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Dynamic steering response of animal-drawn plows

by

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Abstract

Animal-drawn plows can be quite difficult to steer and place considerable physical demands on the operator. Swing plows and beam plows are steered by tilting them to one side and if the degree of tilt is excessive the quality of work may be reduced and extra physical effort may be required.

The paper addresses these problems by presenting the outline of a theory for predicting the dynamic steering behaviour of animal-drawn implements. It is shown that the implement steering behaviour is governed by a first order differential equation. The theory has been tested on an experimental plow whose design is based on the Victory plow, a type widely used in Kenya, and can be used to determine the effect of changes in design parameters and hitch attachment on the speed of response. For example the relationship between the length of the hitch, the position of attachment, the beam length and the angle of tilt and their effect on the speed of reaction to a steering input is clearly illustrated.

The understanding offered by the theory provides a rational basis for improving the performance of animal-drawn plows.

Introduction

The control of animal-drawn plows is a complex matter, involving control of depth, plow attitude and lateral position.

Operators of animal-drawn plows must walk behind the implement and control it by the handles. Steering control depends on the type of plow. Wheeled plows which operate with a pair of wheels running on the ground require careful setting after which they should be largely self steering. Swing plows and beam plows are mechanically simpler and normally operate without the aid of a wheel running on the ground surface. To steer, the operator must lean or tilt the plow to one side. This action can affect the quality of work and may be awkward to manage.

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Static force analysis of the equilibrium of both animal- and tractor-drawn implements is well established (Kepner, Bainer, Barger, 1972). It forms the basis on which implements and hitch systems are designed and provides the understanding necessary for setting up and operating plows in the field.

Steering a plow is a dynamic operation. When an operator attempts to steer a plow the speed with which the implement responds is important. An understanding of the factors determining the dynamic response of an implement to a given steering correction is required.

In this paper a theory for dynamic steering behaviour is presented which relates principally to swing plows but includes beam plows as a special case.

Previous work

Previous research on lateral dynamic behaviour of implements relates mainly to tractor-mounted plows. Reece, Gupta and Tayal (1966) showed that the lateral motion of a freely mounted plow is governed by a second order differential equation. Cowell and Makanjuola (1966) showed that for all practical purposes the motion can be described by a first order differential equation. When an implement is drawn from a real hitch point the spatial time constant (the forward distance travelled to achieve a 63% response to a disturbance) is the hitch length. This research was based on the hypothesis that, if an implement is constrained to move through the soil at a small angle to the direction in which it is pointing, then a side force reaction from the soil will be induced on it proportional to that angle.

Later Cowell and Sial (1976), working on the problem of implement penetration, used the simpler hypothesis that a directional implement such as a mouldboard plow always moves

List of symbols

x	lateral displacement of plow from central position, m
x_0	initial lateral displacement of plow from central position, m
x_{max}	maximum lateral displacement of plow, m
y	implement depth, m
y_o	initial implement depth, m
y_e	equilibrium depth of implement, m
y_h	vertical distance from centre of resistance to hake, m
s	forward distance travelled, m
v	forward velocity, m/s
l	horizontal distance from centre of resistance to attachment point on animal, m
l_p	horizontal distance from centre of resistance to hake, m
a	angle of lateral tilt of plow, rad
b	yaw angle induced by tilting the plow, rad

instantaneously in its preferred direction of travel, ie the direction in which it is pointing. This gave rise to a first order differential equation. Hence, starting from an initial depth y_0, the implement penetrates to its equilibrium depth y_e along an exponential path according to the equation:

$$y \quad y_e \quad (y_0 \quad y_e)\, e^{s/l} \qquad (1)$$

Where l is the "spatial" time constant and governs the rate of penetration. This equation gave very good predictions for the penetration of mouldboard plows. *The significant point to note is that both theories indicate that the rate of response is governed only by the hitch length l.*

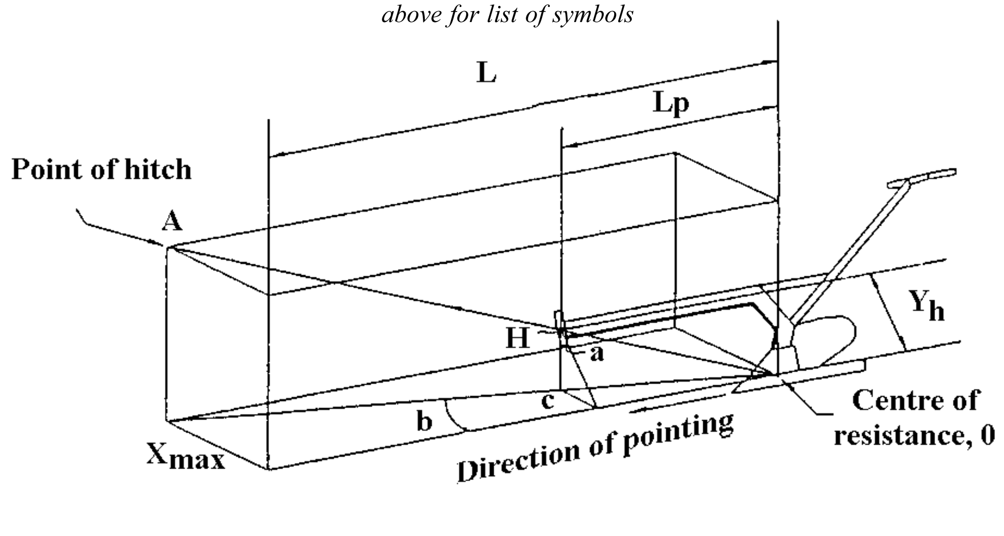
Steering theory for animal-drawn swing plows

Two theories have been developed: one based on the hypothesis used for lateral dynamic behaviour of tractor-mounted implements and the second based on that for plow penetration. In this paper only the latter theory will be described.

When a swing plow of the Victory type is in use, the support wheel is clear of the ground, so that the line of action of the traces passes through the centre of resistance of the plow. The plow is of the type which has a preferred direction of travel (known as the direction of pointing) and the side forces acting on it when in work are approximately balanced.

When an operator steers a swing plow he first tilts it to one side. This is illustrated in Figure 1 in

Figure 1: Isometric view of a Victory-type swing plow inclined at an angle a to the vertical. See box above for list of symbols



which the plow is leaned to the right. At this point the hitch point A, the hake attachment H and the centre of resistance of the plow O are not in line. The combined effect of the force in the traces AH and the soil force acting at the centre of resistance is to cause the hake point H to move into line, causing the plow to point to the left. As the plow moves forward it shifts to a new equilibrium position to the left where it is again pointing in the forward direction.

The hypothesis advanced is the same as that used by Cowell and Sial (1976) on plow penetration, namely that an implement with a preferred direction of travel (this time in the horizontal plane) will instantaneously move through the soil in the direction in which it is pointing. Consequently the implement will move (in this case) to the left until it reaches an equilibrium position where it is moving in the same direction as the animal is moving.

Based on the above hypothesis Mutua (1994) and Cowell have shown that the equation governing the lateral motion is:

$$\frac{dX}{dt} \quad \frac{V}{l} X \quad \frac{V}{l} X_{\max} \qquad (2)$$

The response to leaning the plow sideways through angle a is

$$X \quad X_{\max} (1 \quad e^{\ vt/l}) \qquad (3)$$

If the forward velocity v is constant then the forward distance travelled $s = vt$

$$\text{and } X \quad X_{\max} (1 \quad e^{\ s/l}) \qquad (4)$$

Equation 4 shows that *the rate of response depends only on the hitch length l*. It can easily be shown that the implement achieves 63% of its total response after travelling forward a distance equal to the hitch length.

The maximum lateral displacement $X_{\max}$ obtained by tilting the plow through angle a can be understood from Figure 1 which shows the inclined plow at the equilibrium position.

Now $X_{\max} \quad lb$

From the geometry it is readily shown that, for small angles

$$b \quad y_h \quad a / l_p$$

$$\text{and } X_{\max} \quad a \quad y_h \quad l / l_p \qquad (5)$$

Thus the maximum sideways displacement x increases in direct proportion to the lateral angle of tilt a , the height of the hake attachment y_h and the overall length l, but decreases in proportion to the frame length l_p.

Experimental work

Experiments were conducted using an experimental plow modelled on the Victory plow, a type widely used in Kenya.

Tests were conducted in the soil tank at Silsoe College. These consisted of a series of experiments in which the plow was held at a fixed angle to the vertical and the path taken along the ground was measured.

Good agreement was obtained between the theoretical and experimental paths.

Discussion.

Equation 4 indicates that the exponential rate of return to equilibrium is determined only by the hitch length l. Thus if the hitch length is doubled the implement must travel twice as far forward to achieve a given lateral movement.

Of particular interest is the sensitivity of the implement to a steering input. This is best described by the actual direction taken on the ground by the plow when a steering correction is initially made. From equation 4

$$\frac{dX}{ds} \quad 1 / l (X_0 \quad X_{max}) \, e^{\ s/l}$$

The maximum rate of response is at the commencement of the correction, that is when $s = 0$.

If the implement is initially on the centre of the path, $X_0 \quad 0$, therefore

$$\frac{dX}{ds}\max \quad X_{\max} / l \quad a \quad y_h / l_p \qquad (6)$$

The ratio y_h / l_p is also the slope or gradient of the traces of the plow to the horizontal.

This equation shows that the *initial rate of response (or sensitivity) increases in proportion to the lateral angle of tilt a and to the hitch point ratio y_h/l_p or the gradient of the traces of the hitch.*

These conclusions have been tested and confirmed.

Conclusion

It may be concluded that the parameters which determine the rate of response of an animal-drawn plow of the Victory type are the hitch length, the angle of the traces to the horizontal and the angle of lateral tilt.

In general, the plow makes 63% of its response after it has moved forward a distance equal to its hitch length - the greater the hitch length the further the plow travels to reach a new equilibrium position.

The sensitivity of the plow to a steering correction increases in direct proportion to the steepness of the traces and to the angle of lateral tilt.

It is significant to note that, provided the plow actually penetrates satisfactorily the theory indicates that the soil parameters have little, if any, effect on the steering performance.

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