parts table

2.2. Structural and lightweight design of cone clutch

The cone clutch proposed in this study consists of a bowl, a cone and a spiral spring. The cone angle (α), the outer diameter (D), the inner diameter (d), the friction coefficient of the clutch lining (f) and the width (H) are the necessary parameters for the design of the clutch (Fig. 3). The optimum cone angle is normally between 10º and 15º (normal angle). The axial force (F_a) of the cone clutch engagement for safe power transmission can be determined using Equation 1 [9].

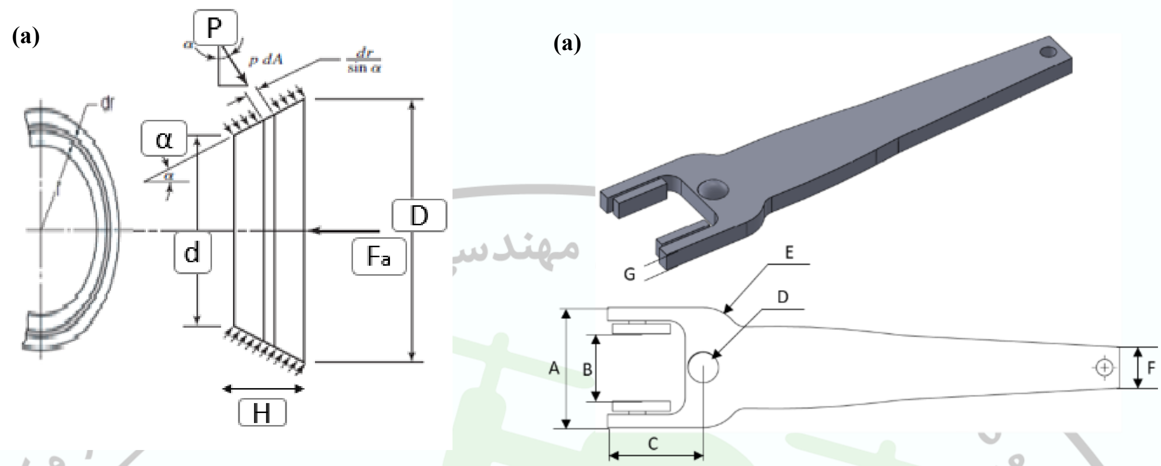


Fig. 3. (a) Structural parameters of the cone clutch (b) Structural parameters of the clutch arm from A to G

$$F_a = \frac{3T(D^2 - d^2)\sin\alpha}{f\ (D^3 - d^3)} \tag{1}$$

D was varied from 120 to 150 mm, *d* from 100 to 140 mm, and α from 10º to 15º (normal angles), while *f* was kept constant at 0.45, as the Woven cotton frictional material is widely used in machines with a friction coefficient (*f*) of 0.45 and yield stress of 100 MPa. Geometry specifications of the clutch were determined based on available space on the rotary axle of the tiller. The aim is to design a clutch with the lowest width, weight and equivalent stress value.

2.3. Response Surface Methodology (RSM)

The RSM was used to investigate the effects of the width and dimensions of the clutch on its mass and maximum von-Misses stress. RSM is a powerful mathematical and statistical technique used for optimizing the process and evaluating the significance of the variables and their effects on the responses [8, 9]. RSM is a multivariate technique that leads to better prediction of output responses using a smaller number of tests with cost-effective procedures and minimal error [10]. The surface response curves of the clutch weight based on its geometry are shown in Fig. 4. As can be seen in Fig. 4, the clutch weight decreases with increasing outer diameter, angle and clutch width.

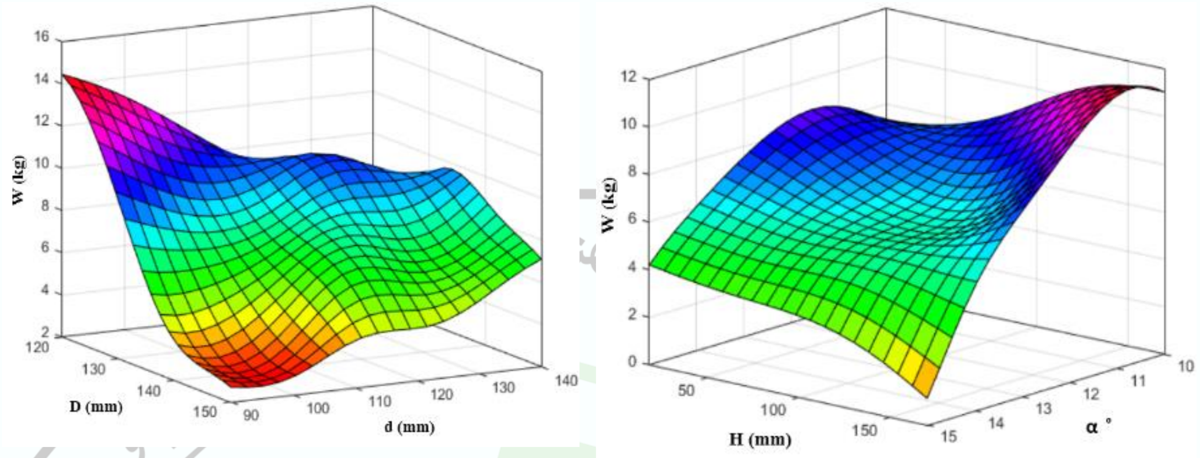


Fig. 4. Surface response graphs of the clutch weight based on its geometry

2.4. FEA for the cone clutch

For the numerical analysis using the finite element method (FEM), ASTM-A572 steel with a yield strength of 345 MPa was used to manufacture the cone clutch. The finite element models of the cone clutch components, including the clutch lent, the inner and outer cone and clutch arm, were created in ANSYS® Workbench 15, a commercial FEA software. The connections between the clutch components were then defined, including bonded and frictional contact (Fig. 5d). The 3D models for the clutch arm are shown in Fig. 5f. The load and static analysis of the cone clutch components is shown in Fig. 6. The maximum load on the cones and clutch arm was 89.5 MPa and 140.5 MPa respectively (Fig. 6). This resulted in a safety factor of at least 2.5.

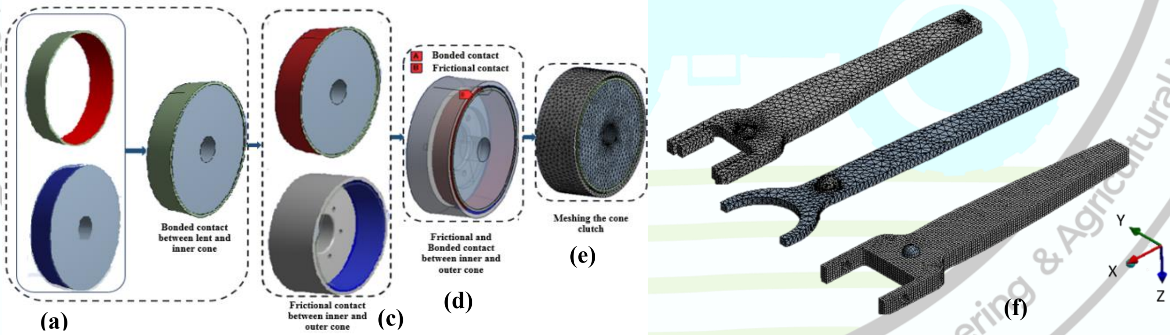


Fig. 5. Definition of connection between clutch parts and meshing (a) lent (b) inside cone (c) Bonded contact between lent and inside cone (d) outside cone (e) Frictional contact between outside cone and lent (f) meshed clutch arm model with solid element.

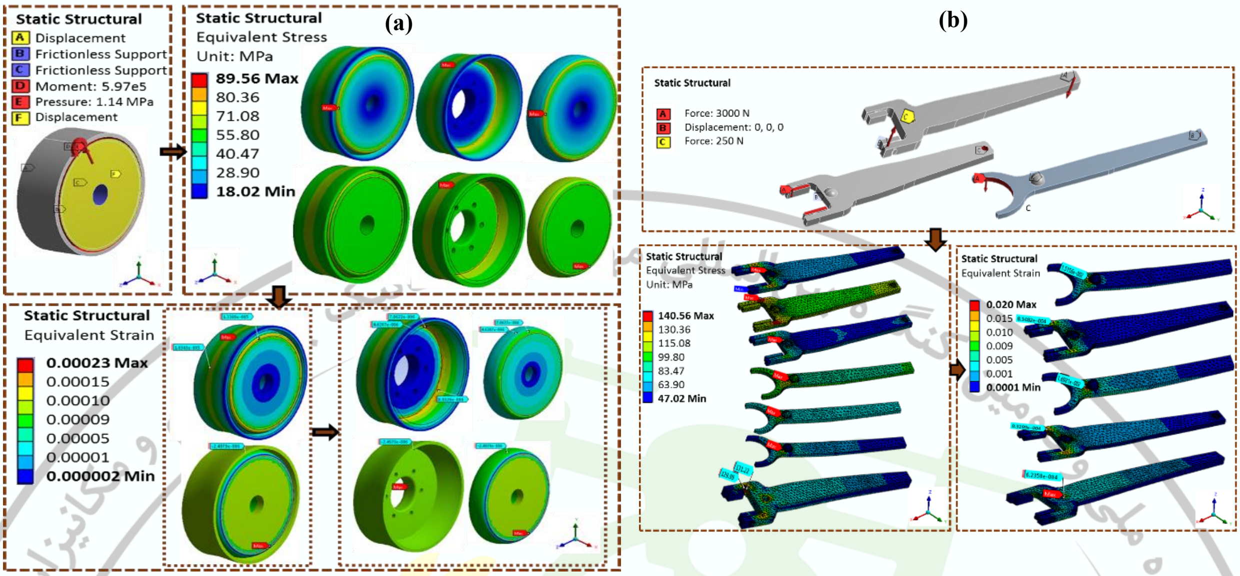


Fig. 6. Definition of static analysis between clutch parts and meshing (a) Distribution of equivalent stress on inner and outer cone (b) Distribution of equivalent stress on clutch arm

2.5. Artificial Neural Network (ANN)

The ANN technique can be used where there is no mathematical model or the nature of the problem is very complex. The finite element models are used to determine the stress state for the different design parameters (Table 1). Due to the complexity of the numerical model, the computational effort for each solution is high. Therefore, an ANN is used to predict the stress behavior based on the input parameters obtained by the RSM method. In this study, the ANN architecture considers 4 parameters as inputs (Table1), 2 outputs (weight and maximum stress) and a hidden layer with ten neurons (Fig. 7). For the training of the ANN, 80% of the data proposed by the RSM method was used. Once the training was completed, the maximum stress behavior was predicted for the remaining design cases.

Table 1. Variables for the prediction of the weight and maximum stress

Component	**Independent variable** **Parameter**		**Unit**	**Response**		**Unit**	**Evaluated values** **Lower-Upper**
Cone clutch	Outer diameter	D	(mm)	Weight	W	(kg)	1.09-5.26
	Inner diameter	d	(mm)	Maximum stress	Ϭ	(MPa)	22-85
	Cone angle	α	(ᵒ)				
	Clutch width	H	(mm)				

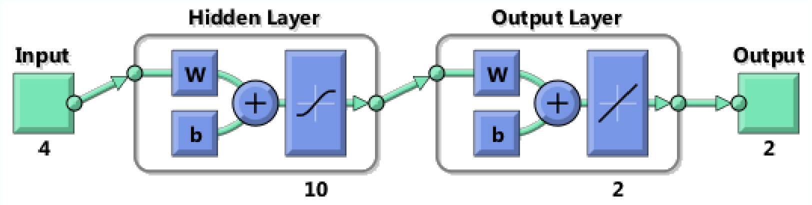


Fig. 7. Diagram of the ANN proposed

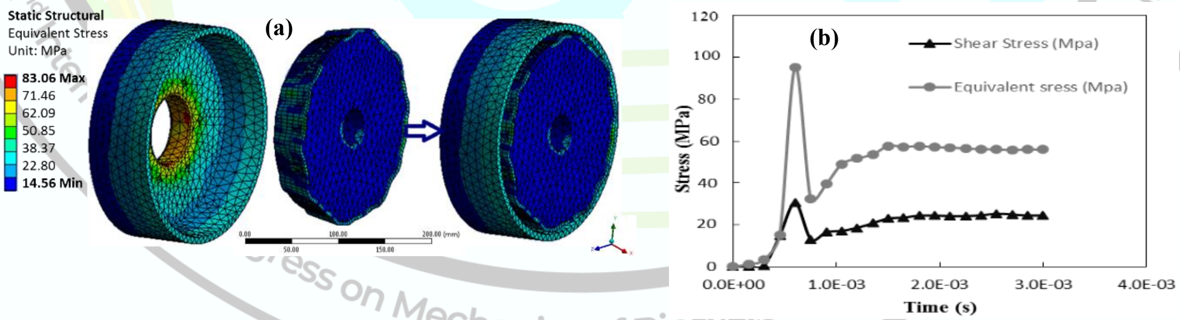
According to the ANN technique, the dimensional values in Table 2 were considered for clutch design. A 3D view of the designed clutch components with their parts table is shown in Fig. 8.

Table 2.
The geometry and frictional specifications of the designed clutch with the lowest width and weight value

D (mm)	d (mm)	α (º)	H (mm)	f	Fa (N)	W (kg)	Ϭ (MPa)
150	140	10º	28	0.45	3000	1.7	82

3. Results and Discussion

Fig. 8(a) shows the distribution of the maximum principal stress on the components of the cone clutch. The maximum stress occurs at the outer cone and is at a value of 76.9 MPa (Fig. 8(a)) and a safety factor of 4.4. Also, the maximum equivalent stress and the maximum shear stress were 90 and 30 MPa respectively (Fig. 8(b)) with a safety factor of 3.8. The maximum equivalent strain reached 0.0006 for the cone clutch components (Fig. 8(c)). On the other hand, the maximum simulated stresses, deformations and strains for the cone clutch components are smaller than the stresses and strains of their components, and the safety factor of these parts is also greater than 1. For more details, see Table 3. Therefore, the components of the cone clutch, including the borrowed inner and outer cone, can function safely.



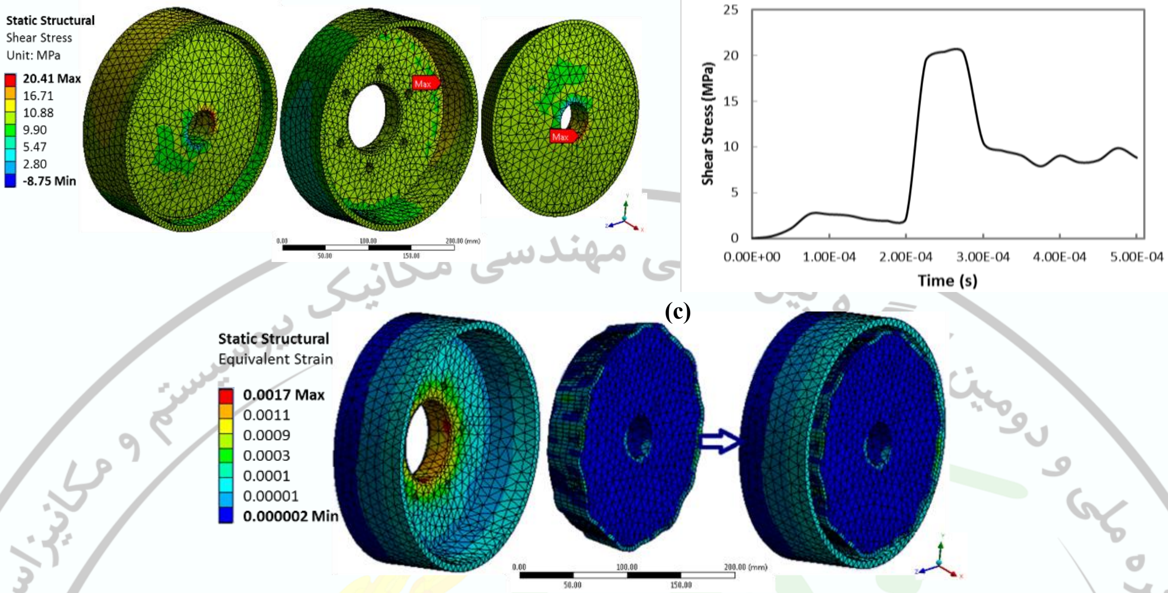


Fig. 8. (a) Distribution of maximum principal stress on the cone clutch, (b) Equivalent and shear stress created on the cone clutch (c) Distribution of Equivalent elastic strain on the cone clutch

Table 3. The safety factor of clutch components in Static and Dynamic Analyses

	Equivalent Stress, von Mises (MPa)	**Maximum Principal Stress (MPa)**	**Material yield Stress (MPa)**	**Principal Strain and Equivalent**	**yield Strain**	**Safety Factor**
lent	50	76.9	100	0.0006	0.10	1.5
Outside cone	90	76.9	345	0.0006	0.81	3.8
Inside cone	90	76.9	345	0.0006	0.81	3.8

4. Conclusions

The design of a conical clutch was carried out using FEA, RSM and ANN, and the strength of the conical clutch components was analyzed using finite element analysis (FEA). The results showed that ANN could predict the clutch weight almost accurately based on the structural variables. The safety factor of the conical clutch components was greater than 1.5. Therefore, the FEA analysis of the conical clutch components showed that the designed conical clutch could operate safely. One of the limitations of this study was the limited access to big data. In fact, if more samples of clutch components are considered for the ANN model, the design variables would be predicted with more confidence. In the following, the use of Multi-Objective Genetic Algorithms (MOGA) with a combination of machine learning (ML) models to achieve an optimal and lightweight design is suggested for future research.

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