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Development and performance evaluation of an electric-hydraulic control system for subsoiler with flexible tines

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ABSTRACT

Subsoiling is primary practice in conservation tillage fields, as it disrupts compacted soil hardpans that restrict crop root growth and water infiltration. Subsoiler with flexible tines presents effective obstacle avoidance and draft force reduction, but the undesired depths, much less than target value, are observed during tillage operation due to the considerable variation in soil resistance. Therefore, an electric-hydraulic control system for subsoiler with flexible tines was developed and a novel method for detecting tillage depth was described. The performance of the electric-hydraulic control system was evaluated in soil bin experiment by the detecting accuracy of the tillage depth and the operation quality (qualified index, distribution uniformity of tillage depths and draft force reduction). The detecting accuracy of the electric-hydraulic control system was determined at target depths of 25 and 30 cm, by testing tillage depths and comparing with manual measurement. The values obtained by the control system differed from manual measurements by less than 3.2% (3.2% at 25 cm; 1.9% at 30 cm), indicating high accuracy. The operation quality of the electric-hydraulic control system was evaluated for the working speeds of 1.4, 2.0, 2.6 km/h at target depth of 30 cm, by testing the tillage depth, draft force obtained with and without the electric-hydraulic control system. Treatments without the electric-hydraulic control system (CP) were five types of constant hydraulic pressure, respectively 2.0 MPa (CP 2.0), 2.5 MPa (CP 2.5), 3.0 MPa (CP 3.0), 3.5 MPa (CP 3.5) and 15 MPa (CP 15). Treatments with the electric-hydraulic control system (AP) were adjustable hydraulic pressure with the range of 2.0–3.5 MPa. Results indicate that flexible tine with AP created more regular cutting cross-section and acquired relatively consistent tillage depth. The qualified indexes of tillage depth (*QI*) were respectively 97.5%, 98.2%, and 96.7% at the forward speeds of 1.4, 2.0, 2.6 km/h. And mean tillage depths with AP were respectively 29.54, 29.53, 28.13 cm, closely to target depths. The distribution uniformity of tillage depth with AP was better than CP. Furthermore, draft force increased at the area with high soil resistance, flexible tines with AP experienced a relatively more stable rise and obtained draft force reduction of 18.17%, 18.35%, and 25.89% at three forward speeds. The results demonstrate that the developed system can be used to improving the tillage quality for subsoiler with flexible tines.

1. Introduction

Soil tillage is a basic practice in agriculture (Hamzei and Seyyedi, 2016; Romaneckas et al., 2015), that loosens the soil, restores proper soil structure, and prepares the seedbed for planting. Tillage is especially beneficial in conservation fields in which crop residues are returned to the soil and surface organics are mixed with the deeper soil layers. Subsoiling is a typical tillage technique used in conservation fields (Gathala et al., 2015), and the crucial purpose of this operation is to create continuous grooves for adequate disruption of compacted soil hardpans (Celik and Raper, 2012).

The compacted soil hardpan severely retards crop growth by limiting root access to water and nutrients (Wells et al., 2005; Hamza and Anderson, 2005) and it is especially deleterious for corn plants because their roots cannot penetrate this layer and thus easy to topple during strong storms (Qi et al., 2012). The corn yield reduction could be approximately 50% in field with severe compaction hardpan and 25% with moderate compaction hardpan (Gaultney et al., 1982). The farm equipment weighed, planting crop and tillage methods are potential to generate this compacted layer (DeJong-Hughes et al., 2001; Sivarajan et al. 2018). In China, rotary tillers are widely used for soil tillage because of their lower cost compared with ploughs and subsoilers (Cui et al. 2016). Rotary tillers break soil clods into small particles; however, the soil surface is disrupted excessively which is unfavorable for retaining soil moisture. Furthermore, when rotary blades cut soil clods, they exert a large squeezing pressure to the top of non-tilled soil, which

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accelerates the formation of compacted hardpan (Rasmussen, 1999; Raper, 2005). This hardpan exists in many Chinese wheat and corn field with the thickness of 15–20 cm at the depth of 20–40 cm soil layer (Dai et al., 2011; Li et al., 2015). The cone index in this layer is up to 1.43 g/cm^3, which is far greater than appropriate values for plant growth (Liu and Zhang, 2012; Zai et al., 2016). On the contrary, subsoiling facilitates the expansion of crop roots and results in significantly increased yields provided that it is conducted prior to planting (Wells et al., 2005; Williams et al., 2006; Raper et al., 1998; Abu-Hamdeh, 2003).

Subsoiling to break up the soil compacted hardpan requires the working depth of more than 30 cm and thus leads to a high degree of draft force (Mouazen et al., 1998; Buston and Rackham, 1981). So, it is a challenging task for development countries because of the less of high power tractors. Soil resistance acting on subsoiling tine is induced by the friction from the bottom soil layer, as well as the movement of shearing no-tilled soil and lifting and compressing tilled clods (Berntsen, 2006). Sakai et al. (1993) stated that tine vibration created short-time separation between the tine and the bottom soil layer thus to eliminate friction acting on the tine and ultimately reduce draft force.

To obtain the reducing draft force for subsoiling, forced vibrating subsoilers were studied first, here, the vibration of tines is generated by the rotation of an eccentric mechanism that is connected to the power output shaft of a tractor. The vibration frequency is determined by the rotary speed of power output shaft, and the amplitude depends on the design parameters of the eccentric mechanism. But the reduction in draft force in a forced vibrating subsoiler was almost determined by the vibration frequency (Buston and MacIntyre, 1981). It can be achieved when the ratio of peak vibration velocity to the forward speed of the tool is greater than 1. Increasing vibration frequency helps obtain larger speed ratios; however, high vibration frequency requires more energy. The draft force reduction of a forced vibrating subsoiler was up to 30% whereas the power consumption increased by 50% at the velocity ratio of 2 (Yow and Smith, 1976).

It is a new concept that subsoilers can be designed to make use of a compressible mechanism to induce the tines vibrating when it works in fields. Tines can be flexible and vibratory because of variable soil resistances. Also, flexible tine presents effective obstacle avoidance and draft force reduction (Cui et al., 2016). Its vibrating frequency and amplitude are determined by soil conditions and the intensity of the compressible mechanism. Flexible tines with compressible springs cause a considerable reduction in draft force (Mouazen and Ramon, 2002). In one comparison, the reduction in draft force of flexible tines was as much as 28% (Moeller, 1959). But the undesired tillage depths, much less than target value, are observed during tillage operation due to the considerable variability in soil resistance. Berntsen (2006) compared flexible tines in tilled and non-tilled fields and found a substantial difference. He concluded that the tillage depth on flexible tines was significantly affected by soil conditions and the intensity of spring. Flexible tines with compressible springs are unable to adapt to different soil conditions because of their unalterable intensity (Zhang et al., 2016). Soil conditions can vary considerably in adjacent fields even within an individual field (Mouazen and Ramon, 2002; Celik and Raper, 2012); hence, designs should allow adjustable intensity of compressible mechanism for flexible tines thus to avoid undesired depth and obtain reducing draft force.

In this paper, we provide a design for flexible tines with an electric-hydraulic control system to avoid undesired tillage depth by adjusting the stiffness of the compressible mechanism timely. The performance of the electric-hydraulic control system was evaluated by the detecting accuracy of tillage depths and the operation quality (qualified index, distribution uniformity of tillage depths and draft force reduction).

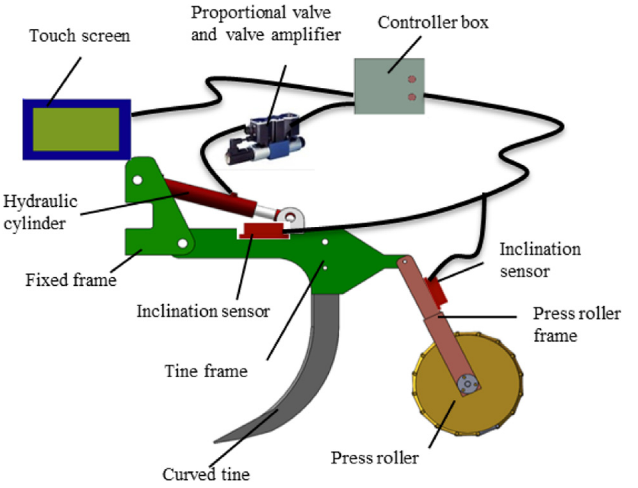

Fig. 1. Components of the flexible tine equipped with the electric-hydraulic control system.

2. Materials and methods

2.1. Describe of the flexible tine

A flexible tine using a hydraulic cylinder as the vibrating mechanism was selected for this study, as shown in Fig. 1. The flexible tine is connected with the fixed frame by a hinge point; thus, it can move up and down under the combined action of soil resistance and the hydraulic pressure of the hydraulic cylinder. A press roller behind the tine travels on the ground and exerts proper pressure on disturbed topsoil so as to reduce the evaporation of water. The structural parameters are as follows: the diameter of the hydraulic cylinder is $D_h = 40$ mm, stroke of the hydraulic cylinder is $S = 514$ mm; the maximum tillage depth of the tine is $D_{max} = 60$ cm; the weight of the press roller is $W = 10$ kg, and the diameter of the press roller is $D_p = 30$ cm.

2.2. Design of the electric-hydraulic control system

The electric-hydraulic control system consists of a controller (STC12C5A60S2, China), a touch screen (OMRON NB7W-TW01B, Japan), two inclination sensors (BWK217VXZ, China), proportional valve (Rexroth DRE6-1X/MG24, Germany) and valve amplifier (Rexroth VT-SSPA1-508, Germany), as shown in Fig. 1. The inclination sensor measures angle from -90° to $+90^\circ$with detecting accuracy of 0.2° and resolution of 0.02°. The proportional valve controls the hydraulic pressure at range of 0–17.5 MPa and the error is less of ± 2% of the maximum set pressure.

The hardware circuit of this control system is shown in Fig. 2. The power supply is twelve volts that could be supplied by tractors battery during field operation. The controller communicates with the touch screen and the two inclination sensor via MAX485 RS485 transceivers. Additionally, the controller sends digital signal to the valve amplifier via the DAC8563 transformer. With the valve amplifier, the input volt signal of 0–10 V is proportionately converted into electric current signal of 0–800 mA to control the proportional valve.

The algorithm flow chart of the electric-hydraulic control system is shown in Fig. 3. The structure parameters (H, h, L_1, and L_2) and position signal (a, β) are illustrated in detail in Section 2.3. D_n and D_m are respective the dynamic and mean tillage depth. P_n is the dynamic hydraulic pressure. T_p is the dynamic time of the timer and T_s is the set time for the timer. Once the power is supplied, the controller starts to initialize and a certain magnitude of pressure is set for hydraulic cylinder so that the tine is able to penetrate easily into soil. Slight Variation in soil resistances cause the tine to vibrate, which creates reducing draft force. The controller acquires the set parameters from the