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Modeling of share/soil interaction of a horizontally reversible plow using computational fluid dynamics

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Abstract

The horizontally reversible plow (HRP) is currently widely used instead of the regular mold-board plow due to its high operational performance. Soil pressure during HRP tillage generally has adverse effects on the plow surface, especially on either the plowshare or the plow-breast. This effect eventually shortens the tool's service life. For this reason, this investigation used a three-dimensional (3D) computational fluid dynamics (CFD) approach to characterize the share/soil interaction and thus assess the effects of different tillage conditions on the interaction. To achieve this goal, a 3D model of the plowshare was first constructed in the commercial software SolidWorks, and soil from Xinjiang, China, was selected and subsequently characterized as a Bingham material based on rheological behaviors. Finally, 3D CFD predictions were performed using the control volume method in the commercial ANSYS code Fluent 14.0 in which the pressure distributions and patterns over the share surface were addressed under different tillage speeds in the range of 2–8 ms^{-1} and at operational depths ranging from 0.1 to 0.3 m. The results show that the maximum pressure appeared at the share-point zone of the plowshare and that the increase in soil pressure was accompanied by either higher tool speed or greater operational depth. The calculated results qualitatively agreed with the preliminary experimental evidence at the same settings according to scanning electron microscopy (SEM). Once again, the CFD-based dynamic analysis in this study is demonstrated to offer great potential for the in-depth study of soil-tool interactions by simulating realistic soil matter.

Keywords: Soil-share interaction; Computational fluid dynamics (CFD); Tillage speed; Operational depth; Horizontally reversible plow (HRP)

1. Introduction

In soil excavation processes, tillage tool interaction is the largest energy-consuming operation because it operates via soil cutting with the objective of attaining suitable conditions for crop production (Natsis et al., 2008). The mold-board plow is widely used in tillage, and its plowshare and mold-board are the two main soil-engaging components. Tillage is the mechanical manipulation of the soil in the tillage layer and results in severe wear on either the plowshare or mold-board (Eltom et al., 2015). The soil pressure distribution and pattern over the plow surface are demonstrated to be strongly associated with the appearance of abrasive wear (Natsis et al., 2008).

The horizontally reversible plow (HRP) is a novel mold-board plow developed by the Xin-Jiang Agricultural Mechanization Institute (XJAMI) of China. The unique advantage of HRP, which is quite different from regular mold-board plows, is that it can facilitate continuous and alternative commuting tillage with excellent operational performance (i.e., steady tilling and orderly soil cutting)

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(Zhu et al., 2006). Fig. 1 shows the commuting tillage process of HRP in real field conditions, where symbols A and B separately denote the two different limited tillage positions of HRP, the pink curves indicate the hypothesized flow of soil clods on the plow surface, and n is the rotational speed of the basic beam (BB) with respect to the main beam (MB) (Zhu et al., 2006). The rotational speed of the plow body is the same as that of the basic beam (BB) with respect to the main beam (MB) because it is attached to the BB.

In practical HRP tillage operations, severe abrasive wear is always found on the plow surface, especially on either the plowshare or plow-breast. Fig. 2 shows the worn area at the share-point of the plowshare at a tool speed of 1.67 ms^{-1} and an operational depth of 0.27 m. This effect not only shortens the tool service life but also affects the plow qualities due to the initial shape changes (Shmulevich, 2010). For the purpose of tool design optimization and performance improvement, a better understanding of the interaction between soil and share is essential to alleviate the worn area that appears on the share-point. In this paper, computational fluid dynamics (CFD) modeling was proposed to investigate the interaction between the soil and the HRP plowshare and examine the wear phenomenon.

Currently, four major methods are available for the investigation of the soil-tool interactions, including empirical and semi-empirical methods, dimensional analysis, the finite element method (FEM) and the distinct element method (DEM) (Karmakar et al., 2007; Barker, 2008). Empirical and semi-empirical models also exist, i.e., mathematical solutions that describe the soil-tool interaction through parametric studies, but they encounter limitations in the pursuit of a better understanding of the soil-tool interaction because they are not based on the real soil failure shapes. The dimensional analysis technique is applied to different parameters of the tillage system, but it is prone to distorted models and obscurity in two-and three-dimensional problems.

The finite element method (FEM) can overcome the drawbacks of the previously mentioned analytical method by supplying the soil-tool interaction with additional information (such as the progressive soil failure zone and field of stress), but the limitation of FEM is large geometry deformation (Barker, 2008; Karmakar, 2005; Xu et al., 2015). This problem indicates that FEM might not accurately simulate the complex dynamic interactions between the soil and tool. As a potential new technique, the distinct element method (DEM) can implement the particle dynamics interaction to obtain adequate soil reaction forces, but it faces certain difficulties in simulating the real particle size and shape of soils (Shmulevich, 2010). Currently, different authors are working to simulate the soil-tool interaction using DEM, but DEM is limited to simulation of wear distribution on tools (Shmulevich, 2010).

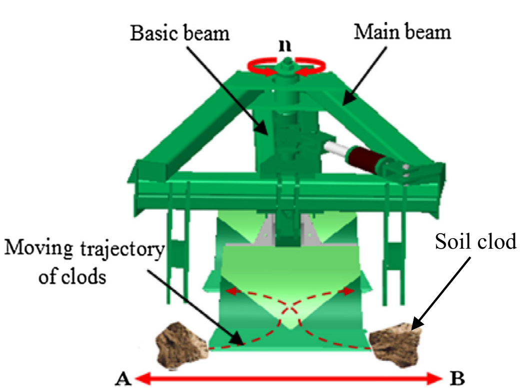

Fig. 1. Commuting tillage process of HRP.

Compared with the above four methods, the main advantage of computational fluid dynamics (CFD) is that it can create a detailed description of the real soil flow distributions (Karmakar, 2005). Hence, CFD is an alternative computational modeling that can assess the pressure distributions that indicate the relative wear of the tool from soil-tool interactions. Considering the soil rheological behavior, Karmakar and Kushwaha (2006) proposed a computational fluid dynamics (CFD) method for soil-tool interaction from a visco-plastic fluid flow perspective and obtained the soil stress patterns around a simple vertical tillage tool and the pressure distributions on the tool surface. However, simulation results of the interaction between the soil and HRP are not available in the literature.

Therefore, this study investigated the feasibility and efficacy of computational fluid dynamic (CFD) modeling in soil-HRP interaction. The CFD-based predictions presented in this paper are primarily focused on the pressure patterns and distributions over the HRP plowshare under high-speed tillage. These numerical simulations were focused on the two key factors, i.e., tool speed and operational depth, that strongly affect the HRP tillage performance (Ranjbar et al., 2013).

2. Materials and methods

2.1. Model geometry of the plowshare

The plowshare of the HRP has a curved surface, the overall dimensions of which are 0.69 m in length, 0.12 m in width and a 0.01 m maximum height (Zhu et al., 2008). These geometric parameters are strongly correlated with the soil types and the operating conditions, thereby affecting tillage quality and power consumption (Gill and Vanden Berg, 1967). Identification of the plowshare surface is, therefore, essential to better understand the soil-plowshare interaction under real field conditions. In this study, combined feature-based modeling and scanning measurement were used to construct the 3D geometric model of the plowshare. The detailed procedures are depicted as follows. First, the real plowshare surface was scanned using a 3D touch-probe measuring bench (Explorer 07.10.05, Qindao, P.R. China) to determine the Cartesian coordinates of the points in the intersection of