Comparison and Optimization of Graphical Methods of Moldboard Plough Bottom Design Using Computational Simulation

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Abstract: The objective of this study was to computational analysis and comparison of a new graphical method of moldboard plough bottom design with previous graphical methods. Results show that the new method made the design and manufacturing process of plough bottom simpler. Also, this method decreased the weight of the bottom up to 7.3% due to the reduction of the overdesigned surface of it up to 273.5 cm^2. Therefore, based on this developed method, the price and magnitude of energy consumption of the moldboard plough decreases due to reduce of the weight of bottom and its friction with soil. Also, a three dimensional model of the new designed bottom was designed using CATIA V5R16. Then, computational simulation of the bottom was carried out by ABAQUS V6.9 utilizing the finite element method. Interactions between the bottom and the test soil (sandy loam) were applied to the simulation using a distributed load applied to the surface of moldboard and share. This distributed load was obtained from interpolation among 14 point forces measured from field tests using piezo-resistive transducers located on the working surface of the bottom. The load distribution was then derived by using spatial interpolation. Results show that this new designed bottom can easily withstand the applied stresses and displacements during plowing process. Results obtained from this study are suitable for the manufacturers of moldboard plough specially those who wish to use the finite element method to improve their products.
[Hamed Shahmirzae Jeshvaghani, Salman Khaksar Haghani Dehkordi, Mahmood Farouzandeh Samani, Hamidreza Rafeie Dehkordi. **Comparison and Optimization of Graphical Methods of Moldboard Plough Bottom Design Using Computational Simulation**. *J Am Sci* 2013;9(6): 414-420]. (ISSN: 1545-1003). http://www.jofamericanscience.org. 50

Keywords: Moldboard plough bottom design; graphical method; CATIA V5-R16; computational simulation; ABAQUS V6.9

1. Introduction

Soil tillage is one of the fundamental phases of agricultural production and also the most expensive process in terms of energy costs. Moldboard plough is the most widespread tillage implement in the world and the biggest consumer of energy in agriculture (Bernacki, 1972; Caproiu et al., 1982; plouffe et al., 1999). Over many years the shape of the moldboard plough bottom has been evolved through the "trial and error" design efforts. For instance, in 1799, Thomas Jefferson developed a physical method to accurately describe the surface of a moldboard that could be used in constructing a plough. He used two straight lines as fixed directives while a third straight line moved and rotated in a fixed plane (Jefferson, 1799). Since then, various researches have been concentrated on the optimization of the shape of bottom, in order to improve energy efficiency (Natsis et al., 1999; Formato & Roncioni, 2001; Shrestha et al., 2001; Shahmirzae et al., 2009).

In Iran, tillage implement manufacturers commonly do not use engineering methods and tools efficiently. So this leads them to overdesign their products. Therefore, designed moldboard ploughs which are still the most essential tillage tools in Iran have material and energy consuming overdimentions resulted in unnecessarily cost allocation.

Optimization of the shape of plough bottom is quite hard to obtain because of the variability in the soil types and plowing conditions which resulted in the variability in shape of the moldboard and share, complexity and difficulty of the design and construction of the bottom surface. Also analysis and optimization of moldboard plough is very difficult due to the convolution of the bottom surface which resulted into the complicated distribution of load on its surface. However, because during agricultural production the most part of energy and cost is dedicated to the tillage and also moldboard plough is the most energy consumption tillage tool, it provides an important incentive to improve bottom shape to reduce the power required. Different authors have achieved significant reductions through empirical studies of plough moldboard design, and provided guidelines to improve either design or tool manufacturing (Suministrado et al., 1990b; Araya et al., 1996; Desbiolles et al., 1997).

Due to the variability in shape of the plough bottom, complexity and difficulty of the design and construction of it which makes the field optimization of plough very expensive, computational simulations can help the researchers very good. Several mathematical models have been developed to study the interaction between soil and moldboard shape. Although, these models were at first very simple but, subsequently, they have been improved by the application of numerical procedures. Several researchers have tackled different aspects of the problem by adopting different types of hypotheses and procedures and eventually reached interesting results that have contributed to a better understanding of the soil–plough moldboard interaction phenomena (Formato, 2005). Furthermore, other authors have given useful information about other types of models, by conducting soil tests in different conditions (Araya et al., 1996; Desbiolles et al., 1997; Eradat Oskoui et al., 1982; Harrison, 1982; Hendrick &Bailey, 1982) and with tools set in different ways (Kuczewski, 1981; Licsko & Harrison, 1988). The main objective of the present paper is to show an optimized method of moldboard plough bottom design, comprise it with previous methods and computational analysis of soil-new plough bottom interactions referring to finite element method.

2. Materials and Methods

The working surface of the moldboard plough bottom has two parts: the share and the moldboard. The share could have either a cylindrical or a plane surface. The moldboard has a spatial surface with a complex geometry, which varies from a cylindrical surface to a helical one. Moldboard is the main part of the plough and has the function of shattering the soil, displacing it laterally and inverting the furrow-slice to cover plant residue. The moldboard geometry determines the quality of the tillage process and energy consumption during the tillage.

a. Theory of moldboard design

In this study, like some other previous studies, the share and the moldboard are designed at the same time. All of plough bottom design approaches are based on graphical methods which are quite troublesome and inaccurate. Based on Goriyachkin theory, a moldboard plough bottom could be considered as a wedge-shaped surface. This wedge (a trilateral pyramid which one edge is perpendicular to the base) is consisted of three triangular prisms. Prisms with angle α, β and γ have the function of shattering the soil, inverting the furrow-slice and displacing it laterally to cover plant residue, respectively (Reintam, 1969).

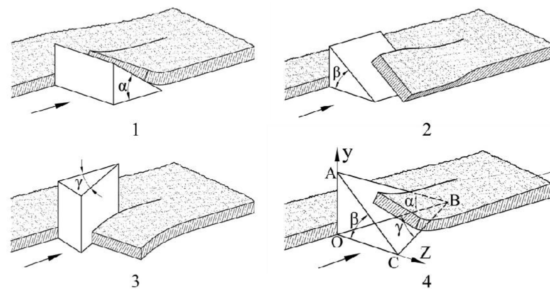

Figure 1. Structure of a moldboard plough bottom and its function

Variation of these angles along the mentioned surface defines the moldboard. Because of a large variety of soil types and plowing conditions, many different shapes of moldboards have been developed: cylindrical, cylindroidal, and helical. The cylindrical and cylindroidal surfaces are the most frequently used. One of the graphical approaches to the design of plough bottom is the generation of the surface by a generatrix line which is moving on a directrix curve (Figure 2). Movement of the generatrix line on the directrix curve shapes the surface of bottom (Caproiu, 1982; Murgulescu, 1962; Ros, 1978).

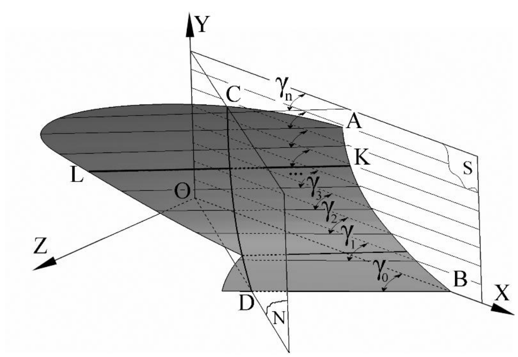

Figure 2. Movement of the generatrix line on the directrix curve to shape the surface of bottom

During the movement, the generatrix line is always parallel to the horizon and its angle with the plowing direction (γ) varies with the function γ(Y). The variation function of the angle γ(Y) may be represented as a third degree function mentioned below. As recommended by different authors, Coefficients m, n, p, q, depend on which form of the graphs in figure 3 is chosen. The form of the graph determines the type of the moldboard. These coefficients are considered known.

$$\gamma(Y) = mY^3 + nY^2 + pY + q$$

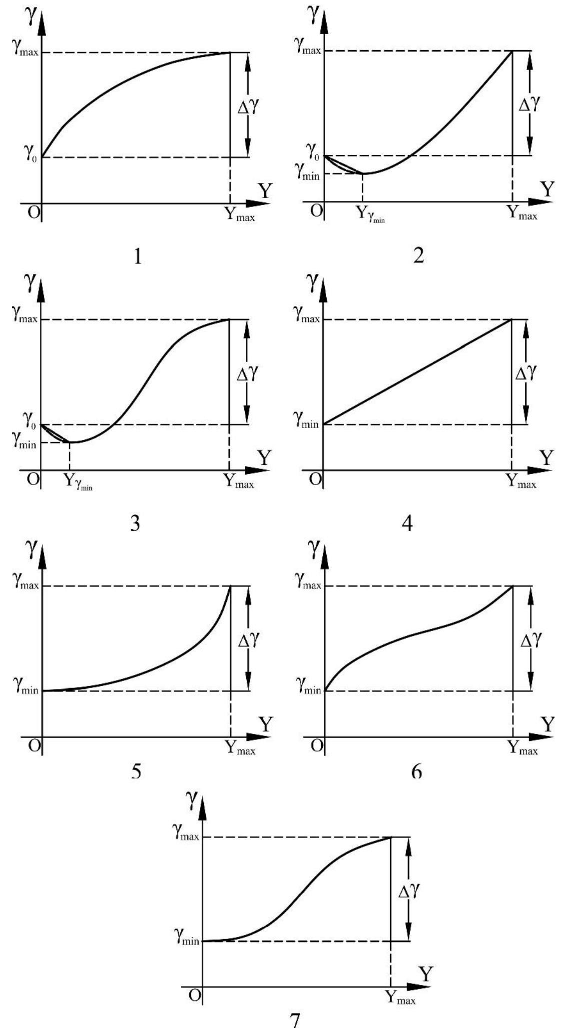

Figure 3. Different graphs to determine the variation function, γ(Y)

Determination of the spatial contour of the working surface of the plow bottom starts from its projection on the vertical plane which is perpendicular to the plowing direction (vertical-transverse plane) (Bernacki et al., 1972; Caproiu et al.,1982; Richey et al., 1989; Ros, 1978).

b. Dimensions of furrow slice and vertical-transverse view of bottom

The plow bottom is designed to turn over a furrow slice which, theoretically, remains unaltered and has a rectangular section. Theoretically, we accept the hypothesis that, in the inversion process, the rectangular cross-section of the furrow slice, *ABCD*, remains unchanged (Caproiu, 1982; Ros, 1978). First, the cross-section rotates around the point *A* until it reaches the position $AB_1C_1D_2$, then it rotates around the point D_2 until it reaches the final position $A_2B_2C_2D_2$, when the height of the point C_2 has the value *a* (Figure 4).

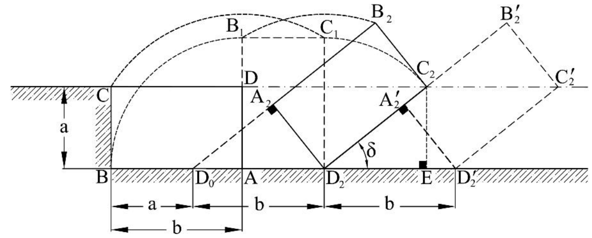
Figure 4. Inversion process of the furrow slice (cross section)

Figure 5 shows the vertical-transverse projection of plough bottom which is drawn based on the inversion of rectangular furrow slice.

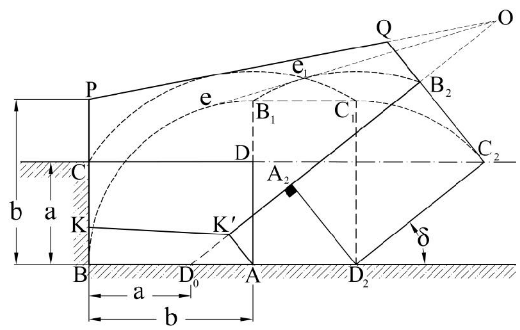
Figure 5. Vertical-transverse projection of plough bottom

Based on Shouchkin researches, the vertical-transverse projection of the bottom improved to the form in figure 6 (shouchkin, 1952).

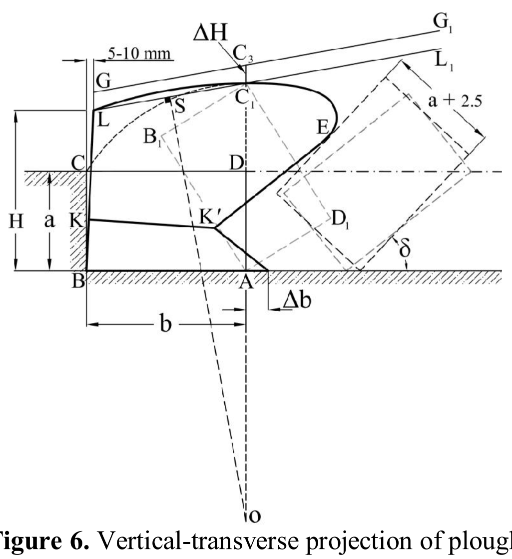

Figure 6. Vertical-transverse projection of plough bottom improved by shouchkin

His method optimized the contour of the bottom by reducing the friction between the bottom edges and the soil (Figure 7). But still his method had some disadvantages which made the process of bottom design and construction difficult.

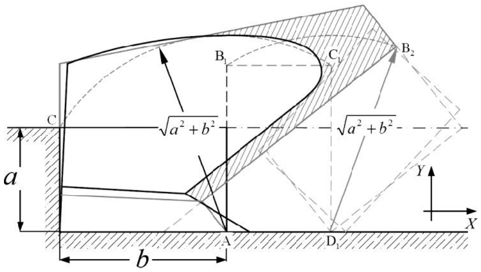

Figure 7. Comparison of shouchkin method with the old one

Shahmirzae et al., 2009, optimized this graphical method and presented a simpler way to the bottom design (Figure 8). Their method reduced the surface of the bottom up to the working surface and made it lighter. Also this method made the graphical method of plough bottom design simpler (Figure 9).

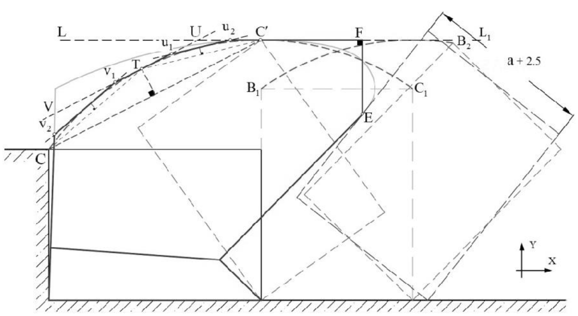

Figure 8. Vertical-transverse projection of plough bottom method presented by Shahmirzae et al., 2009

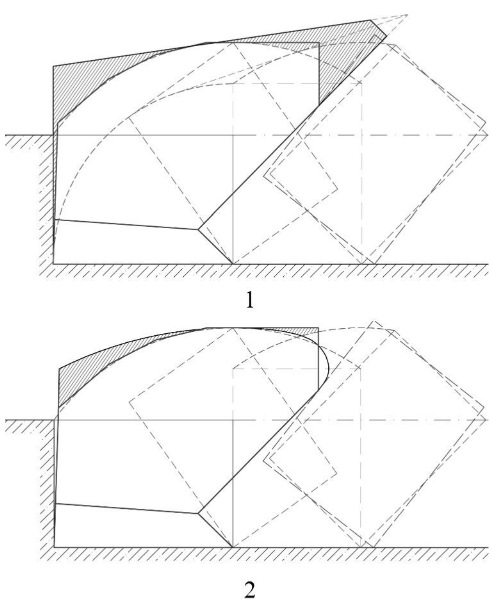

Figure 9. Comparison of Shahmirzae method with the old ones

Computational modeling of plough bottom makes the simulation of it simpler, easier and cheaper compared to field tests. For a better comparison among mentioned methods, a cylindroidal bottom was modeled in CATIA V5-R16 based on the three mentioned methods. Other steps of all these methods are the same and are mentioned in reference books.

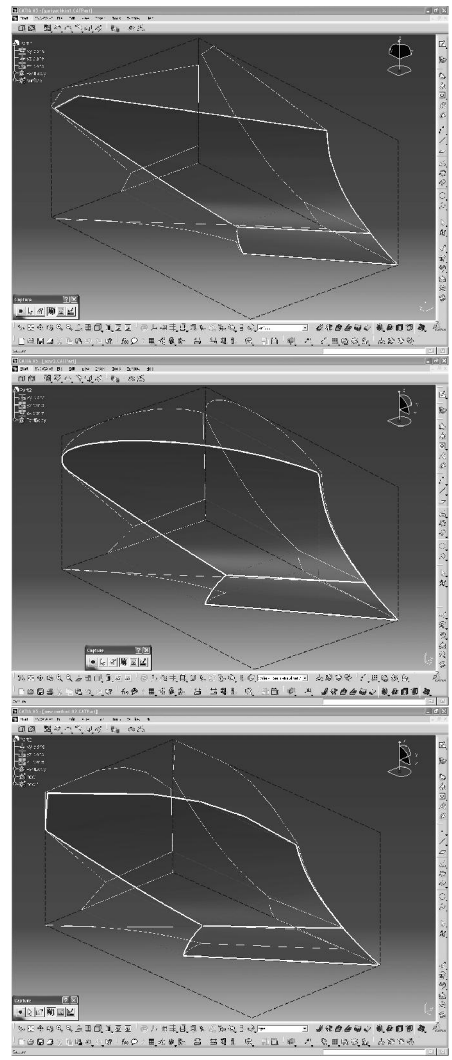

Figure 10. Plough bottom modeling in CATIA based on each three methods

The modeled bottom is designed using parameters of a real condition. Then the 3D modeled bottom was imported to the ABAQUS V6.9 and was simulated under the real soil-moldboard plough conditions. Interaction between the bottom and the test soil (sandy loam) was applied to the simulation using a distributed load applied to the surface of bottom (Figure 11). This distributed load was obtained from interpolation among 14 point forces measured from field tests using piezo-resistive transducers located on the working surface of the moldboard (Formato et al, 2005). The load distribution was then derived by using spatial interpolation.

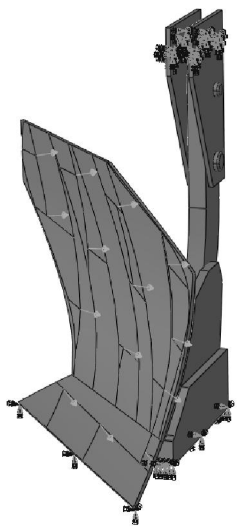

Figure 11. Modeled plough bottom based on new method under the real plowing conditions in ABAQUS V6.9

Based on real conditions, all constraints and boundary conditions were applied to the model. After the auto meshing of the model by the software, it was simulated under the static loading (Figure 12).

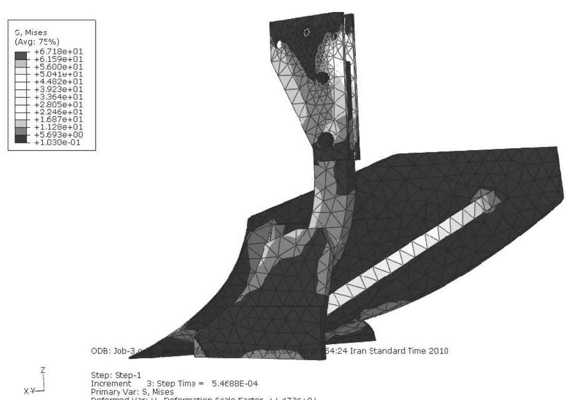

Figure 12. Simulated plough bottom under the field conditions in ABAQUS V6.9

3. Results

The new developed method to the graphical design of the moldboard plough bottom is detailed in this study. After the modeling a cylindroidal bottom using parameters of real condition in CATIA V5-R16, the new method is compared to the previous methods.

Table 1 shows the improvements of the new method in comparison with previous methods through the area of Vertical-transverse projection and the volume of plough bottoms.

Table 1. Comparison of each method through the area and the volume of plough bottoms

	Basic method	Shouchkin method	Shahmirzae method
Vertical-transverse projection area (cm^2)	1660	1530	1415
Overdesigned area in Vertical-transverse projection (cm^2)	200	84.5	15.5
plough bottom volume (cm^3)	2830	2380	2230
Overdesigned volume of material used in plough bottom (cm^3)	300	132.5	26.5

It is obvious that the new method decreases the weight of the bottom up to 7.3%. Also, this method follows the pattern of the furrow slice better than previous methods. Results show that the new method makes the procedure of plough bottom design simpler and easier. It also resulted in the reduction of overdesigned surface of the bottom up to the 184.5 cm^2 which decreases the volume of the bottom and it's constructing material up to 273.5 cm^3. It means that the weight of the bottom decreases about 7.3%. This leads to reduction of cost of plough and also the energy consumption during plowing. Another advantage of this method is that it makes the procedure of construction of the bottom simpler and easier due to producing the contour of the bottom by straight lines.

Stress and displacement distributions were obtained through calculations using ABAQUS V6.9. Due to the limited volume of this paper, we confine ourselves to graphical results. Results show that the bottom designed by the new method can withstand the real field conditions very good. The most dangerous areas are those surrounding the two fixed points of the moldboard to its stem (Figure 13). As the maximum values of stress intensities occur at two fixed points of the moldboard, it may be useful to increase the thickness of the supports of the moldboard near these regions, or to use a complementary support under the free end of the moldboard. It is expected that the maximum displacement magnitudes occur at the free end of the moldboard. Displacements are predominately negative and the moldboard can withstand them (Figure 14).

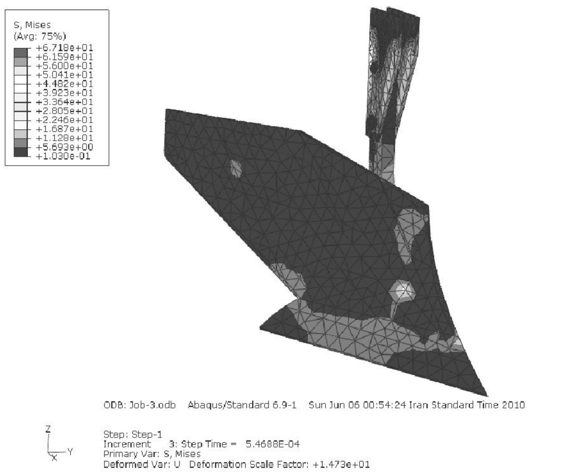

Figure 13. Stress distribution of the bottom simulated under the real conditions.

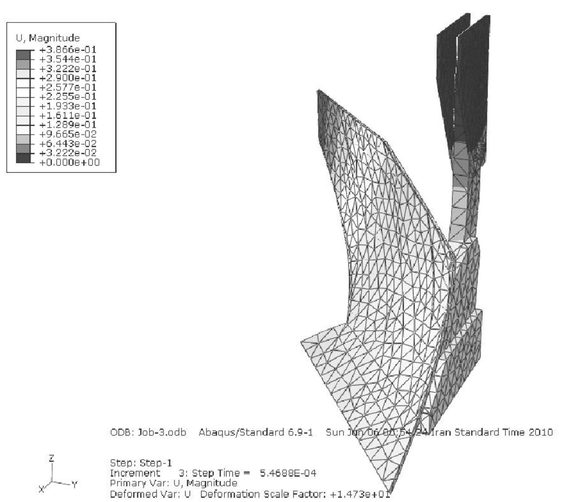

Figure 14. Displacement distribution of the bottom simulated under the real conditions.

4. Discussions

Due to the graphical methods description of the working surface of the plough bottom may be fully determined by the dimensions of the furrow slice, the position and equation of the directrix curve, the equation for the generatrix line, and the vertical-transverse projection of the working surface. The new method presented in this study permit an easy and simple geometrical description for the shape of a moldboard plough bottom. Then this method was used to model a plough bottom using CATIA software and was simulated under field test conditions using ABAQUS software. Thus, the creating of the new developed graphical model in the CATIA environment, entering this model into an ABAQUS environment for creating the soil-moldboard plough bottom simulation and carrying the results of computations were successful. This alternative possibility is suitable for the manufacturers of moldboard ploughs who wish to use the finite element method to improve their products.

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