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A torque calculator for rotary tiller using the laws of classical mechanics

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ABSTRACT

The theoretical understanding of the working mechanism of a machine, prepares an opportunity to re-design it without performing the re-fabrication process. In this study, a thorough mechanical model for a rotary tiller is developed that contains both kinematics and kinetics viewpoints of its operation. Specifically, the main aim of this model is to develop a theoretical calculator concerning the torque and power requirement of this active tillage machine. To perform the required calculations simply, and automatically, the derived equations were entered into an Excel spreadsheet, and the results was presented as the torque and power of a rotary tiller. The developed formulas were verified by comparing the results of the model with the acquired results of other studies. The average errors of the calculated specific work of a rotary tiller compared with the results obtained in the studies of Asl and Singh (2009) and Bernacki et al., (1972) were 16% and 14%, respectively. The average error of the calculated power by comparison with the results of Perdok and Burema (1977) was 21%. The average error of the calculated fetch ratio in comparison with the results of the study of Thakur and Godwin (1989) was 9%. Finally, the average error of the calculated torque in comparison to the study of Chertkiattipol and Niyamapa (2010), was 5%. Therefore, good estimates are expected to be obtained when using the developed calculator.

1. Introduction

Tillage practices are performed using various machines. These machines are generally divided into two broad categories, namely passive implements and active machines. While passive tillage implements consume only drawbar power to break the soil, active machines can utilize rotary power to prepare soil for planting (Aday, 2015). An active implement can be attached to a wheel tractor and is powered via the tractor power take off shaft (PTO). Alternatively, its power can be supplied through a walking tractor (power tiller). In the latter case, the tractor may have its own propulsion wheels to develop the required thrust force, or the required propulsion force may be produced by the action of the tiller blades (Sakai, 1978). The thrust force that is produced by the action of the tiller blades is generally called the negative draft. The shaft of a rotary tiller may be rotated in the forward direction, which leads to the soil down-cut (Matin et al., 2015), or the backward direction, which leads to the soil up-cut (Shibusawa, 1993). A negative draft is only produced when the rotation of the shaft is in the forward direction (like the rotation of the driver wheels of a tractor). Since the power requirement of a rotary tiller is high (Srivastava et al., 2006), researchers have tried to measure it (Chertkiattipol and Niyamapa, 2010), estimate it (Elgin, 1979) or calculate it (Thakur and Godwin, 1989). While measurement and estimation of the required power of a rotary tiller were based on experimental methods, power calculation can be performed using theoretical procedures. In order to acquire a formula for the calculation of the required power of a rotary tiller, the soil-blade interaction must be analyzed from the kinematics and kinetics viewpoints. The aim of the kinematics analysis is to consider the motion of the blades, and the kinetics analysis leads to the calculation of the exerted external forces on the blades, and hence these forces can be used to estimate the required torque of the rotary tiller shaft.

In this paper, the development of a theoretical calculator to obtain the power requirement of a rotary tiller is achieved. The rotation of the examined L-shaped blades of the tiller is assumed to be in the vertical plane and in the forward direction (driver-wheel-wise direction). To perform the required calculations automatically, the derived equations are entered in the Microsoft Excel software, and the finalized spreadsheet is utilized as the torque and power calculator of a rotary tiller. Finally, the developed formulas are verified by comparing the results of the developed model with the acquired results of other studies.

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Nomenclature

$(\pi/4-\phi/2)$	angle of soil failure plane with the horizon (rad)
BL	Blade length (m)
BW	Blade width (m)
c	soil cohesion (N/m^2)
d	working depth (m)
FR	Fetch ratio (L_b/d)
L_b	length of bite of a blade (m)
N_b	number of blades per flange
N_f	number of flanges of the rotary tiller
P	power requirement of the rotary tiller (kW)
R	radius of the rotor (m)
SW	specific work of the rotary tiller (Nm/m^3)
SW_d	specific work in the dynamic phase (Nm/m^3)
SW_s	specific work in the static phase (Nm/m^3)
T	required torque of the rotary tiller (Nm)
$\tan(\phi)$	coefficient of soil internal friction
T_d	required torque of a flange in the dynamic phase (Nm)
T_{db}	required torque of a blade in the dynamic phase (Nm)
T_s	required torque of a flange in the static phase (Nm)
T_{sb}	required torque of a blade in the static phase (Nm)
v	forward velocity (m/s)
ω	angular velocity of the rotor (rad/s)
γ	specific weight of soil (N/m^3)
δ	angle of soil-metal friction (rad)
ϕ	angle of soil internal friction (rad)

2. Material and methods

It was assumed that the rotary tiller has ten flanges, which are attached to the shaft of the machine; furthermore, each flange contains four blades on each side, which are bolted radially to it and separated by the angle of 90°. Moreover, the L-shaped blade is selected for this study with 4 cm length of the cutting edge (6 cm including the radius of curvature of the blade) and 5 cm width. The height of the blade from the center of the rotating shaft is assumed to be 24 cm. The shaft of the machine is installed horizontally, perpendicular to the direction of the tiller's forward direction, and is rotated in the driver-wheel-wise direction. The shape of a blade and the installation method of the blades on a flange are depicted in Fig. 1a and b respectively:

2.1. The kinematics of the blade operation

In order to analyze the operation of a blade of a rotary tiller from the kinematics viewpoint, the position vector of the horizontal cutting edge of the blade must be known. If this position is obtained as a function of time, its first derivative will result in the velocity vector, and its second derivative will give the acceleration vector of the horizontal cutting edge of the blade. To obtain the position vector of the cutting edge of the blade in the Cartesian coordinate system (X-Y coordinates), the origin of the coordinate system is assumed to be located at a fixed point. This point has the same height as the height of the center of the tiller shaft, and with the X-axis in the same direction as the direction of the tiller forward speed. The Y-axis of the coordinate system is pointed vertically upward. Moreover, the position of the center of the tiller shaft is initially located at the origin of the coordinate system. Utilizing this layout, if the forward speed of the tiller, which is considered to be a constant value, is denoted by v, the position vector of the center of the tiller shaft at the time t will be obtained as (vt,0). Moreover, the position coordinates of the cutting edge of the blade, which is located initially on the positive side of the X-axis, will be calculated at the time t as:

$$\begin{cases} x_b = vt + R\cos\omega t \\ y_b = -R\sin\omega t \end{cases} \quad (1)$$

In Eq. (1), the principle of the relative position is utilized, which means that the position of the cutting edge of the blade is calculated by summing vectorially the position coordinates of the center of the tiller shaft and the relative position coordinates of the cutting edge of the blade relative to the center of the tiller shaft. It is valuable to note that the function given in Eq. (1) is a cycloid (trochoidal path), furthermore, the shape of this function with the input values of (v = 1 m/s, R = 0.24 m, $\omega = 15 rad/s$), is depicted in Fig. 2:

From Eq. (1) suitable information can be concluded. For example, if the working depth of a tiller (d) is known, the time,

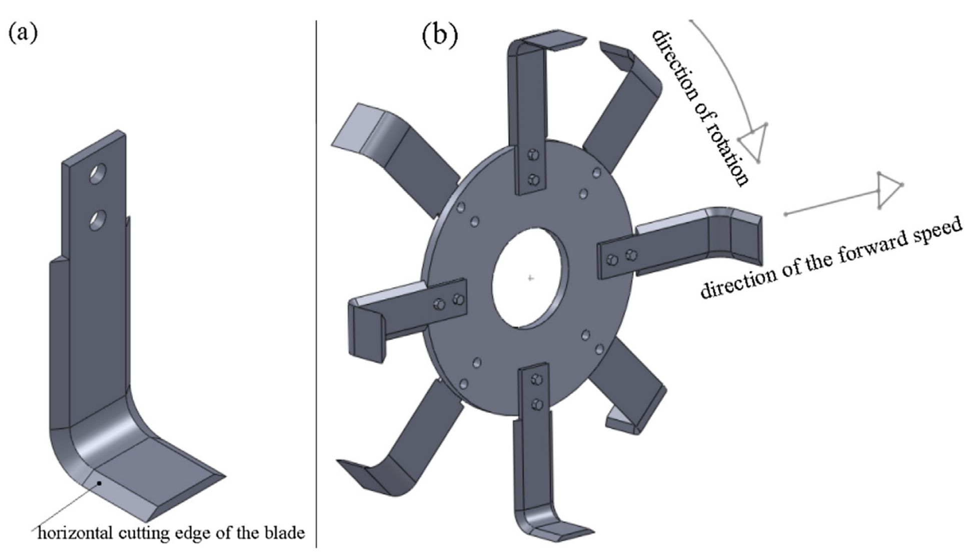

Fig. 1. a) The shape of a blade b) the installation method of the blades on a flange.