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Design and Finite Element Analysis of a Curved-Slot Disc Harrow Blade for Crop Residue Incorporation

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ABSTRACT: Finite element analysis (FEA) provides valuable information, necessary for optimal matching of agricultural machinery to the right tillage tools. Soil-blade contact, deformation, working speed, tillage depth and other key factors that affect tillage discs performance were studied in this work. FEA was used to optimize the design of the disc harrow blade by introducing a curved cutting profile. ANSYS, Autodyn explicit dynamics solver was used to simulate and compare performance of the new design to the conventional type. The discs were tested at three different forward speeds of 3m/s, 2m/s and 1.5m/s and three tillage depths of 10cm, 7cm and 4cm. The boundary conditions included a fixed support at the base of the soil body and disc angular velocity of 300rpm. Introduction of a curved profile on the slots of the harrow disc provided excellent shape for better soil-blade interaction. It was concluded that using the curved-slot disc would enhance the process of crop residue incorporation into the soil by saving on the energy demands of the agricultural machines and minimize the farm operational costs. The tillage and crop residue burial process will also be smoother and faster.

KEYWORDS: finite element analysis; equivalent stress; crop residue incorporation; deformation; curved-slot disc blade; autodyn explicit dynamics.

I. INTRODUCTION

Crop residue retention and incorporation is of great concern in crop farming, as it affects productivity, soil quality and environmental conditions. Management of crop residues is thus critical in sustainable farming systems [1]. The disc harrow is a popular implement used for secondary tillage and crop residue incorporation. Its performance is affected by the geometry of the disc blade, soil mechanical properties and the working conditions [2].

Farm preparation through tillage is often expensive, complex, laborious and energy consuming. About a half of the total energy used for cultivation is for tillage operation, because of high draft forces [3]. This high-energy demand is not only because of the motion of bulky amounts of soil, but also because of inefficient means of energy transfers to the soil [4]. Optimum design of any tool should ensure efficient use of energy and smooth operation.

Theoretical analysis and experimental research facilitate the design of soil-cutting tools for incorporating crop residue. Some researchers have attempted to optimize the geometry of the tillage tools using physical experiments [5]. The impacts of the operational conditions on the energy needs of tillage tools including depth, cutting angles and velocity have been studied as well [6,7]. Other studies have shown that theoretical modeling approaches for the estimation of tillage forces can predict the energy needs for different tool geometries [8]. The energy consumption should be determined in order to select the best suitable implement features.

Experimental tests in tillage tool design are costly, time-consuming and may be limited to certain operating conditions. The outcomes are also highly subjective to the precision of the measuring equipment. Advancement in modern computing and the development of better material models have enabled the application of numerical methods in the study of soil–blade interaction. Accurate modeling is key to the optimization of tool design and may simplify the expensive field tests, and shorten the research time [9]. Soil reaction in numerical analysis provides a guide in designing and experimenting with several configurations in order to reduce draft and energy needs at different speeds.

The aim of this work was to explore a new concept of disc harrow blade design in finite element analysis (FEA), which would improve tillage and crop residue incorporation. Stress-strain and deformation characteristics were simulated using Autodyn Explicit dynamics solver in ANSYS software and the results compared to that of the conventional notched disc type. From the solutions, soil-blade interaction behavior and draft forces on the discs during operation were investigated. Furthermore, ways of reducing energy demands by lowering resistance to tractor forward motion and improving operational performance by optimizing the design of the disc were explained. The new disc consisted of curved slots instead of trapezoidal notches of the conventional disc type.

II. RELATED WORK

Finite element method (FEM) is a powerful technique for analyzing complex engineering problems [10-12]. It has been used to research on the forces acting on soil-tool surfaces, stress patterns in soil and soil failure criteria [13]. Coleman and Perumpral [14] noted that the use of FEM could avail information, which is challenging or impossible to obtain through experiments. Yong and Hanna [15] analyzed soil cutting blades in two dimensional plane models, and Liu Yan and HouZhi-Min [16] used it to study the three-dimensional soil cutting action of narrow blades. Aluko [17] suggested that FEM is suitable for analyzing soil-cutting problems where shear failure with substantial plastic deformation occurs. Dehghan-Hesar and Kalantari [18] also did an investigation on the stress distribution on a new designed disc harrow in ANSYS software. Mo [19] derived a biomimetic stubble-cutting disc and numerically analyzed the structural strength and working efficiency of the three-dimensional models of the disc.

III. DESIGN AND MODELLING OF THE DISCS

The profile of the mole rat's claw (Figure 1 (a)) inspired the design of the curved-slot disc. Its front claws moves like rotary spades when burrowing soil. The distinct physiological features of the claws have been used to design a biomimetic stubble-cutting disc [19]. Figure 1 (b) shows the biomimetic disc outline designed to mimic the mole's claw.

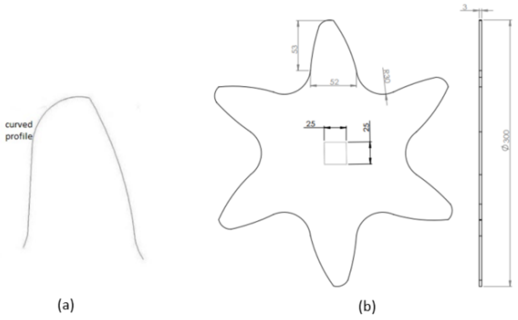


Figure 1. (a) Curved profile of the mole rat's claw and (b) outline of biomimetic disc

The curved profile of the biomimetic design presents an advantage in digging soil. However, it uses only the front part of the tooth when working. The merits of this design can be exploited further by extending the disc-soil contact surface to the external perimeter of the parent disc to give it a longer continuous curve.

The designed curved-slot disc integrates both the designs of the biomimetic disc and that of the curved blade of a fodder crop-cutter. Both the fodder cutter blade and the disc harrow blades have the same function of cutting down crop stalks.

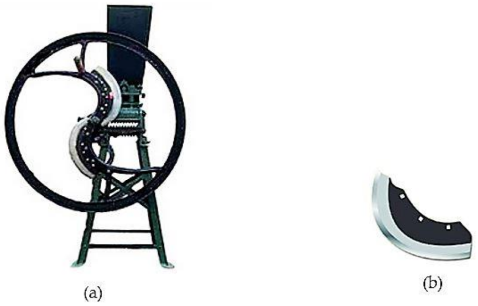


Figure 2. (a) Hand-operated chaff cutter and (b) curved cutting blade

The discs used for this study were made from circular steel plates, with a diameter of 300mm, thickness of 3mm and a square axial allowance of 25mm at the center. The design details of the discs are as shown in Figure 3 below. Other design features like tooth size and tooth number were referred to in the design manual of agricultural machines [20] and experience method.

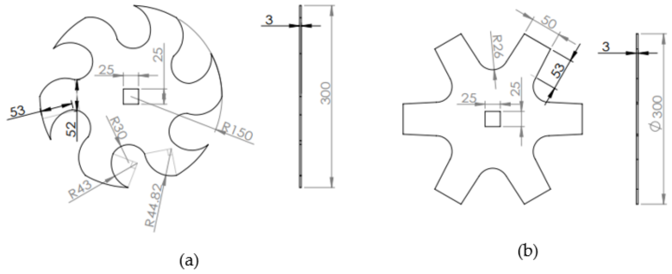


Figure 3. (a) New curved-slot disc and (b) conventional notched disc dimensions.

IV. PRE-PROCESSING AND MESHING

Three-dimensional models of the discs and the soil body were designed using CAD Solid works 2016 and simulated in ANSYS 18.1 software. The soil molds developed were rectangular prisms with dimensions of 600mm × 500 × 300mm (length, width and height). Disc material was taken to be structural steel of bulk modulus 160.67GPa, Young's modulus 20 GPa, density 7850kg/m^3, Poisson's ratio 0.3, and shear modulus 76.923GPa.

The models were meshed using adaptive size function with a minimum edge length of 3mm and a refinement to a scale of one was added at the disc surfaces (Figure 4). The total number of nodes used to describe the soil mold and the conventional disc were 17361 and 42165 elements. For the curved slot disc, 11024 nodes were used and 17540 elements.

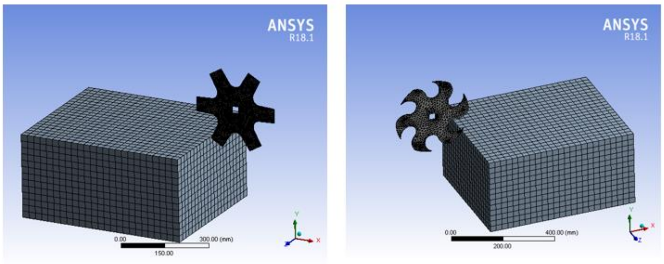


Figure 4. Meshing of soil mold and the discs

V. SOIL PROPERTIES

Soil has numerous and diverse properties that define its mechanical behavior[21]. Several yield criteria have been formulated to explain soil deformation. The Mohr-Coulomb, Cam-clay and Drucker-Prager are some of the criteria commonly employed to define soil models under maximum strain and maximum stress conditions. In this work, the soil was assumed an elastic-plastic material under Drucker-Prager criterion. This yield criterion can be defined as below.

$$f = 3\alpha\sigma_m + \bar{\sigma} - k = 0 \qquad (1)$$

Where α, k are the material properties, $\sigma_{\mathrm{m}}$is the mean compressive stress on the soil body and $\bar{\sigma}$ is effective stress.

Soil samples from the field analyzed were clay loam and the soil material properties were assumed in tri-axial compression. The values used in the FEA were bulk density 1.8Mg/m^3, Poisson's ratio 0.3, frictional angle 0°, Young's modulus 1.15, yield stress ratio 0.3, and dilation angle of 0°.
Young's modulus was calculated from the stress–strain $(\sigma_1 - \sigma_3)$ curve at zero confining pressure as shown below.

$$E = \frac{100\times\Delta(\sigma_1-\sigma_3)}{\Delta\varepsilon} \qquad (2)$$

Where E is Young's modulus (MPa), $\Delta(\sigma_1 - \sigma_3)$ is the difference in deviatoric pressure (MPa) and $\Delta\varepsilon$is the difference in elastic strain.
Poisson's ratio was calculated from equation below.

$$E = \frac{\varepsilon_{1r}-\varepsilon_{2r}}{\varepsilon_{1A}-\varepsilon_{2A}} \qquad (3)$$

VI. BOUNDARY CONDITIONS AND LOADING

A fixed support was set at the bottom face of the soil body as shown in Figure 5 below. Forward velocity was applied to the discs along the x-axis, towards the soil body and displacement constrained in the y-axis and z-axis. The velocity was varied from 1.5m/s to 2m/s and 3m/s. A constant angular velocity of 300rpm was also caused to act on the discs alongside the forward translation.

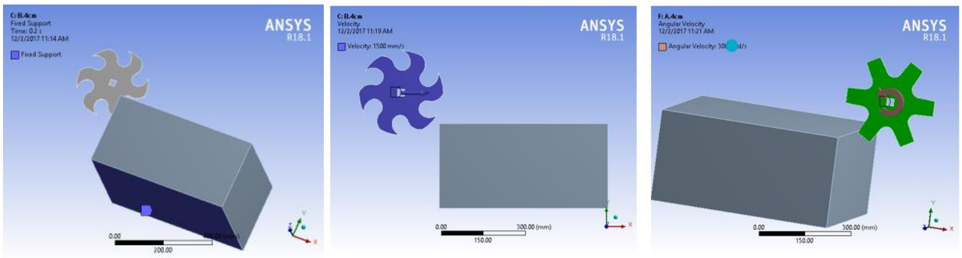


Figure 5. Fixed support at the bottom and variable forward speed of the disc and Constant angular velocity

The tillage depth was adjusted by setting the disc at three different points of 4cm, 7cm and 10cm as shown in Figure 6 below.

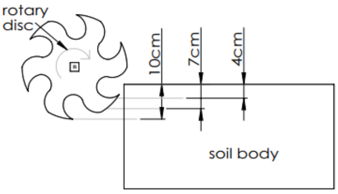
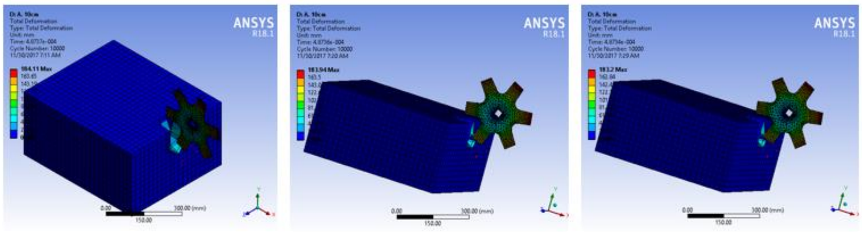


Figure 6. Tillage depth adjustment done in design modeler.

Time step of 0.02seconds and 10000 execution cycles were used in simulating the models to save on computational time and improve analysis efficiency. The simulation was set at an update interval of 2.5seconds, to solve the analysis. The maximum values of each solution were plotted on a contour diagram and the results saved for analysis.

VII. TOTAL DEFORMATION

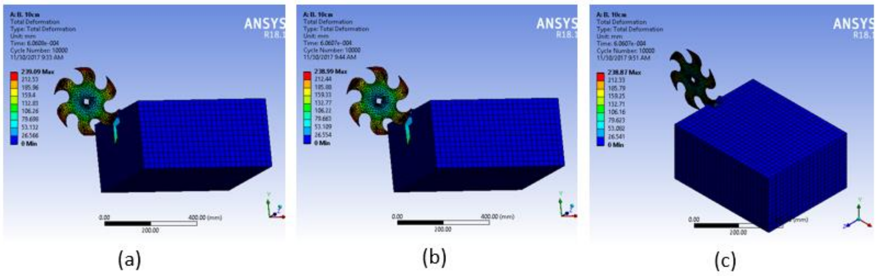
Figure 7 below present the simulation results for deformation when the conventional disc was at 10cm depth for the three speeds of 3m/s, 2m/s and 1.5m/s.



(a) (b) (c)

Figure 7. Deformation of the conventional disc at 10cm depth and working at different speeds (**a**: 3m/s, **b**: 2m/s and **c**: 1.5m/s).

Figure 8 below shows the simulation results for deformation when the new curved-slot disc was at 10cm depth for the three speeds.



(a) (b) (c)

Figure 8. Deformation of the curved slot disc at 10cm depth and working at three different speeds (**a**: 3m/s, **b**: 2m/s and **c**: 1.5m/s).

The deformation increased with the working rate because of the increased energy transferred to the soil by the rotational and forward motion of the discs. When the depth of tillage was reduced from 10cm to 7cm and 4cm, the deformation remained relatively constant on the new curved slot disc. The conventional disc however showed more variation.

The deformation registered on the curved-slot blade disc was more than on the conventional disc (Figure 9). This was attributed to longer curved profile that increased soil-blade interface compared to the straight working surface of the conventional type.

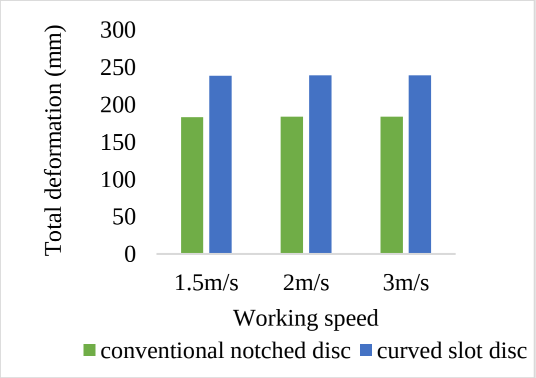
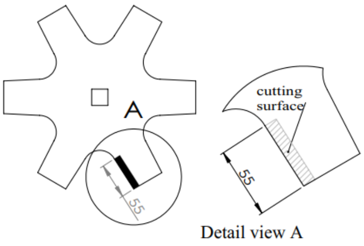


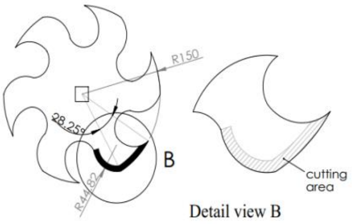
Figure 9. Comparison of the deformation on the discs at 10cm depth

The large contact area between the disc and the soil improved the cutting efficiency by handling more crop residue on the ground, due to the increased contact area. On the contrary, the protruding sharp edges on the conventional disc would cause it to skip various points in the field and some straw on the surface will be left untouched. The comparison of cutting areas of both discs are shown in Figures 10 and 11 below.



Effective soil contact area
$A = 55 \times 3$
$=165mm^2$

Figure 10. Conventional disc soil-contact surface



Effective soil contact area =

$$B = 2\pi\left[\left(\frac{28.5}{360}\times 150mm\right)+\left(\frac{90}{360}\times 44.82mm\right)\right]\times 3mm$$

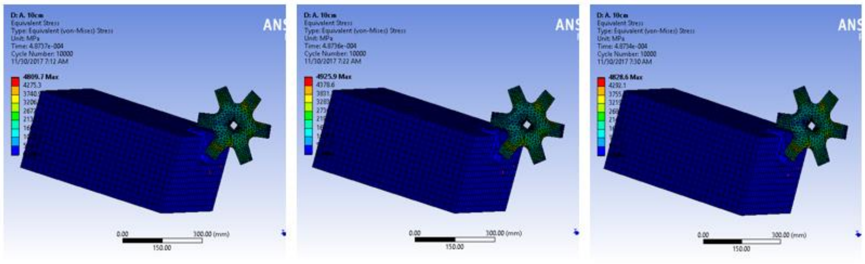
$= 435.05\text{mm}^2$

Figure 11. Curved slot disc soil-contact surface

VIII. STRESS, STRAIN ANALYSIS

The conventional notched disc showed higher stress levels compared to the curved slot design. The curved profile of the new disc was able to reduce the pressure exerted on the blade by significant amounts. This would ensure that the disc cuts through the soil with ease and breaks down crop residue present on the surface. The operation of the disc harrow would thus be smoother and uniform.

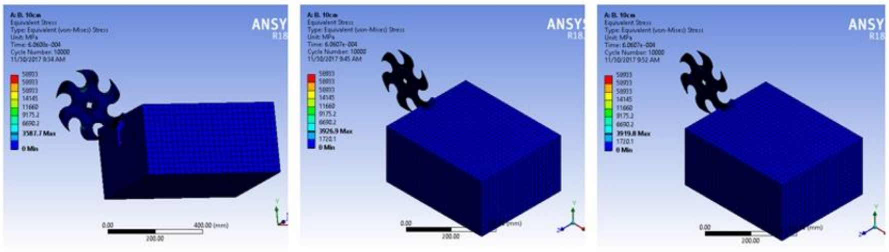
The solutions to the equivalent stress analyses at the three different speeds on the conventional notched disc cutting through the soil body is as shown in Figure 12 (a, b and c) below. Elastic strain varied linearly with the stress values, similar deductions were therefore applicable.



(a) (b) (c)

Figure 12. Stress levels (MPa) on the conventional notched disc at three different speeds (**a**: 3m/s, **b**: 2m/s and **c**: 1.5m/s).

The solution to the equivalent stress simulations at three different speeds on the new curved-slot disc is as shown in Figure13 (a, b and c) below.



(a) (b) (c)

Figure 13. Stress levels (MPa) on the curved slot disc working at three different speeds (**a**: 3m/s, **b**: 2m/s and **c**: 1.5m/s).

From the contour plots, it can be seen that the equivalent stresses were reduced on the new curved-slot disc by 25.4% at 3m/s; 20.3% at 2m/s and 18.8% at 1.5m/s. This means that the new disc was able to minimize draft force and in turn lower the energy demands of the tractor. Figure 14 below compares the stress levels of the two discs when working at 10cm depth.

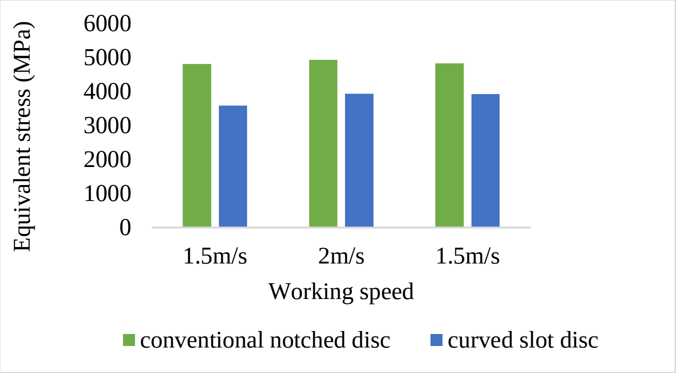


Figure 14. Comparison of equivalent stresses for conventional disc and curved-slot disc

The recorded stresses on the conventional disc varied much with the increase in velocity from 1.5m/s to 2m/s to 3m/s, while that of the new design remained more consistent over the same range. This shows that the new disc would be steadier in its operation despite alternations in the tractor forward speeds. The work done would therefore be of better quality.

At more shallow depths of 7cm and 4cm, the stress levels on the conventional disc, were high as pressure was concentrated at a small area near the cutting edge. On the curved slot disc however, the stress levels remained low. This would cause the conventional type of disc to be at risk of faster erosion and possible fracture. The new design would therefore have more elongated lifespan.

IX. CONCLUSIONS

This work used FEA to optimize the geometric features of a new disc harrow blade by increasing the cutting efficiency through increased contact area and reduced draft forces on the discs. The new curved-slot disc proved to be of better structural strength and had an improved working efficiency due to the low stress levels attained compared to the conventional type. Introducing the curved profile on the slots of the notched harrow discs provided excellent shape for better soil-blade interaction. This will enhance the process of crop residue incorporation into the soil by saving on the energy demands of the agricultural machines and minimize the farm operational costs while lengthening the tool life. The curved profile will also make the digging and crop residue burial process smoother, deeper and easier due to reduced resistance to motion.

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