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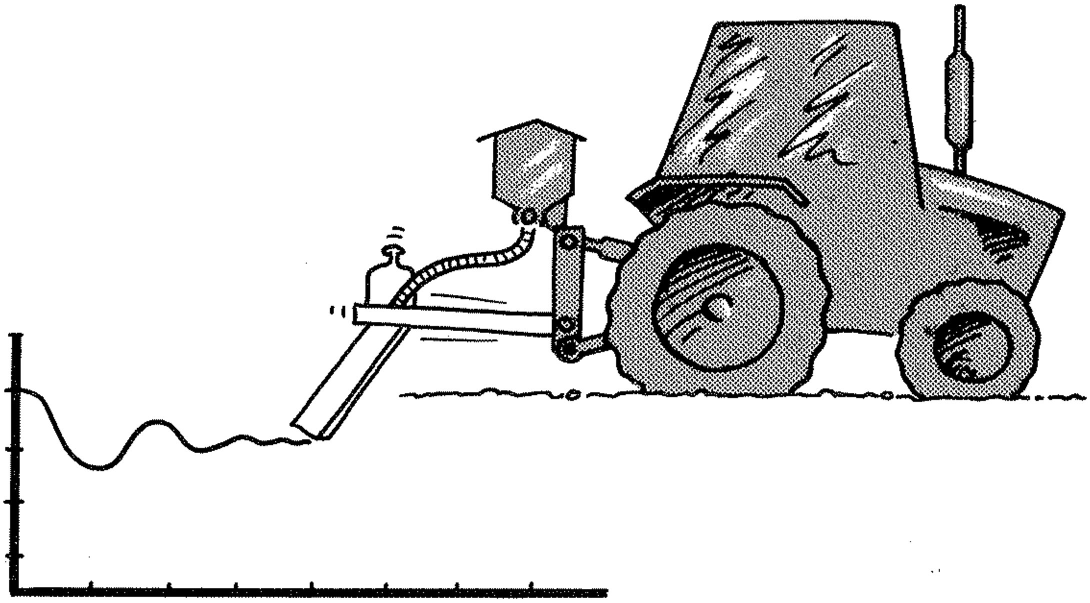
Dynamics of Rigid Soil-Engaging Implements and Parts of Implements

Lateral motion of soil-engaging implements and vertical motion of seed drill coulters

Håkan Jönsson



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To the memory of my father Per Bertil Jönsson (1914-1979)
a very warm person
who always supported freedom of thought

A sower went out to sow and, in his sowing, some seeds fell along the road and the birds came and ate them. Some fell on rocky soil, where they had little earth and sprang up quickly because the soil was shallow; but with the rising sun they were scorched and having no root, withered. Some fell among the thorns and the thorns grew up and choked them. But the rest fell on the good soil and bore a crop - some a hundredfold, some sixty and some thirty.

Matthew 13:4-8

ABSTRACT

In this thesis the lateral motion of rigid, soil-engaging implements hitched to a tractor with a one-point or a three-point hitch, as well as the vertical motion of seed drill coulters for use in tilled seedbeds are investigated.

The motion of most tractor-hitched soil-engaging implements is heavily overdamped, it was therefore described by a first order model, based on a quantitative description of the lateral properties of the implement and a functional description of the hitch. For each hitch-implement combination an effective hitch-point, towards which the implement tends to move, was defined and a method to calculate the effective hitch length was developed.

The return of a laterally disturbed implement was shown to be exponential. The disturbance is reduced to 10 % of its initial value when the implement moves forward a distance of 2.3 times the effective hitch length. The tractional hitch point and the directional hitch point coincide for one-point hitches but not for three-point hitches. This gives the three-point hitches unique properties: The angular as well as the lateral deflection of a three-point hitched implement will normally be smaller compared to those of a one-point hitched version of the same implement. This is true both when it is used on a hillside and when it is used with an asymmetric load. The three-point hitch is also shown to be versatile enough to enable the construction of a laterally movable and, for both directional and non-directional implements, self-centring front mounted three-point hitch.

The horizontal and vertical soil forces on coulters with different rake angles (70-135°) were measured under both pseudostatic (no vertical velocity and no accelerations) and fully dynamic conditions. Most of the measurements were made in a soil bin with dried sand, but some of the pseudostatic measurements were made in a clay field. Empirical models were developed for the soil forces acting on the coulter under both pseudostatic and dynamic conditions. These models were used to simulate coulter equilibrium depth and coulter penetration. The simulations led to the following conclusions:

Coulters with a large rake angle (≥110°) have several advantages when compared to coulters with smaller rake angles; their equilibrium depth is less sensitive both to speed and to soil parameters and their penetration is faster, better damped and less sensitive to suspension parameters (pivot arm length and pivot axis height) and to suspension type (single armed or parallel armed). The coulter penetration was found to improve with decreasing speed, decreasing moment of inertia and increasing depth of operation. No reasons were found for complicating the coulter suspension by using a parallel arm suspension or by using separate pivot axes for front and rear row coulters.

The above conclusions apply to well tilled seedbeds without stones or clods. If there are frequent stones or clods in the seedbed the present recommendation of using coulters with rake angles around 90° seems valid.

CONTENTS

1 NOTATION

The time derivative of a variable (e.g. x) is denoted by a dot above that variable ($\dot{x}$).

A	amplitude
F	force
F_d	directional force; force generated by an implement perpendicular to its direction of motion (Fig. 2 in I)
F_{nd}	non-directional force; force generated by an implement in the direction opposite to its motion (Fig. 2 in I)
F_r	the resultant hitch force acting on an implement (Fig. 2 in I)
F_u	the force in the upper link (Fig. 12 in I)
g	constant of gravitational acceleration
K	directional force constant
k	constant
L_c	distance between the point of convergence of the lower links and the vertical plane that intersects the centre of resistance of the implement and is parallel to the symmetry plane of the tractor (Fig. 12 in I)
L_{dht}	horizontal distance between the projection, in the directional plane of the implement, of its centre of resistance and the symmetry plane of the tractor along a line from the former point to the point of convergence of the lower links (Fig. 11 in I)
L_{hd}	directional hitch length; distance between the centre of resistance of the implement and the directional hitch point (Fig. 2 in I)
L_{he}	effective hitch length; distance between the centre of resistance of the implement and the effective hitch point (Fig. 2 in I)
L_{ht}	tractional hitch length; distance between the centre of resistance of the implement and the tractional hitch point (Fig. 2 in I)
L_s	distance between the symmetry plane of the tractor and the projection of the centre of resistance in the directional plane of the implement (Fig. 10 in I)
L_{s0}	value of L_s at time zero
L_{scr}	distance between the centre of resistance of the implement and its directional plane (Fig. 10 in I)
L_u	horizontal distance between the line of action of the upper link force F_u and the point of convergence of the lower links (Fig. 12 in I)
m	mass
m_i	mass of the implement
t	time
x	displacement along the x-axis
β	angle between the tractor's plane of symmetry and the implement's directional plane (Fig. 2 in I)
γ	slope; angle of the ground relative to a horizontal plane
ϕ	angle between the tractor's plane of symmetry and the direction of motion of the implement (Fig. 2 in I)
τ	angle

2 LIST OF INCLUDED PAPERS

This thesis is based on the three papers listed below. In the text they are denoted by their Roman numerals.

I **Jönsson, H.** A theory for the influence of the hitch on lateral displacement of implements. Journal of Agricultural Engineering Research 1989, 44(1): 33-52.

II **Gebresenbet, G.; Jönsson, H.** Performances of seed drill coulters in relation to speed, depth and rake angles. Journal of Agricultural Engineering Research 1992, 52(2): 121-145.

III **Jönsson, H.** Dynamic Performance of seed drill coulters with varying working depth in relation to speed and rake angle. (Submitted for publication).

Papers I and II are reproduced with the kind permission of Journal of Agricultural Engineering Research.

Paper II was written in cooperation with Dr. G. Gebresenbet. Together we planned the experiment, did the experimental work and wrote the paper. The force transducers, the soil analyses and the literature review were mainly the responsibilities of Dr. Gebresenbet, while the rest of the measurement system, the experimental set-up, the measurement program, the statistical analyses, the simulations and the calculations were mainly my responsibilities.

This is a cumulative thesis, which means that it consists of this summary and discussion of the results and of the three papers listed above. The reader is recommended to read this thesis in the following order; sections 1-6, paper I, section 7, papers II and III and finally the rest of this summary and discussion.

3 INTRODUCTION

This thesis deals with the dynamics, the motion in relation to force, of rigid soil-engaging bodies, whole implements or parts of them such as seed drill coulters.

The foundation for the study of the dynamics of solid bodies was laid down 1687 by Isaac Newton in Philosophiae Naturalis Principia Mathematica (Stora Focus, 1988), where he published the three basic laws of mechanics. These laws led to the analytical solution and understanding of second order linear systems such as the undamped and the damped harmonic oscillator, the mathematical and the physical pendulum. The harmonic oscillator and the pendulum are well described by linear models with one degree of freedom. The analysis of many dynamically interesting systems is, however, often more complex. The systems may have many degrees of freedom and/or they may be non-linear. This latter property makes analytical solutions difficult and often practically impossible. Often the best way to gain an understanding of such a system is to simulate it. The development of computers with rapidly increasing computing power has tremendously increased the possibility to simulate systems and thus to increase our knowledge of them.

The lateral motion of soil-engaging implements hitched to a tractor and the vertical motion of seed drill coulters are both similar to the pendulum in that they essentially rotate around an axis, they have one degree of freedom. However, due to the soil forces and the geometry involved, these systems are complex. Their analysis mainly has to be based on simulations and experiments. Using this approach it was found that the lateral motion of most tractor-hitched soil-engaging implements can be simplified by a linear model (I) while no such simplification was possible for seed drill coulters. In spite of this, several conclusions concerning coulter design and coulter motion could be made (II and III).

4 BACKGROUND

The three-point hitch is an extremely versatile hitch, invented and patented by Harry Ferguson. Nowadays it is standard equipment on tractors all over the world. One major drawback of this hitch is that the hitching and unhitching operations are both difficult and dangerous, especially when heavy implements are involved. (According to Leuchovius (1980) approximately 4000 narrow accidents and 800 real accidents took place in Sweden in 1980.) The use of a three-point hitch coupler virtually eliminates these drawbacks. However, most three-point hitch couplers influence the geometry of the linkage, which in turn influences the behaviour of the implement. It is important to know the nature and degree of this influence before recommending the use of three-point hitch couplers on a large scale. Many studies have concerned the movement of three-point hitched implements in the vertical plane (e.g. Bjerninger, 1960; Have & Kofoed, 1972; Cowell & Len, 1967; Cowell & Sial, 1976). Thus, that movement was, at the initiation of these studies, well known. Furthermore, the driver can, with the hydraulics, to a large extent control the movement of the implement in the vertical plane by force. This is not the case for the implement movement in the horizontal plane. The lateral motion of three-point hitched implements has only sparingly been treated in the literature. Thus, the present work on the tractor hitch was initiated by a need to know how geometric changes in the hitch influence the behaviour of the implement and of the whole tractor-implement combination in the horizontal plane. Farmers, as well as tractor and implement designers, can influence the geometry of the hitch. Therefore a simple and quickly understood description of the geometric influence on the dynamics was preferred.

For germination to take place it is essential that sufficient moisture is available for the seed. In areas with a dry spring climate and clay soil the seed should be placed on the moist seedbed bottom (Håkansson & von Polgar, 1984). However, in a field this bottom is always more or less uneven and in order to place each seed at the correct depth the coulter has to move vertically. The ability of the seed drill coulter to follow the undulations of the seedbed bottom is of prime importance for the germination and thus the ultimate yield of the crop. To place the seed directly on the seedbed bottom the coulter must both follow it and place the seed at the same depth at which the coulter itself is running. The latter part of the problem has been thoroughly investigated by Möller (1975). However, very little research has been done concerning the vertical dynamics of seed drill coulters. Therefore the present work on seed drill coulters focused on this aspect.

5 OBJECTIVES

The overall objective of my research has been to increase our knowledge concerning the dynamics of soil-engaging implements and implement parts. This has been accomplished in three studies. In study I the objective was to describe, preferably in a simple way, how the geometry of the tractor implement hitch influences the dynamics of the implement in the horizontal plane. The objective of studies II and III was to investigate how coulter design parameters and coulter suspension parameters influence the dynamic behaviour of the seed drill coulter. In study II this was done under pseudostatic conditions and in study III under fully dynamic conditions.

6 BASIC THEORY

Like the pendulum, both systems studied in this thesis are nonlinear, second order, one degree of freedom, dynamic systems that include at least one feedback loop (Fig. 1). The dynamic variable acceleration (and thus implicitly the velocity and/or the displacement) of the body influences the force on, and therefore also the acceleration of, the body.

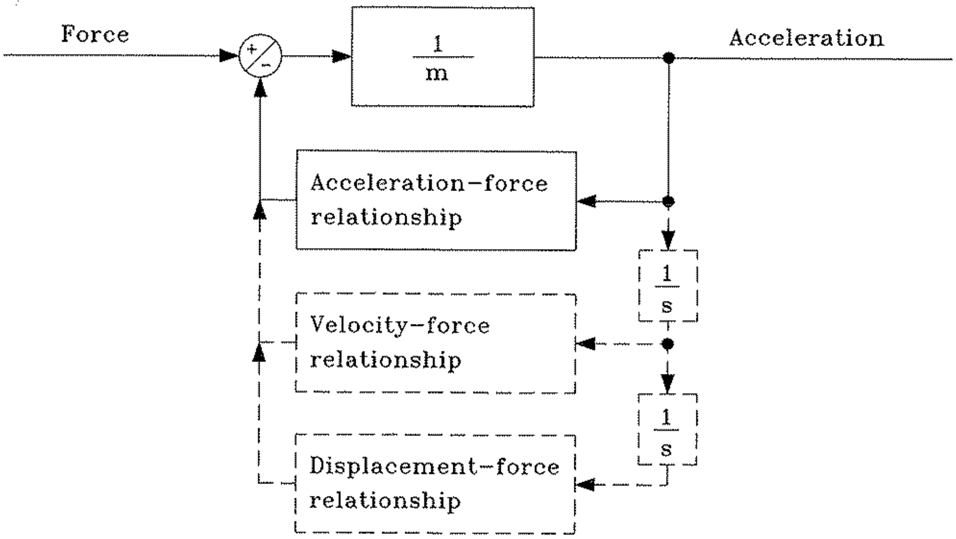

Figure 1. Layout of a second order, one degree of freedom feedback system describing the motion dynamics of a rigid body. The dashed feedback loops are drawn out for clarity, even though they are implicit in the first feedback loop, the acceleration force relationship, whenever this is a dynamic relationship.

This closed loop dynamic system approach is demonstrated below for the undamped harmonic oscillator. It is assumed that no external force acts on the oscillator. The undamped oscillator has only one feed back loop, the one due to the displacement force relation

$$F = -kx \tag{1}$$

The force acceleration relationship of the rigid body is

$$F = m\ddot{x} \tag{2}$$

The second order differential equation which results from combining Eqns (1) and (2) has the well known solution

$$x = A \sin\left(\sqrt{\frac{k}{m}}t + \tau\right) \tag{3}$$

However, this analytical solution can be used neither on three-point hitched implements nor on seed drill coulters due to nonlinear relationships, unknown soil forces and complicated geometry.

7 LATERAL BEHAVIOUR OF RIGID SOIL-ENGAGING IMPLEMENTS

7.1 Order of model

The lateral movement of three-point hitched implements is complicated for two reasons; the implement does not rotate about a real axis and soil forces are involved. It was long before these soil forces were described in a way that was constructive for the development of a quantitative theory for the lateral motion of these implements.

The general model given in section 6 is a second order model. The lateral motion of most tractor-hitched soil-engaging implements, except for mounted disc ploughs and poly discs, is heavily overdamped and slow (Reece et al., 1966; Makanjuola & Cowell, 1970; Cowell, 1989; own unpublished observation). Therefore, the inertia forces are small compared to the other forces involved and can be neglected. Thus, the system can be well described by a first order model. A second order model is only necessary for those rare tractor-implement combinations that are not heavily overdamped. Compared to a second order model, a first order one is simple, which enhances a widespread use by farmers, designers and decision-makers. The disadvantage is that such a model does not cover mounted disc ploughs and mounted poly discs, since their inertia forces often cannot be neglected (Reece et al., 1966). This disadvantage was considered to be of minor importance since those implements are rarely used in Sweden. Therefore, study I was limited to heavily overdamped implements, which enabled the use of a first order model.

7.2 Soil forces

One basic prerequisite for the development of a theory for the lateral motion of implements is that the soil forces on the implement are known as functions of the yaw angle, the angle between the heading of the implement and its direction of motion. A very fruitful and commonly used (Clyde, 1954; Kepner et al., 1978; Cowell & Makanjuola, 1966) qualitative classification of implements according to their lateral properties is to describe them as directional, tending to move in a specific direction, or non-directional, having no preferred direction of motion. This classification was implicitly used already by Skalweit (1953), who treated the plough as an ideal directional implement.

Reece et al. (1966) quantified the lateral description of the implement. They defined, and used in their experiments, the parameter lateral stiffness, which, for a given hitch, would be minimum, but not zero, for a non-directional implement. It would be larger the more directional the implement was. However, the lateral stiffness depended not only on the implement but unfortunately also on the hitch geometry. Realizing this, Cowell & Makanjuola (1966) defined the directional force constant (K). The advantages of this parameter are that it is zero for non-directional implements and that it is independent of the hitch geometry. This was also the parameter used in paper I. Unfortunately, in paper I the term "lateral stiffness" and not the term "directional force constant" was used for K. However the term "the directional force constant" is better suited to denote K and it was also the first term to be used for this definition. Thus, the term "directional force constant" will be used in this thesis.

The empirical basis for the directional force constant is that the directional force has been found to be proportional to the yaw angle of the implement, that is $F_d = K(\phi - \beta)$. Reece et al. (1966) verified this as a reasonable assumption for a single circular tine, a tine cultivator and a three-furrow mouldboard plough. However, the directional force constant of the plough was not the same when it was deflected towards the ploughing as when it was deflected towards land. These observations agree with those of Getzlaff (1952). He studied the relationship between the yaw angle and the directional force for two different types of plough bodies. However, the bodies were not complete, since the landside was missing. In graphs he showed that for both bodies the lateral force varied almost proportionally to the yaw angle. Cowell & Makanjuola (1966) and Makanjuola (1967) verified the linear relationship between the yaw angle and the directional force as reasonable for a single blade experimental implement and Makanjuola (1967) verified it for a three blade experimental implement. Thus, the linear relationship between the yaw angle and the directional force was found to be sufficiently verified to constitute a basis of the theory of the lateral dynamics of implements (I).

Getzlaff (1952) found that for one of the two plough bodies studied (nota bene without landside), the draught force, the non-directional force, changed with its angular displacement, while for the other body the draught was unaffected. Cowell & Makanjuola (1966) claimed that Reece et al. (1966) found that the non-directional force of a complete three furrow plough was independent of its angular displacement. A similar independence was found by Makanjuola (1967) for experimental single blade and three blade implements. Sufficient evidence existed that the non-directional force was independent of the angular displacement. This was used as a basis for the theory of the lateral dynamics of implements (I).

The two assumptions above, that the directional force is proportional to the yaw angle and that the non-directional force is independent of it, are of course never absolutely true. However, to develop a general theory for most implements some general assumptions about their soil forces have to be made. From the literature review the above assumptions seemed reasonable for most implements under most soil conditions.

7.3 Geometry of the three-point hitch

The motion of an implement is controlled by two hitch points, the tractional hitch point, where the tractional force seems hitched to the tractor and the directional hitch point, where the directional line of the implement seems hitched to the tractor (I). For a one-point hitch, like the drawbar and the hitch hook, the tractional hitch point and the directional hitch point coincide with the real hitch point (I).

For the three-point hitch, Kepner et al. (1978), without giving any further references, indicate that line segments exist which essentially correspond to the tractional and to the directional hitch point. Kepner et al. (1978) indicate that these line segments exist whether the top link force is zero or not. In paper I this geometric approach was verified for two different hitch geometries, that of a Volvo BM 650 tractor and that used by Cowell & Makanjuola (1966), Makanjuola (1967) and Makanjuola & Cowell (1970). For both these geometries the top link force was neglected. The line segment corresponding to the directional hitch point was found to be approximately 25 mm long for the BM 650 tractor and 13 mm for the hitch used by Cowell & Makanjuola (1966), Makanjuola (1967) and Makanjuola & Cowell (1970). For the line segment corresponding to the tractional hitch point the figure is 6 mm for both hitch geometries. Considering the other dimensions involved, the line segments were considered short enough to be approximated by points (I). They were considered the tractional and directional hitch points of the three-point hitches.

There are several advantages in basing the implement motion model on the concept of a tractional and a directional hitch point. 1) This concept simplifies the description and understanding of the behaviour of mounted implements, directional as well as non-directional. 2) The approximations involved are easily calculated and understood. 3) This concept is also true when the top link force is not zero (Kepner et al., 1978) and thus the motion model should also cover this case. This last point was, however, not verified in the thesis.

Cowell & Makanjuola (1966), Makanjuola (1967) and Makanjuola & Cowell (1970) all used a more straightforward approach to the three-point hitch geometry, an approach which initially seems more stringent. However, the authors did point out that they used small angle approximations and a close check of their relationships reveals that the accuracies of both approaches are approximately equal. One disadvantage of the straightforward approach is that the derivations involved are complicated, especially when also the top link force is included (Makanjuola, 1967). A second and more important disadvantage is that this geometric approach does not lead to any easily understood functional description of the three-point hitch, like the concepts of the tractional and the directional hitch point in the previously mentioned approach.

7.4 Results of study I

7.4.1 Return from a lateral displacement

Most implements are neither ideally directional nor ideally non-directional. They are something in between. These implements move towards an effective hitch point located somewhere between the tractional and the directional hitch point (I). If the implement soil forces follow the assumptions in section 7.2, and if the directional and tractional hitch lengths are constant, then it is possible to show (Appendix A of I) that the effective hitch length of such an implement-hitch combination is given by

$$L_{he} = \frac{L_{ht}L_{hd}(K + F_{nd})}{F_{nd}L_{hd} + KL_{ht}} \tag{4}$$

Thus, the effective hitch length always lies in the interval between the tractional hitch length and the directional hitch length (including the end points). The simulations in I revealed that, over the interval of possible lateral motion, the tractional hitch length and the directional hitch length were relatively constant for the investigated three-point hitch geometries, at least when the force in the top link is negligible. Thus Eqn 4 is applicable for three-point hitches.

Using the assumptions in section 7.2 concerning the soil forces on a heavily over-damped implement, it is simple to show (I) that the return from a lateral deflection is given by the equation

$$L_s = L_{s0}e^{-x/L_{he}} \tag{5}$$

This equation holds for perfectly non-directional implements ($K = 0$) as well as for implements with different values of the directional force constant ($K > 0$).

7.4.2 Hillside and asymmetric load operations

The implement is subjected to a torque around the directional hitch point both when operated in an asymmetrical load situation and when operated on a hillside. This torque rotates the implement. The lateral deflection resulting from this is derived in I. When operated on a hillside the lateral deflection is

$$L_s = \frac{L_{hd}m_i g \sin\gamma}{K + \frac{L_{hd}}{L_{ht}}F_r} \tag{6}$$

When operated with an asymmetric load it is

$$L_s = \frac{L_{scr}F_{nd}}{K + \frac{L_{hd}}{L_{dht}}F_{nd}} \tag{7}$$

where L_{dht} equals the tractional hitch length L_{ht} that would result if the centre of resistance was located in its projection in the directional plane of the implement. This means that the ratio L_{hd}/L_{dht} equals the ratio L_{hd}/L_{ht} in the corresponding (projected) situation with a symmetrically located centre of resistance.

The angular deflection is, as always, given by

$$\beta = \frac{L_s}{L_{hd}} \tag{8}$$

7.4.3 Self-centring front mounted three-point hitch

In I it is pointed out that the concept of a directional hitch point also holds for a front mounted three-point hitch. If the directional hitch point is located in front of the implement's centre of resistance and if the directional force constant of the implement is large enough, then the implement will be laterally stable, even if the force in the top link is zero. It was also pointed out that if there is no force in the top link, then a non-directional implement is laterally unstable when used with any front mounted hitch. It was shown that such an implement can be stabilized by a sufficiently large tensile top link force, provided that the top link is short enough (Eqn 36 in I has to be fulfilled).

7.5 Discussion of the results in study I

7.5.1 Return from a lateral deflection

Reece et al. (1966) derived the return path of a heavily overdamped one-point hitched implement as (their notation)

$$\theta = \theta_0 e^{(-v/l)t} \tag{9}$$

where θ denotes the angular deflection of the implement, θ_0 the initial value of θ, v the tractor velocity and l the length of implement from hitch point to tool.

By multiplying Eqn (9) by l and by using small angle approximation for θ, the controlling Eqn (5) is arrived at. Thus, it is not surprising that the predictions made by the two theories agree well with each other, as is shown in the top part of Fig. 6 in I. However, it was surprising that the agreement was good also for the case with least damping (damping coefficient = 2.58) reported by Reece et al. (1966). This implies that the return paths predicted for the implements were mainly a function of the effective hitch length. The varying damping coefficients had only minor influence on the predicted responses. However, for the measurements with minimum and maximum damping, the discrepancies between the predictions of both theories and the measured values were quite large. This can be explained by the experimental conditions. The measurements were made under rough soil conditions on a level pasture with hard soil and only two replicates were made for each parameter combination.

In Fig. 7 of I, predictions made by the theory in Eqns (4) and (5) for 18 parameter combinations are compared with measurements and predictions made by Makanjuola (1967). For all parameter combinations the agreement between the theories was good. The theoretical predictions also agreed well with the measured return paths. These measurements were made in a soil tank with uncompacted quarry sand. Cowell & Makanjuola (1966) reported the same measurements as Makanjuola (1967), however their predictions differ somewhat from Makanjuola's (1967). The reason for this might be that Makanjuola (1967) measured the position of the centre of resistance of the single blade implement used. He found that the centre of resistance was at the leading edge of the blade and not, as expected, at the centre of the blade.

The theoretical expressions given by Cowell & Makanjuola (1966) and Makanjuola & Cowell (1970) for the distance travelled by an overdamped implement after a disturbance before the implement has returned to 10 % of the initial disturbance can, both for the real hitch point and the virtual hitch point case, be shown to be approximately (small angle approximations) equal to the expressions given in I (Appendix A).

Skalweit (1953), using a manual geometric simulation procedure from Hain (1953), predicted the distance a two furrow plough would move forward before a deflection of 80 mm had been reduced to 20 mm. In his simulations, Skalweit (1953) considered the plough to be an ideal directional implement and he also let the centre of resistance move around. In each iteration he changed the angular position of the plough until any of the landsides somewhere touched the side wall of the already cut furrow.

With a reasonable estimation for the position of the centre of resistance (somewhere between the two plough bodies) the agreement between Skalweit's (1953) predictions and those made by the theory in I is good for the three virtual hitch point cases (within 12 %). However, the discrepancy is large for the two real hitch point cases. For the longer hitch length the prediction supplied by the theory in I is 20 % smaller and for the short hitch point case it is 52 % smaller than the predictions made by Skalweit (1953). In this latter case the discrepancy is probably due to the extremely short hitch length and the procedure adopted by Skalweit (1953), allowing the centre of resistance to move around. If the centre of resistance is placed close to the rear end of the rear body landside (this is the part normally touching the furrow wall when such a short hitch is used) the discrepancy between the predictions is eliminated.

7.5.2 Hillside operation

Makanjuola & Cowell (1970) derived an expression for the lateral drift of an implement used on a hillside. In Appendix A it is shown that their expression approximately equals Eqn (6).

For the one-point hitch the directional and the tractional hitch point coincide. This is normally not the case for the three-point hitch. For this hitch the tractional hitch length is usually smaller than the directional one (Fig. 2). The angular deflection on a hillside of a non-directional implement used with such a hitch will, compared to using a one-point hitch, be reduced by the factor $(1 - L_{ht}/L_{hd})$. For the BM 650 tractor-implement combination in Fig. 2 the angular deflection is reduced to approximately 50 % of what it would be if the implement was one-point hitched. While the tractor driver on a hillside can compensate for the lateral deflection, he is unable to do so for the angular deflection.

For many implements, like seed drills and harrows, the quality of work is negatively influenced by an angular deflection. Thus, for the quality of work of such an implement, it is beneficial to use a three-point hitch $(L_{ht} < L_{hd})$. However, the relative merits, the reduction of β, of using such a hitch instead of a one-point hitch, decrease with increasing lateral force constant of the implement.

The lateral drift of a three-point hitched implement is reduced by the same factor as the angular drift, if compared with a one-point hitch of equal directional hitch length. If instead, for a non-directional implement, the comparison is made with a one-point hitch of equal tractional hitch length, then the lateral drift is the same for both types of hitches. However, normally the tractional hitch length is smaller for a three-point hitched implement than for a corresponding one-point hitched one. This means that **for a non-directional implement used on a hillside normally both the lateral and the angular deflection will be smaller if the implement is three-point hitched ($L_{ht} < L_{hd}$) than if it is one-point hitched.**

7.5.3 Asymmetric centre of resistance

The angular deflection of an asymmetrically loaded non-directional three-point hitched implement is, compared to a one-point hitched implement with equal directional hitch length, reduced by the factor $(1 - L_{dht}/L_{hd})$. Thus, for the BM 650 tractor-implement combination in Fig. 2 the angular deflection is reduced by approximately 50 %. For a one-point hitched implement the angular deflection due to an asymmetric load can be reduced by increasing the hitch length. However, if the implement in Fig. 2 was one-point hitched, then it would need a 6.88 m long hitch (Jönsson, 1987) to achieve the same low angular deflection as it achieves with the present three-point hitch. (However, with such a one-point hitch the implement would get a very large lateral deflection on a hillside.)

The lateral deflection of an asymmetrically loaded, three-point hitched implement is also reduced by the factor $(1 - L_{dht}/L_{hd})$. This holds, for non-directional implements, whatever the hitch length of the compared one-point hitched implement. Thus, **when operated with an asymmetric load the lateral deflection on a three-point hitched ($L_{ht} < L_{hd}$) implement is always smaller than that of a one-hitched one.** In an asymmetric load situation, just as in a hillside situation, the relative merits of a three-point hitch decrease with increasing lateral force constant of the implement.

The increased stability of an asymmetrically loaded three-point hitched implement is taken from the tractor. This is achieved at the expense of the stability and/or cornering ability of the tractor being somewhat affected.

7.5.4 Self-centring front mounted three-point hitch

Already with no top link force the versatility of the three-point hitch is great. With a top link force the versatility of the hitch becomes even larger and stable operation can be achieved with almost any implement, as was pointed out already by Thaer (1956) and by Bjerninger (1961). Another example of this is given in study I where the possibility of a laterally self-centring front mounted three-point hitch is pointed out.

Makanjuola & Cowell (1970) concluded that the commonly used forward diverging front mounted three-point hitch is laterally unstable, while a forward converging hitch

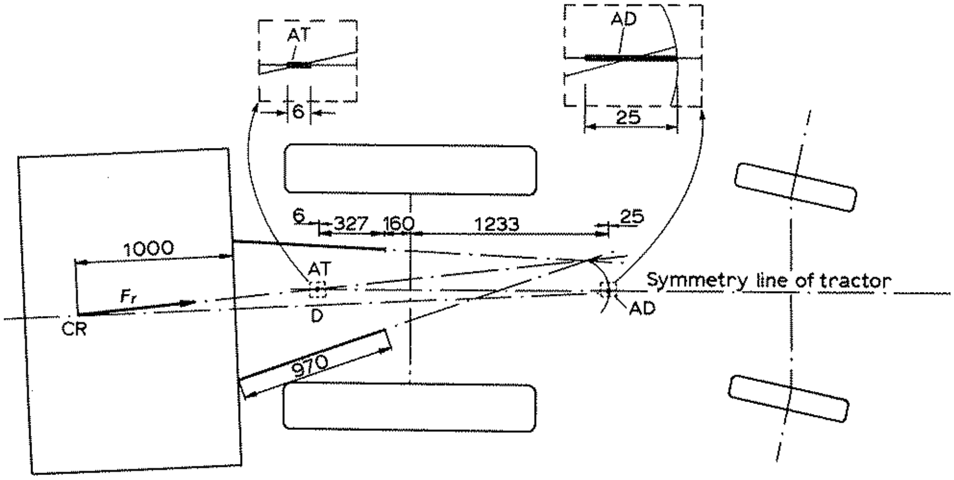

Figure 2. A non-directional implement three-hitched to a BM 650 tractor. In the horizontal plane the implement points towards the line segment AD, which is considered its directional hitch point, while it is pulled towards the line segment AT, which is considered its tractional hitch point. There is no force in the top link. The ratio between L_{ht} *and* L_{hd} *for this tractor-implement combination is approximately 0.5. Dimensions in mm. (Calculated from Jönsson, 1987. Figure from I.)*

would be laterally stable, provided that the virtual hitch point was in front of the soil-engaging parts. They claim that if this is the case then both the directional and the non-directional force will stabilize the implement. This is only partly correct. As is shown in I, the directional force will help to stabilize such an implement, however the non-directional force will destabilize it. This conclusion is shared by Sarfert (1990). Makanjuola & Cowell's (1970) misjudgement about the effect of the non-directional force is due to them overlooking that the expression for their angle ψ differs between the front mounted hitch and the ordinary rear mounted one. (This also shows the importance of keeping theories as simple as possible.) Thus, with no top link force the lateral stability of front mounted implements depends on a balance between the stabilizing torque from the directional force and the destabilizing torque from the non-directional force. Analytical expressions for this balance have been developed by Sarfert (1990).

However, non-directional implements will always be laterally unstable if the top link force is zero. As pointed out in I, it is possible to stabilize them if the top link is short enough and if it is subject to a tensional force that is large enough. This has been qualitatively but not quantitatively verified for both a small table top model and a full scale front mounted hitch built by Svensson (1987). Svensson, as probably the first person in the world, achieved laterally stable operation with the following two non-directional and three directional front mounted implements, a single tine, a harrow with 13 spring tines, a single disc, a row crop cultivator and a single-furrow mouldboard plough running immediately in front of the tractor's right front tyre (Fig. 3).

Figure 3. The self-centring front mounted three-point hitch built by Svensson (1987), here used with a one-furrow plough that runs directly in front of the tractor's right front tyre. (Photo: Jan Svensson)

The top link force is usually small for rear mounted implements. The weight of the implement gives a tensile top link force, while the soil forces usually give a compressive top link force. Thus, these two sources of top link force counteract each other and the resulting force tends to be small. This justifies the top link force being disregarded in I and in most other similar studies. However, on a front mounted hitch both the weight and the soil forces produce tensile top link forces, thus the resulting top link force tends to be a very large tensile one. It is difficult to neglect such a large force, especially since this force is needed to stabilize non-directional implements.

Sarfert (1990) developed several motion equations for front mounted three-point hitched implements. Some of them include the top link force and some do not. However, when the top link force is included, the top link is assumed to be approximately the same length as the lower links, and thus his motion equations do not apply to those front mounted hitches which are stable also with non-directional implements.

7.6 Practical use of the theory

Without a quick coupler the lateral geometry of the three-point hitch can be affected by the tractor manufacturer, who decides the distance between the two lower link points and the length of the lower links, as well as by the implement manufacturer and/or the farmer who decides the distance between the two lower hitch points. Of these parameters only the last one, the distance between the two lower hitch points is standardized in ISO 730 and thus in many national standards.

An implement manufacturer can never know what directional and tractional hitch length his implement will have when used with a tractor. Since these hitch lengths are critical for the function of most implements and especially of ploughs, plough manufacturers often supply crossbars of different lengths. To achieve the desired hitch length with a certain tractor, the farmer changes the crossbar length. However, if a single-phase quick-coupler is used, then the length of the crossbar can no longer be changed. Therefore the length of the lower links and the distance between the lower link points have to be such that ploughs and other implements function well when they have the standardized distance between the two lower hitch points.

The theory in study I was an important theoretical foundation in a comprehensive investigation (Jönsson & Svensson, 1986) of the changes necessary in the three-point hitch standard before hitch couplers could be introduced on a wide scale. In that investigation the large and very thorough research by Flerlage (1956) and Thaer (1956) on the influence of different three-point hitch parameters on ploughing was re-evaluated using the theory presented in study I. The investigation proposed a standard for the distance from the lower hitch points to the directional hitch point. This proposal was introduced by Sweden to the ISO in 1987 (ISO, 1987). In February 1992 ISO decided that a DIS (Draft International Standard) should be issued where the recommended distance between the lower hitch points and the directional hitch point is given in an informative appendix (ISO, 1992a, 1992b).

As mentioned, such a standard is important for the possibility of a wide scale introduction of hitch couplers. It is also important for the information of young tractor designers. The research and discussion of all aspects of the three-point hitch was very lively in the fifties and early sixties. Since then only little research has been done on the geometry of the hitch. Thus, there is an increasing risk that young tractor designers do not know how the three-point hitch geometry influences the behaviour of implements. The German three-point hitch standard, DIN 9672, has traditionally been a very extensive standard incorporating many old research results. Thus, it has served as a reminder to tractor designers that fulfilling ISO-730 does not warrant a well functioning hitch. However, DIN 9672 will probably not serve this purpose in the future. The 1990 proposed version of the standard (DIN, 1990) is close to being just a translation of the ISO-standard. All additional dimensions, results of old research that were included in the earlier versions of the DIN-standard but not in the ISO-730, have been removed.

7.7 Future research and development

Study I showed that the properties of the three-point hitch are quite unique and, if taken advantage of, they can help to improve the quality of work achieved by the implement. However, often full advantage is not taken of the hitch, because its theory is not fully understood. This is not surprising. Most textbooks (e.g. Culpin, 1986; Kepner et al., 1978; Renius, 1985; Liljedahl et al., 1979) treat it very briefly and furthermore many of them use the term "instantaneous centre of rotation" for the point of convergence of the lower links. This term is misleading since the implement rotates around the directional hitch point rather than around that point of convergence. Thus one major future task is to spread information about the theory of the three-point hitch.

Two main theories, the one by Cowell & Makanjuola (1966) and Makanjuola & Cowell (1970) and the one proposed in study I, exist for the lateral behaviour of rear mounted highly damped implements. However, so far both theories have neglected the influence of any top link force. Thus one interesting task is to verify that Kepner et al. (1978) were correct when they claimed that the geometrical approach used in study I holds also when a top link force is present. If this is verified, then all results on rear mounted three-point hitches presented in I will automatically apply also when there is a force in the top link.

The work done by Svensson (1987) showed that a carefully designed front mounted hitch can centre directional as well as non-directional implements. The slow and well damped lateral motion that he achieved with a front mounted row crop cultivator indicates that such a hitch would greatly improve the situation for the tractor driver (good visibility and "forgiving" steering characteristics) in that kind of operation. To adjust the front mounted hitch correctly proved, however, to be both important and difficult. An easily understood theory for the lateral motion of front mounted implements is needed as a help in the performance of this task. Such a theory should take into account the influence of a short top link with a large top link force.

8 VERTICAL DYNAMICS OF CONVENTIONAL SEED DRILL COULTERS

8.1 Order of the model and linkage geometry

The vertical motion of the seed drill coulter often is, and has to be, rapid. Lines (1986) reported that the coulter was sometimes fully in the air. He also measured the natural frequency of a seed drill coulter and reported that it was 3-3.5 Hz. Thus it was obvious that the inertia forces could not be neglected when modelling the coulter motion. A second order model was required.

The two most common types of coulter suspensions are the single arm suspension and the parallel arm suspension. The analyses of both these suspensions were simple and straightforward. Therefore, no special geometric approach was needed.

8.2 Soil forces acting on the coulter

For the coulter the displacement-soil force relation, the speed-soil force relation and the acceleration-soil force relation were neither known nor believed to be simple. However, forces on tines had been studied extensively and models existed for calculating these forces. It was natural to investigate whether these models could be used to calculate the soil forces on coulters. Therefore the available tine force models are reviewed below.

Payne (1956) calculated the draught force of vertical tines in an ambitious study where he used the theory of classical soil mechanics. Osman (1964) and Siemens et al. (1965) continued the theoretical work by applying logarithmic spiral solutions to wide blades (two-dimensional failure).

O'Callaghan & Farrelly (1964) and O'Callaghan & McCullen (1965) divided the soil failure caused by vertical or forward raked (acute rake angle, when measured from the forward horizontal) deep tines into two zones, a shallow one, where the tine was treated as a retaining wall, and a deep one, where the tine was treated as a footing, thus in both zones the failure was essentially treated two-dimensionally.

Reece (1965) postulated an additive equation for the soil force contributions due to cohesion, soil density, surcharge and adhesion. This equation constitutes a major step towards a simplified prediction of soil forces on soil-processing equipment. Using the logarithmic spiral method Hettiaratchi et al. (1966) calculated the N-factors (Reece-factors) needed in the additive equation for the two-dimensional (wide blade) passive soil failure case. They also showed that the errors introduced by the simplifications implicit in the additive equation were comparatively small. Hettiaratchi & Reece (1974) re-evaluated the N-factors using the method by Sokolovski (1960). Hettiaratchi & Reece (1967) used the additive equation to work out a solution for the symmetrical three-dimensional soil failure of a tine. Compared to the two-dimensional solution, several additional assumptions were made in the development of this three-dimensional one.

Godwin & Spoor (1977) extensively studied the soil forces and soil failure patterns of narrow tines. Like O'Callaghan & Farrelly (1964) they found that the failure could be divided into two zones; the crescent failure, which occurred above the critical depth, and the lateral failure, which occurred below this depth. They calculated the forces involved in the three-dimensional crescent failure using the N-factors worked out by Hettiaratchi & Reece (1974) for two-dimensional failure, while they used a logarithmic spiral solution worked out by Meyerhof (1951) to calculate the forces involved in the lateral failure. The experimental data presented by them indicated that their solution, for tines of high (>3) aspect ratios (depth/width), was more exact than the previous ones by O'Callaghan & Farrelly (1964) and Hettiaratchi & Reece (1967).

Stafford (1979), studying the effect of speed on tine force, found that at low speed the force was vastly overestimated (by a factor of 10) by the Hettiaratchi & Reece (1967) three-dimensional model, while the two-dimensional model by Hettiaratchi et al. (1966) produced force predictions of correct magnitude. At low moisture content, when the soil failed like a rigid, brittle Mohr-Columb material, he found that the speed-force relationship was well described by a polynomial in speed, while an exponential function gave a better fit when the failure was plastic. Later, Stafford (1984) included the effect of speed in both the brittle and the flow failure model. The measurements reported by him indicate that for both failure models the predicted force was of correct magnitude and the predicted speed-force relationships were of correct type.

McKyes & Ali (1977) developed a three-dimensional soil failure model for narrow tines. This model used the general additive equation postulated by Reece (1965) but, compared with the models by Hettiaratchi & Reece (1967) and Godwin & Spoor (1977), it was vastly simplified by assuming that the failure surface from the tip of the tine to the soil surface was a plane and not a logarithmic spiral surface and by neglecting the adhesive forces on the tool interface. Good agreement was reported for measurements in moist sand and in sandy loam. McKyes (1978) showed that for the horizontal force this theory agreed well with tine measurements previously published by Payne (1956), Payne & Tanner (1959), Tanner (1960), Dransfield et al. (1964), O'Callaghan & Farrelly (1964), Willatt & Willis (1965), Balaton (1971) and Luth & Wismer (1971). The agreement of the vertical force was not reported.

Grisso et al. (1980) and Perumpral et al. (1983) simplified the tine failure problem even more. They not only approximated the failure surface from the tip to the surface by a plane but they also approximated the contributions from the side lobes by assumed cohesive and frictional contributions on the sides of the central wedge. However, they included in the model the adhesive effect on the tool interface (even as a function of rake angle). Their measurements agreed fairly well with the model.

Swick & Perumpral (1988) used an approach similar to that of McKyes & Ali (1977) but they also incorporated dynamic effects due to soil acceleration and due to velocity effects on shear strength and on soil-metal friction. However, in the artificial soil that they used the two latter effects were not present. Their experiments indicated that the magnitude of the acceleration effect was correctly estimated.

Thus in the mid 80's several three-dimensional models existed for the prediction of the soil forces on a tine. Plasse et al. (1985) compared the predictions from the models by Hettiaratchi & Reece (1967), Godwin & Spoor (1977), McKyes & Ali (1977) and Grisso et al. (1980) using measurements made by Desir (1981). They found that the draught force predictions of the models, except for the prediction of the Hettiaratchi & Reece (1967) model, agreed reasonably well with each other and with the measurements. This result is in accordance with an earlier comparison made by Grisso & Perumpral (1981). However, Grisso & Perumpral (1981) also noted that the McKyes & Ali (1977) model gave poor predictions of the vertical force.

The geometry and the motion of the seed drill coulter differ from the assumptions made in the previously mentioned tine force models; coulters normally have a rather sharp cutting angle (45° for the coulters used in studies I and II, see Fig. 4), they have spout wings, their rake angle normally is oblique, normally the seed bed cohesion has been reduced to low values through secondary tillage, the depth of the coulter as well as its horizontal and vertical velocities and accelerations change dynamically during operation. On the other hand, in the previously mentioned models only cutting angles far above 45° were considered, no soil contact and no forces on the sides of the tine were considered, only few studies consider the effect of the horizontal velocity, and no studies consider effects due to vertical velocity or due to horizontal or vertical acceleration. Furthermore, the experimental verification of the models is considerably weaker for oblique angled tines in soils with negligible cohesion than for acute angled tines in soils with cohesion.

Only one study (O'Callaghan & McCullen, 1965) considered cutting angles below 180°. In that study three different cutting angles were considered; 180° (flat tine-front), 90° and 60°. (The "cutting angle" of the soil wedge in front of the flat vertical tine in the experiment ought to have been in the range of 76-86°.) The horizontal force was found to be independent of the cutting angle.

The soil will cause a frictional force on the spout wings. These probably also will change the lateral failure discussed by Godwin & Spoor (1977) and Hettiaratchi & Reece (1967), since in their models the side surfaces of the trench behind the tine were assumed to be free surfaces.

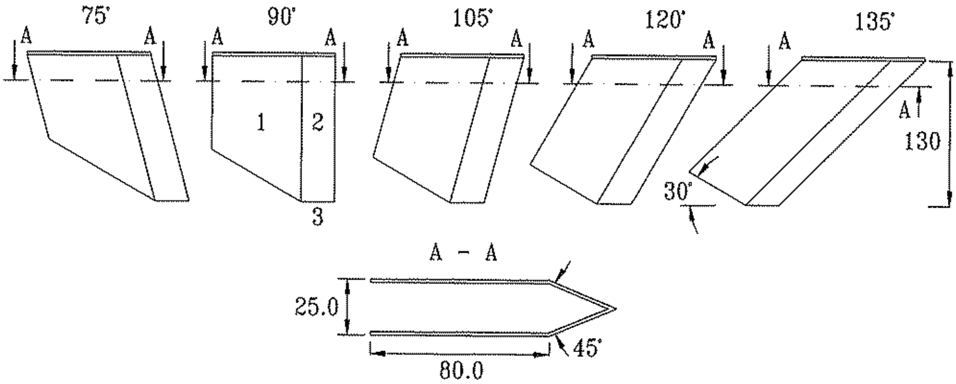

Figure 4. The five different coulters used in study III. The design of the coulters used in study II was similar. The numbers refer to; 1, spout wing; 2, front and 3, footing. The scale of section A-A is twice that of the rest of the drawing. Dimensions in mm. (From study III.)

While many of the models theoretically apply to all rake angles, their experimental verification is considerably weaker for oblique rake angles than for acute ones. Force measurements with oblique rake angle tines were reported only by Payne & Tanner (1959), Tanner (1960) and Stafford (1981). Of these only the measurement by Tanner (1960, cited by McKyes, 1978) was done in a soil with low cohesion.

Often a soil wedge will form when an oblique rake angle is used, at least in the two-dimensional failure case (Harrison, 1973a, 1973b; Hettiaratchi, 1968 cited in Hettiaratchi & Reece, 1974; Hettiaratchi & Reece, 1975). For a tine, this phenomenon is probably influenced by its cutting angle. However, no report studying this phenomenon has been found. Such studies would be very interesting.

The seedbed preparation reduces the cohesion in the seedbed to low values. Tine force measurements in soil with low cohesion have been reported by Payne (1956), Tanner (1960, cited by McKyes, 1978), Grisso et al. (1980) and Perumpral et al. (1983). Of these only the measurement by Tanner (1960) included an oblique rake angle tine. In most of the verifying experiments the cohesion has been the single most important factor influencing the draught force. In some reports (Stafford, 1984; O'Callaghan & Farrelly, 1964) the total force has therefore been approximated by the cohesive contribution alone. Thus the verification of the contribution due to cohesion is comparatively strong, while the verification of the contributions due to self weight and due to adhesion is weaker. In the same way, the verification of the horizontal force is stronger while the verification of the vertical force, which is very important for coulter dynamics, is much weaker. This is natural, since the prime objective of the models has been to predict the horizontal force. The vertical force prediction has been considered secondary. Often the vertical force measurements are not even reported in the papers. In several of those papers where they are reported, the vertical force predictions are not as good as the horizontal ones. Grisso & Perumpral (1981) report this concerning the McKyes & Ali (1977) model and Godwin & Spoor (1977) show this for their own model and for the models by O'Callaghan & Farrelly (1964) and by Hettiaratchi & Reece (1967).

The influence of horizontal speed has been studied in several reports (Dransfield et al., 1964; Stafford, 1979, 1981, 1984; Stafford & Tanner, 1983a, 1983b; Swick & Perumpral, 1988). However, no studies have been found concerning the influence of vertical speed or of accelerations.

Summarizing: In relation to the coulter dynamics problem several important parameters are not at all accounted for in the existing tine force models. Furthermore, the experimental verification is weak for parameter combinations typical for coulter operation. Therefore, the dynamic coulter force models were not based on any of the previously mentioned tine force models. Instead, an empiric approach was developed and used in studies II and III.

Recently, the Finite Element Method (FEM) has been used to analyze the soil-tine interaction (Chi & Kushwaha, 1987, 1989, 1991a, 1991b). This approach has several advantages; 1) realistic tool-soil interface geometries can be investigated, 2) the solution is a **true three-dimensional solution** (all the previously mentioned solutions have, in different ways, simplified the three-dimensional problem to one, or more, two-dimensional problems), 3) the solution gives the stress distribution in the tool-soil interface and in the soil as well as the soil motion, 4) the incorporation of dynamic and inertial effects due to tool velocity and tool acceleration ought to be possible. Thus, this approach ought to be considered in any future work on coulter dynamics.

8.3 Methods and results of studies II and III

In study II the soil forces on the used coulters were measured under pseudostatic conditions (no vertical velocity and no accelerations) both in a clay field and in a soil bin filled with dry sand. Within the parameter range investigated (see Table 1 and Fig. 4) the horizontal speed-force relationships for the used coulters proved to be second order polynomials in which the second order terms were far more important for the fit than the first order terms. Also the depth-force relationships were second order polynomials, but these polynomials had their intercepts at the origin. The rake angle-force relationships were linearized by second (field measurements) or third (soil bin measurements) order polynomials. The multifactorial relationships between horizontal speed, depth, rake angle and force, both horizontal and vertical, proved to be well described by multifactorial polynomials.

These multifactorial polynomials were used to calculate the change in steady state equilibrium depth that a change in horizontal velocity or in soil parameters would produce. Compared to coulters with a smaller rake angle, coulters with a large rake angle proved to be less sensitive to these disturbing factors. The soil bin measurements also indicated that the depth variation due to a horizontal speed change was independent of coulter width. For a 130° rake angle coulter only minor effects were found on the equilibrium depth sensitivity due to changes in pivot arm length, pivot axis height and type of coulter suspension used (single arm or parallel arm). The field measurements were not as conclusive as the soil bin ones, probably because the field measurements were fewer and had larger errors which disguised minor effects.

Table 1. Parameter range covered in studies II and III

Parameter	Study II Field	Study II Soil bin	Study III Soil bin [1]
Coulter width, mm	15	15, 40	25
Rake angle, °	90, 110, 130	70, 90, 110, 130	75, 90, 105, 120, 135
Depth, mm	25, 45	35, 70 [2]	0-90 [3]
Horizontal velocity, m/s	0.3, 1.2, 2.1, 3.0	0.3, 1.2, 2.1, 3.0 [2]	0.6, 1.4, 2.2, 3.0 [4]
Vertical velocity, m/s	-	-	±0.45
Horizontal acceleration, m/s^2	-	-	±8
Vertical acceleration, m/s^2	-	-	±30

[1] *The values for this study are valid for the signals after they have been filtered with a low pass filter with 18 Hz cutoff frequency.*

[2] *In the main experiments. In preliminary experiments a larger range and more levels were investigated.*

[3] *99% of the observations were above the 80 mm depth level, 77% above the 60 mm level, 49% above the 40 mm level and 20% of the observations were above the 20 mm depth level.*

[4] *Individual measurements vary up to 14% (0.3 m/s) from set level.*

In study III the soil forces on the used coulters were measured under fully dynamic conditions. The measured soil forces were described by empiric dynamic models, which consisted of a pseudostatic term, similar in structure to the multifactorial model used in study II (except that no velocity term of third order was included), and three additional dynamic terms. Each of these three dynamic terms was linear to one of the three dynamic factors, the ratio between vertical and horizontal velocity (r-ratio), the horizontal acceleration and the vertical acceleration respectively. Each of these terms was at the same time a polynomial in depth, horizontal velocity and rake angle similar in structure to the pseudostatic term. Based on this structure, models were developed for both the horizontal and the vertical soil force. They agreed well (standard deviation approximately 0.7 N) with the measured data.

The pseudostatic contributions in these dynamic models agreed well with the pseudostatic models developed in study II. The horizontal soil force was affected by all three dynamic contributions. The effect due to horizontal acceleration, which can be expressed as an equivalent soil mass that is accelerated together with the coulter, increased almost linearly with depth, it decreased sharply and almost linearly with coulter speed, while it only increased slightly with rake angle. The effect on horizontal soil force due to vertical acceleration changed sign at intermediate rake angles (100-110°), it increased with depth and decreased slightly with horizontal speed. The study did not confirm any influence from horizontal or vertical acceleration on the vertical soil force.

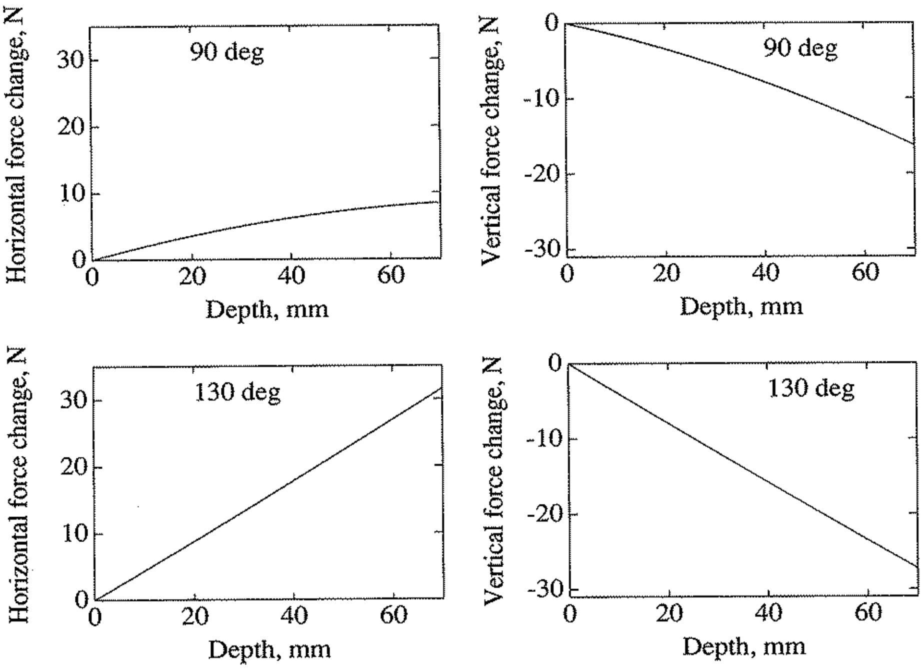

Figure 5. The horizontal and vertical soil force changes due to an r-ratio of 1 as functions of depth. The horizontal velocity of the coulter is 2.0 m/s.

The soil force changes found in study III due to the third dynamic term, the ratio between vertical and horizontal coulter velocity, r, are shown in Figs. 5 - 7. These soil force changes will damp the oscillatory motion of the coulter. The size of these force changes increases relatively linearly with depth, especially for the 130° rake angle coulter (Fig. 5). They increase in a more quadratic manner with speed and rake angle (Figs. 6 and 7).

The dynamic soil force models were used to simulate the step responses of coulters penetrating from the soil surface. These simulations, together with some penetration measurements, led to the following conclusions.

The penetration is improved (the coulter reaches its equilibrium depth after a shorter horizontal movement and the motion is better damped) by decreasing the moment of inertia of the coulter, by increasing its rake angle, by increasing its depth and by decreasing its speed.

The step response of large rake angle coulters (>110°) proved to be relatively insensitive to changes in pivot arm length, pivot axis height and suspension type (single or parallel arm), while the opposite applied to coulters with acute rake angles. The step response of parallel arm coulter was generally found to be slower than that of single arm coulters.

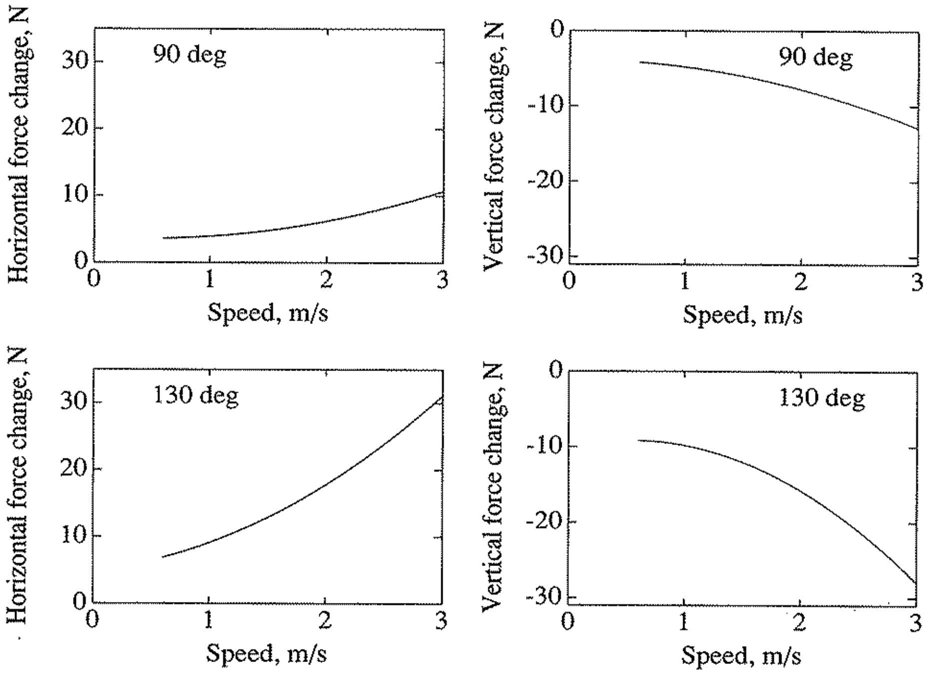

Figure 6. The horizontal and vertical soil force changes due to an r-ratio of 1 as functions of speed. The depth of the coulter is 40 mm.

8.4 Discussion of results in studies II and III

8.4.1 Soil forces on the coulter

In study II the speed-force relationship was found to be a second order polynomial. Many different researchers have reported similar relationships for different types of soil working equipment. Siemens et al. (1965) did this for the two dimensional soil failure of blades. Möller (1975) empirically found this relationship for conventional seed drill coulters and Stafford (1979) found it for tines, when they caused a brittle soil failure. Stafford (1984) explained the second degree relation by soil inertia forces and by the effect of speed on soil-metal friction. Also Swick & Perumpral (1988) found that inertial soil forces led to a quadratic term in the speed-force relationship. They expected effects also due to soil shear strength and soil-metal friction increasing with shear rate. However, in their artificial soil these parameters proved to be rate independent. Söhne (1956) and Goriachkin (1968) have theoretically shown that the inertial soil forces ought to lead to a quadratic term in the speed-force relation.

In study II the depth-force relation was found to be a second order polynomial with its intercept at the origin. This was expected, because all of the previously mentioned force models based on classical soil mechanics include such a relationship. Thus the verification of those models has also been a verification of this structure of the depth-force relationship (e.g. Payne, 1956; O'Callaghan & Farrelly, 1964; Reece, 1965).

Since no usable soil failure model was found for the three-dimensional soil failure of a seed drill coulter, no specific type of rake angle force relationship was expected. Instead, the knowledge was used that this relationship and its derivatives ought to be continuous. The rake angle-force relationship was approximated by second order (field part of study II) or third order polynomials (soil bin part of study II and study III). Since the field part and the soil bin part of study II only included three and four rake angle levels, respectively, the goodness of fit of these rake angle models could not be tested. Study III, however, included five different rake angle levels. The good agreement (considering the complexity of the dynamic measurements) of the dynamic force models to the measurements (standard deviation ≈ 0.7 N) indicates that the third order polynomials give a good description of the rake angle force relationships over the parameter range investigated.

The horizontal soil force was found to depend on all three dynamic terms in the model. The influence due to horizontal acceleration was expressed as an equivalent soil mass that was accelerated together with the tine (Table 3 in III). At low speed this mass was quite large, around 400 g at 50 mm operating depth. The shape of the failure surface was not registered. However, if this surface is approximated by two quarter-cones joined by a plane in front of the coulter, then the soil mass inside of this surface can roughly be estimated to 300-450 g, including the soil heaved up by the coulter. Thus, it seems as if most of the soil inside the failure surface was accelerated together with the coulter when the speed was low. The measured equivalent mass decreased rapidly with increasing speed. One possible explanation of this is that the shape of the failure surface changed with speed. However, it is unlikely that this alone could explain such a sharp decrease in equivalent mass. Another and more probable explanation is that the turmoil inside the failure surface increased with speed and that this turmoil interfered with the transmission of coulter acceleration to the soil in the outer parts of the failure zone, thus less soil was affected by the acceleration and therefore the equivalent mass decreased.

The equivalent mass increased almost linearly with depth and it increased slightly with rake angle. This was expected, since it reflects a fairly similar increase of the soil mass inside the failure surface.

The horizontal soil force was also influenced by vertical coulter acceleration (Table 4 in III). This influence was, as expected, rake angle dependent. At a coulter depth of 50 mm the effect changed sign in the rake angle interval between approximately 105 and 110°. One obvious cause of this effect is the "wedge effect". When an acute rake angle, for example 75°, coulter is accelerated upwards, then some of the soil in the failure zone may be accelerated upwards together with the coulter. However, this soil will also slide somewhat along the coulter front, and thus the soil will be accelerated also in the horizontal direction. The inertial force from this acceleration will be along the negative x-axis, which agrees well with the measured effects. This "wedge" effect ought to change sign at a rake angle of 90°.

The "wedge effect" is probably amplified by a "frictional effect". Vertical coulter acceleration affects the stress on the coulter front-soil interface. This will affect the soil friction on the interface. Since the soil flow across the front of the coulter probably is mainly horizontal, this change in soil friction will mainly influence the horizontal soil force, which will be affected in such a way that the "wedge effect" is amplified.

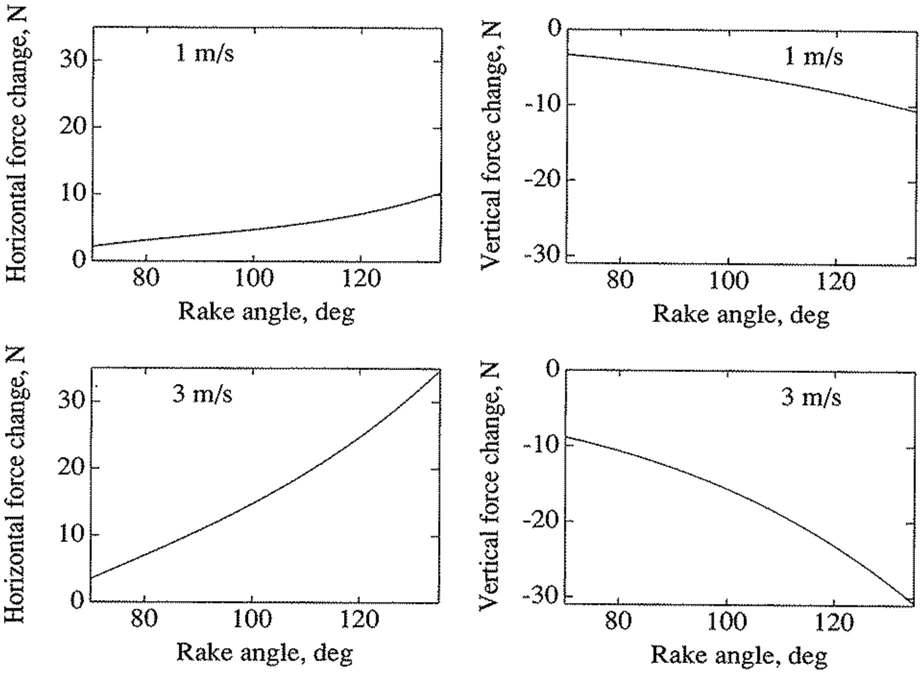

Figure 7. The horizontal and vertical soil force changes due to an r-ratio of 1 as functions of rake angle. The depth of the coulter is 40 mm.

The effect on horizontal force due to vertical acceleration decreased with increasing horizontal velocity. This was expected since the equivalent soil mass in the horizontal direction, which has similar causes, decreased with speed.

At a working depth of 50 mm the measured effect on the horizontal force due to vertical acceleration changed sign at a rake angle of 105-110° and not, as expected, at 90°. Furthermore, the rake angle where this effect changed sign strongly depended, for the chosen H2 model, on working depth and, at 10 mm working depth, also on speed (Table 4 of III). (At such a shallow working depth model H1 seems to describe this effect better than model H2.) These two observations indicate that the measurement accuracy was insufficient to accurately determine the relationship between vertical coulter acceleration and horizontal soil force.

In the vertical direction no equivalent soil mass and no effect due to horizontal acceleration was found. As pointed out in study III this is taken as a sign of insufficient measurement accuracy rather than a verification that these effects do not exist. It seems unlikely that the soil should be accelerated together with the coulter in the horizontal direction and not in the vertical one.

Even though the footing areas of the used coulters were very small, the effect on soil forces due to vertical coulter velocity was found to be large (Figs. 5-7). This effect, which damps the vertical motion of the coulter, is probably mainly caused by the failure surface changing its shape due to the vertical coulter velocity. Harrison (1973a, 1973b) has investigated this effect at low speed for the two-dimensional failure of a plate-grouser. The failure surface area, and thus the soil forces, increases when the coulter moves downward and decreases when it moves upward. This explanation agrees well with the effect increasing with depth, with speed and with rake angle (Figs. 5 - 7).

8.4.2 Pseudostatic behaviour of coulters

The sensitivity of coulter equilibrium depth to speed changes, to soil parameters changes and to suspension parameter changes was found in study II to decrease with increasing rake angle, at least between 70 and 130°. This sensitivity was also found to be independent of coulter width and almost independent of suspension type (single arm or parallel arm). These conclusions were mainly based on the measurements in the soil bin, because the measurements in the field had too few replications and too large replication errors to be conclusive.

The concluded decrease in equilibrium depth sensitivity with increasing rake angle agrees well with Herbst (1990), who found that a 150° coulter was less sensitive to changes in soil resistance than a 120° coulter. No other relevant study on this subject has been found in the literature. The above conclusion is however in line with the fairly widespread recommendation and common practice to use hoe coulters mainly on cloddy or stony fields (Segler & Dencker, 1961; Wilkinson & Braunbeck, 1977; Berglund & Hæggblom, 1966; Kepner et al., 1978; Heyde & Kühn, 1976). On other fields shoe coulters are recommended.

8.4.3 Dynamic behaviour of coulters

In study III the dynamic behaviour of a coulter was found to improve (i.e. a shorter horizontal movement was needed for the coulter to penetrate to equilibrium depth and this penetration was better damped) with increasing rake angle (at least up to 135°), decreasing moment of inertia, decreasing horizontal velocity and increasing working depth. Coulters with large rake angles were also found to be relatively insensitive to changes in suspension parameters and in type of suspension (single or parallel arm).

Seed drill coulter dynamics have been studied only sparingly. Most of the relevant studies are either hard to understand, because they are written in Russian, or hard to find, because they are unpublished departmental notes. Therefore a literature review of the relevant literature precedes the discussion of the results.

Klyuev (1966) described the coulter as a second order system without any damping. Since he had measured and could functionally describe the autocorrelation function of the system input, i.e. the soil reaction on the coulter, he could also compute the variance of the output, i.e. the angular displacement of the pivot arm, as a function of the input variance. From an expression of this he concluded that the vertical movement of the coulter would decrease with decreasing torque arm of the soil reaction force, with increasing rate of the coulter spring and with increasing mass of the coulter. (This latter solution was ruled out, since it would lead to an increased metal consumption.) No experimental support was given for any of these conclusions. However, he also found, and experimentally verified, that the variance of the depth of operation increased with speed.

Anilovich & Basin (1968) also described the motion of a seed drill coulter as a second order system without damping. Their conclusions, which agree with Klyuev's (1966), were that a stiff coulter spring and a large coulter mass improve the stability of motion of the coulter. They also concluded that a parallel suspension was superior to a single arm suspension. The performance of the latter could be improved by making the pivot arm as long as possible. The authors realized, however, that a stiff spring and a large coulter weight would impair the surface following characteristics of the coulter. To alleviate this they theoretically investigated and recommended the use of supporting devices (wheels or runners) in front of and/or behind the coulter. No experimental data were supplied.

The use of wheels or runners, to prevent the coulter from sinking too deep when used on soft ground, is well known and described in several textbooks (e.g. Segler & Dencker, 1961; Heege, 1973; Pedersen, 1940). Kolinsky (1980) experimentally showed that a runner improves the surface following characteristics of the coulter. However, in locations where the rainfall between time of sowing and emergence is scarce, it is usually desirable to place the seed on (or in) the moist seedbed bottom (Håkansson & von Polgar, 1984). Thus, under these conditions the coulter should follow the seedbed bottom and not its top surface. A runner or roller obviously also increases the risk of soil and/or crop residues building up and blocking the coulter. These two drawbacks are, together with the cost of the wheels or the runners, the probable reasons that coulters with such devices have not come into common use.

Shiryaev (1968) described the coulter motion as a second order damped system. He considered three types of disturbances; changing soil resistance, motion over an obstacle and motion over a rough surface. He concluded and experimentally verified, that the depth of operation of the coulter would be more even if the coulter spring was 2-3 times stiffer than normal and if a low speed of operation was used. Through measurements he also found that the standard deviation of the depth of operation of a rear row coulter, with a long pivot arm, was approximately equal to that of a front row coulter, with a short pivot arm.

The probable reason that he could experimentally verify that a stiff spring decreased the variance of the depth when operating on a rough ground is that, instead of a real rough ground, he used a smooth ground on which he had placed obstacles at regular intervals. Under these circumstances a stiff spring is beneficial for the coulter motion. After each obstacle the spring forces the coulter to quickly penetrate the even surface down to set depth. However, the coulter's behaviour on this type of ground gives no information about its behaviour in a field, where the coulter should follow the surface undulations.

Rybakov (1972) measured the performance of coulters equipped with different types of suspensions; parallel arm, single arm and an intermediate type. He found that the depth of operation was most even for the intermediate type closely followed by the single arm suspension, while the performance of the parallel arm suspension was clearly worse. He also found that reducing the coulter weight from 40 kg to 20 kg decreased the standard deviation of the operating depth from 1.01 to 0.91 cm. Since he states that a stiff coulter spring should be used if the primary cause of coulter vibration is varying soil resistance, while a weak spring should be used if the primary cause is surface undulation, he realized the importance of the coulter following the surface relief instead of the machine frame.

Kaskulov (1975) experimentally showed that the standard deviation of the operating depth of the used coulters (probably not disc coulters but the rake angle is not given) increased when the speed was increased from 2.2 to 3.0 m/s. He also found that a single arm suspension was superior to a parallel arm one. Finally, he found that the use of a stiffer spring decreased the variance of the depth of operation.

Pologikh (1977) considered the coulter as a damped second order system. He derived that the depth variance decreases with increasing stiffness of the coulter spring and that it increases with increasing velocity. The latter conclusion was experimentally verified.

Also Valge (1973) modelled the coulter motion as a second order damped system. The equation of the coulter motion given by him is (in his notation)

$$T_1^2\Delta\ddot{\phi} + T_2\Delta\dot{\phi} + \Delta\phi = f(t) \tag{10}$$

where T_1 and T_2 are time constants, $\Delta\phi$ the angle of vibration of the coulter relative to the seed drill frame and $f(t)$ the inducing force.

Valge (1973) measured T_1 and T_2. They both decreased with speed, T_1 by 25% from 0.06 s at 5.6 km/h to 0.045 s at 13.9 km/h. The corresponding figures for T_2 were 71%, from 0.07 s to 0.02 s. From the suspension parameters, Valge (1973) also calculated T_1 for the front and rear row disc coulters to 0.025 and 0.035 s respectively while his measured values were 0.06 and 0.07 s. The differences between calculated and measured values were explained by the effects of the soil interacting with the coulter. He measured coulter depth and found that its standard deviation increased with speed. He also added a hydraulic damper to a front row coulter suspension. This decreased the standard deviation of the measured coulter depth by up to 38%. However, the conditions and procedures of the measurements were not given.

Heege (1974), in a study of the sowing depth produced by different coulters, found that the standard deviation of a coulter with a large rake angle ("Säbelschar", full runner) was smaller than that of an ordinary shoe coulter ("Schleppschar"). The difference between them was not statistically significant and the depth of sowing is not the same as the depth of operation. Furthermore, no information is given concerning the masses or the suspension parameters of the coulters. Nevertheless, his result points in the direction of one of the conclusions of study III, that an increased rake angle improves the dynamics of the coulter.

Between 1974 and 1988 the NIAE carried out a large project on the metering and depth control systems of seed drills. In this project, Lines (1986) tested the hypothesis that coulter dynamics could be improved by including a damper in the coulter suspension system. He measured the movements of one damped and one undamped coulter. His results indicated that the damped coulter followed the machine frame instead of the ground profile. Since the seed drill itself vibrated with a natural frequency of approximately 3.5 Hz, his conclusion was that the undamped coulter followed the ground better than the damped one. He did not rule out the possibility that the inclusion of a damper could improve the dynamics of a coulter, however, in that case the degree of damping would have to be fairly precise (Lines, 1986; Patterson, personal communication 1988).

Vosshenrich & Heege (1984), in a study of the requirements placed by rape seed on sowing, noted that lowering the speed from 6 to 4 km/h in a field with a cloddy seedbed significantly improved coulter dynamics. This was substantiated by their measurements of the emergence. Their measurements and observations show that the clods in a coarse seedbed can be quite detrimental for the performance of a coulter with a large rake angle, a shoe coulter.

Herbst (1990) modelled the seed drill coulter as a damped second order dynamic system. The input of this system was the soil resistance changes, which he measured with a horizontal penetrometer, and the output was the depth of the coulter. To verify the model he measured the step responses of three different commercial coulters (Fig. 8).

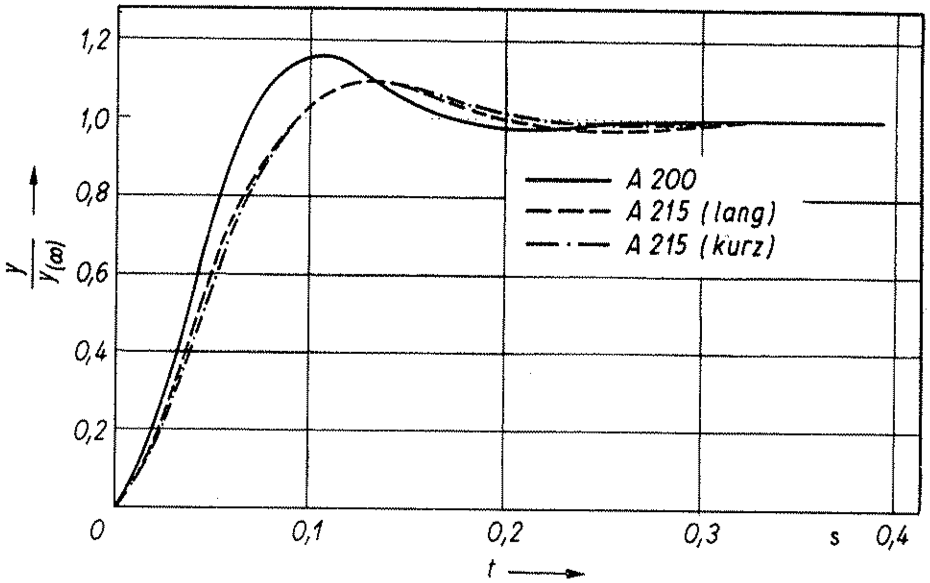

Figure 8. The three penetration measurements reported by Herbst (1990). A 200 and A 215 are two different seed drill models. The terms "lang" and "kurz" denote two different versions of the coulters for the A 215 seed drill. Coulter depth is denoted by "y". (Figure from Herbst, 1990.)

Several objections can be raised against the theoretical approaches reported in the above literature review. Some researchers (Klyuev, 1966; Anilovich & Basin, 1968) did not include any damping in the coulter system, while the results of Valge (1973), Herbst (1990) and study III clearly show that the coulter motion is damped by the soil. In some studies (Klyuev, 1966; Anilovich & Basin, 1968) the coulter motion relative to the machine frame instead of the deviation of the coulter from a set depth was minimized. This clearly results in erroneous conclusions since the minimum relative motion between the machine frame and the coulter occurs when the coulter is welded together with the frame, however this obviously does not promote an even depth of operation. Only Valge (1973) and Herbst (1990) have considered the possibility that the coulter-soil system might have, in addition to the feed-back loop from coulter displacement (i.e. depth), also feed-back loops from coulter velocity and from coulter acceleration. Study III has confirmed the existence of several of these additional feed-back loops.

There is an overwhelming agreement that a stiff coulter spring improves the dynamics of the coulter (Klyuev, 1966; Anilovich & Basin, 1968; Shiryaev, 1968; Kaskulov, 1975). However, some of them also realized that this decreases the ability of the coulter to follow a rough surface. Thus, in the case of such a surface they recommend a weak spring (Rybakov, 1972) or the use of additional supporting wheels or runners on the coulter (Anilovich & Basin, 1968). Apart from Lines (1986) none of the studies has considered the possibility that the seed drill frame might vibrate. Since measurement of the vibration of the seed drill frame was outside of the scope of studies II and III, it was decided to use a spring rate of zero in the simulations made in studies II and III. Such a spring rate minimizes the transmission of vibration from the machine frame to the coulter. It promotes and simplifies the analysis of the influence of other parameters on coulter dynamics. Probably a very low spring rate together with a maximum depth catch, attained for example by the use of hydraulic or pneumatic cylinders, would be beneficial for the dynamics of coulters in general.

Most of the theories considering the case of a rough ground surface have assumed that this surface is sinusoidal (Shiryaev, 1968; Pologikh, 1977). Thus they have found that, as the frequency of the surface roughness increases, the stiffness of the coulter spring should also increase. However, measurements of seedbed surface reliefs in the direction of cultivation by Harral (1981) and of stubble fields in the direction of sowing by Wendenborn (1966) reveal no prevalent frequency. There is no frequency towards which to match the spring stiffness.

Thus, the theories reported in the literature review were, with the exceptions of the ones by Valge (1973) and by Herbst (1990), found inadequate and they are therefore not considered in the following discussion. Instead, the relation between the measurements reported in the literature review and the conclusions arrived at in study III will be discussed.

In the above review there is a general agreement that coulter dynamics are impaired by an increased **speed of operation** (Klyuev, 1966; Shiryaev, 1968; Valge, 1973; Kaskulov, 1975; Pologikh, 1977; Vosshenrich & Heege, 1984). This is in good agreement both with study III and with common knowledge. Valge (1973) reported a small decrease in T_1 and a large decrease in T_2 with speed. This agrees well with the observations in study III that the equivalent soil mass decreases, that the soil forces increase and that the vertical motion of the coulter becomes more oscillatory with increasing speed.

In study III it was concluded that a decreased **moment of inertia**, for a constant pivot arm length, would improve the dynamics of the coulter. Such a decrease of the moment of inertia implies a decrease of the coulter mass. Thus, the above conclusion agrees well with Rybakov (1972), who experimentally found that a decrease in coulter mass improves coulter dynamics.

In study III it was concluded that in a seedbed without clods or stones the dynamics of a large **rake angle** coulter are better than those of a coulter with a smaller rake angle. This conclusion agrees well with the result of Herbst (1990), who found that the depth of operation of a 150° coulter did not, for a given change in soil resistance, change as much as that of a 120° coulter. It also agrees with the result of Heege (1974), who found that the standard deviation of the depth of sowing was smaller for a large rake angle coulter ("Säbelschar", full runner) than for an ordinary shoe coulter. The above conclusion is also in line with the widespread recommendation and common practice to use hoe coulters mainly on cloddy or stony fields (Segler & Dencker, 1961; Wilkinson & Braunbeck, 1977; Berglund & Hæggblom, 1966; Kepner et al., 1978; Heyde & Kühn, 1976). On other fields, ordinary shoe coulters are recommended.

In study III it was also concluded that the dynamics of a large rake angle coulter were fairly independent of the **type of suspension**, while the dynamics of a coulter with a small rake angle would be impaired if a parallel arm suspension was used instead of a single arm one. This conclusion agrees with Kaskulov (1975), who reported a larger variance of the depth of operation when a parallel arm suspension was used than when a single arm one was used. However, he did not state the type of coulter used. Also, Rybakov (1972) found, by measuring the variation of the operating depth, that the single arm suspension (standard deviation 0.71 cm) was superior to the parallel arm one (standard deviation 0.91 cm). From Rybakov's (1972) drawings it seems as if he used coulters with a rake angle of 110-120°. If so his measurements agree well with the results in study III where, for a 110° coulter, the step response of a parallel arm suspension was slower than that of any of the investigated single arm suspensions. For a 130° coulter the parallel arm step response was slower than some, but faster than some others, of the investigated single arm suspensions. Rybakov (1972) used real suspensions with friction. In the simulations the suspension joints were assumed to be perfect, i.e. without friction. Friction impairs the dynamics of a parallel arm suspension more than those of a single arm suspension.

In study III it was concluded that the dynamics of coulters with a large rake angle were fairly insensitive to **pivot arm length and pivot axis height**. This agrees well with the measurements of Shiryaev (1968), who measured the dynamic performances of front row (short pivot arm) and rear row (long pivot arm) coulters and found that they were similar. Valge (1973) reported different dynamic parameters for the front and rear row disc coulters, however he did not report how these differences affected coulter depth.

No direct comparison is possible between the **step responses** simulated and/or measured in study III and those measured for three commercial coulters by Herbst (1990). However, it deserves to be noted that the general shape of his measured step responses agree well with those reported in study III for large rake angle coulters operating at a low speed (Fig. 8).

In the literature no measurement has been found which relates to the conclusion of study III that the dynamics of a seed drill coulter improve with increasing **depth of operation**.

The **summary** of the literature review and of the discussion is that only a small number of reported measurements have been found which are relevant in relation to the conclusions of study III. Most of these measurements agree well with the conclusions of III and none disagrees with them. Since the measurements found in the literature review were made with, more or less, commercial coulters and in, more or less, normal seedbeds, it seems reasonable to believe that the conclusions in study III apply not only to coulters of simple shape used in dry sand, but also, when interpreted in a reasonable way, to commercially available coulters used in real seedbeds, provided that these seedbeds do not contain large clods or stones.

8.5 Practical implications of the results on seed drill coulters

Neither in study II nor in study III was the parallel arm suspension found to possess any significant advantage when compared with the common single arm suspension. On the contrary, study III indicated that the dynamics of a coulter with a rake angle below approximately 110° are impaired if a parallel arm instead of a single arm suspension is used. This is supported by the measurements made by Rybakov (1972). In study III this result was arrived at under the assumptions that the joints of the parallel suspension were without friction and that the mass and mass distribution of the parallel arm suspension were the same as those of a single arm suspension. Normally, coulter suspension joints have some friction. Since the single arm suspension contains one joint and the parallel arm suspension four joints, and since the joint forces are considerably higher in the parallel arm suspension, the dynamics of the latter will be considerably more impaired by friction than the dynamics of the single arm suspension. Furthermore, the increased complexity and increased forces of the parallel arm suspension imply that this suspension normally will be heavier and have a larger moment of inertia than the corresponding single arm suspension. One further disadvantage of the parallel arm suspension is its higher cost. Thus, based on these studies, single arm and not parallel arm suspension is recommended, at least when the seedbed is free of clods and stones.

Provided that the rake angle of the coulters is larger than 90-110°, the advantage of the rear and front row coulter pivot arms having the same length, necessitating two separate pivot axes, is very small. This is shown by the step responses in study III and by the measurements by Shiryaev (1968). However, when the rear and front row coulters have different pivot arm lengths, then this must be considered when the coulter loading is designed.

The coulter mass should be as small as possible in order to minimize the moment of inertia for any given pivot arm length. Thus, it is desirable that the coulter loading is done by spring force and not by weight.

The dynamics of the coulter is sensitive both to speed and depth. This means that a speed as low as possible should be used when the depth of operation is of primary concern. Keeping the speed low is especially important when a shallow depth of operation is used.

Study III clearly showed that an increased rake angle, at least up to 130°, improves coulter dynamics, when the coulter is used in a seedbed without clods or stones. This conclusion was supported by measurements made by Heege (1974) and Herbst (1990). It is both supported by, and an explanation of, the common recommendation and usage of shoe coulters in areas where the seedbeds normally do not contain clods or stones. Where stones or clods are frequent the common recommendation is to use coulters with a rake angle around or below 90° (hoe coulters) (Segler & Dencker, 1961; Wilkinson & Braunbeck, 1977; Berglund & Hæggblom, 1966; Kepner et al., 1978; Heyde & Kühn, 1976). The relevance of this recommendation is supported by the observations by Vosshenrich & Heege (1984), who found that shoe coulters jumped excessively when used in a cloddy seedbed.

Thus the recommended rake angle depends on whether there are clods or stones in the seedbed or not. In many locations the amount of clods vary within and between fields, with season (spring, summer, autumn) and between years. Thus, a single arm coulter with an easily adjustable rake angle over a large range is desirable.

8.6 Need and direction of further research

Although the crop establishment is a most critical and vulnerable phase in crop production, it is hard in most western countries to find financial support for research concerning seed drill coulters, probably because of the present over-production of food in the industrialized part of the world. This is very unfortunate, since good crop establishment is a prerequisite for efficient use of plant nutrients and thus for minimal leaching. A good crop establishment is also very important for the economic survival of farms with large fixed costs. Furthermore, the world population increases by approximately 90 million per year and at the same time the area of arable land decreases. Thus it is just a matter of time until research into crop establishment will receive renewed attention.

In studies II and III the influence on coulter dynamics of speed, depth, width, rake angle, suspension type and suspension parameters has been investigated. However, to simplify the dynamic force models, the experimental design and analysis, all coulters used in the experiments have had just a small footing surface, while most commercial coulters have fairly large footing surfaces. It is reasonable to believe that a larger footing will increase the damping of the coulter. This will probably improve the performance of the coulter. Thus, research on the influence of the coulter footing is needed. Research is also needed on the vibrations of the machine frame and the transmission of these vibrations to the coulter itself. The increased spring loading of the coulter, which becomes necessary when coulter weight is decreased, stresses the importance of this research.

The dynamic behaviour of coulters when they bounce on, or cut into, the firm bottom, or clods caught between the bottom and the coulter, deserves attention, as do the dynamics of direct drill coulters. However, the fully empirical approach used in studies II and III is not suited for this research. The used approach requires a large number of force measurements performed under well defined conditions and with a high degree of reproducibility. This can, with reasonable effort and cost, be achieved in dry sand, which to some extent resembles a well tilled seedbed. The cohesion of the firm bottom, of the clods and of the untilled soil in which the direct drilling is done, is generally not negligible and therefore it is not reasonable to do that research in dry sand. However, using a cohesive-frictional soil will require very large experimental resources. Thus, for this research the finite element method, used for tines by Chi & Kushwaha (1987, 1989, 1991a, 1991b), seems a better choice, even though the method still requires a lot of development. One very interesting advantage of the finite element method is that it gives not only the motion and forces of the coulter, but also the soil motion, the soil velocity and the soil acceleration. Furthermore, it probably would simplify research on layered soils and complicated coulter shapes, like band sow coulters.

9 CONCLUSIONS

The motions of both tractor-hitched implements and coulters are controlled by the soil forces and by the used hitch/suspension. Although the implement and the coulter are both rigid bodies and although the tractor-implement hitch and the coulter suspension are both fairly similar simple mechanical devices, the dynamics of the lateral implement motion and the vertical coulter motion have been shown to be very different.

The lateral motion of most soil-engaging implements hitched to a tractor is heavily overdamped, thus their lateral motion is well described by a first order model. For these overdamped implements the lateral dynamics have been shown to depend on the lateral characteristics of the implement (the lateral force constant and the non-directional force) and on the tractional and directional hitch lengths. These hitch lengths are given by the geometry of the hitch and of the implement. From these four parameters the location of the effective hitch point (the point towards which the implement tends to move) can be calculated for any tractor-implement combination having a lateral motion that is heavily overdamped. Such an implement returns exponentially from a lateral displacement. This displacement is reduced to 10 % of its initial value as the implement moves forward a distance of 2.3 times the effective hitch length.

For one-point hitches the directional and the tractional hitch points coincide. For three-point hitches this is not the case. This gives three-point hitched implements quite unique and, if used with care, favourable properties. Both when used on a hillside and when subjected to an asymmetric loading situation, the lateral as well as the angular deflection will normally be smaller for an implement using the three-point hitch than for the same implement using a one-point hitch.

The versatility of the three-point hitch is immense. A striking example of this is that laterally self-centring front mounted three-point hitches can be constructed such that they function with non-directional as well as with directional implements. To achieve this, the point of convergence of the symmetrical lower links should be in front of the implement and the upper link must be short enough and its tensile force large enough to satisfy the Eqn

$$\frac{F_u}{F_{nd}} > \frac{L_c}{L_u}$$

The inertial forces are quite important for the vertical dynamics of seed drill coulters. Thus a second order model was used to describe the vertical coulter motion.

The horizontal and vertical pseudostatic soil forces on the coulters were, within the parameter space spanned by the experiments, well described by empirical models containing zeroth, first and second order terms of the horizontal velocity, first and second order terms of depth and zeroth, first, second and third order terms of rake angle and the products of these terms. The dynamic soil forces were well described (standard deviation ≈ 0.7 N) by empirical models, which consisted of four parts, one pseudostatic and three dynamic. The pseudostatic part was similar in structure to the pseudostatic soil force models, while the structure of each of the three dynamic parts essentially was that of the pseudostatic part multiplied by one of the three dynamic parameters r-ratio (ratio between vertical and horizontal velocity), horizontal acceleration and vertical acceleration.

These soil force models were used to simulate the penetration of different coulters. Some measured coulter penetrations were also, with good agreement, compared to simulated ones. The following conclusions were drawn:

The coulter dynamics are improved (i.e. a shorter horizontal movement is needed for the coulter to penetrate to equilibrium depth and this penetration is better damped) by decreasing horizontal velocity, by decreasing moment of inertia, by increasing depth and by increasing rake angle. Thus it is especially important to keep a low speed if the coulters are set for a shallow depth. Large rake angle (≥110°) coulters not only offer the fastest and best damped response, they are also relatively insensitive to changes in pivot arm length, pivot axis height and suspension type (single or parallel arm), while the opposite applies to coulters with acute rake angle.

The force measurements were made in dry sand and thus the conclusions apply to this condition. However, to a large extent the literature review has validated the above conclusions also for ordinary coulters and seedbeds provided that they do not contain stones or clods.

In the present studies, the costly and complex parallel arm suspension was found to have no advantage over the single arm suspension. The parallel arm suspension proved to impair the dynamic of coulters with rake angles below 110-120°.

Provided that coulters with a large rake angle are used, there is no need of having the same pivot arm length for front and rear row coulters, which would necessitate two separate pivot axes.

If there are no clods or stones in the seedbed, coulters with a large rake angle are recommended since their dynamics are superior (at least up to 135-150°) to those of coulters with a smaller rake angle, provided that they are correctly loaded. However, if there are stones or clods in the seedbed then coulters with a large rake angle are prone to jump excessively. In this case, coulters with a rake angle around 90° are recommended. Since seed drills sometimes are operated in seedbeds with stones or clods and sometimes in seedbeds without these obstacles, there is a need of inexpensive single arm coulters with a rake angle that is easily adjustable over a large range.

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APPENDIX A. Comparison of some previously derived results with those given in I

Return from a lateral deflection

The expressions given by Cowell & Makanjuola (1966) for the distance an implement has to travel before a disturbance is reduced to 10 % of its initial value are approximately equal to the corresponding expressions given in I. The expression given by Cowell & Makanjuola (1966) for a real hitch point case is (using their notation)

$$s_e = 2.3026\, l \tag{A1}$$

This is, except for differences in notation and numerical accuracy, equivalent to the corresponding expression in I

$$x = 2.3\, L_{he} \tag{A2}$$

The expression given by Cowell & Makanjuola (1966) for a virtual hitch point case is

$$s_e = \frac{2.3026\,(D+N)l_2^2}{Nl_2 + D\left[l_2 + \frac{w_1(w_1 + r\sin\alpha)}{r\sin^2\alpha\cos\alpha}\right]} \tag{A3}$$

This is also the expression Makanjuola & Cowell (1970) intended to give, however, due to a printing error, their Eqn 14 looks somewhat different.

Substituting the effective hitch length into Eqn (A2) gives for the virtual hitch point case

$$x = 2.3\,\frac{L_{ht}L_{hd}(K + F_{nd})}{F_{nd}L_{hd} + KL_{ht}} \tag{A4}$$

Now, let us assume that Eqns (A3) and (A4) are equivalent. We then test this assumption (using the same numerical precision in both expressions);

$$2.3\,\frac{L_{ht}L_{hd}(K + F_{nd})}{F_{nd}L_{hd} + KL_{ht}} = 2.3\,\frac{(D+N)l_2^2}{Nl_2 + D\left(l_2 + \frac{w_1(w_1 + r\sin\alpha)}{r\sin^2\alpha\cos\alpha}\right)} \tag{A5}$$

Changing D, N and l_2 according to table A1 gives

$$\frac{L_{ht}L_{hd}(K + F_{nd})}{F_{nd}L_{hd} + KL_{ht}} = \frac{(F_{nd} + K)L_{hd}^2}{KL_{hd} + F_{nd}\left(L_{hd} + \frac{w_1(w_1 + r\sin\alpha)}{r\sin^2\alpha\cos\alpha}\right)} \tag{A6}$$

Table A1. Translation table between notation used by Cowell & Makanjuola (1966; called C & M) and Makanjuola & Cowell (1970; M & C) and the notation used in I

Notation used by C & M and M & C	Notation used in I	Notation stands for
W_I	$m_i g$	Weight of implement
D	F_{nd}	Non-directional force
ψ	α	Angle between the plane of symmetry of the tractor and the resulting hitch force
k	γ	Slope, angle of the ground relative to a horizontal plane
θ	β	Angle between the plane of symmetry of the tractor and directional plane of the implement
N	K	Directional force constant

Furthermore we notice that the notation l_2, distance from virtual hitch point to implement body (Cowell & Makanjuola, 1966) or to the point at which the resultant horizontal force meets the tool (Makanjuola & Cowell, 1970), is equal in size to the notation L_{hd}, distance from centre of resistance of the implement to directional hitch point. We also notice that the distance L_1, distance from the virtual hitch point to the implement's centre of gravity (Cowell & Makanjuola, 1966; Makanjuola & Cowell, 1970) is equivalent to L_{hd}, if the centre of gravity of the implement coincides with its centre of resistance.

This expression can be simplified to

$$\frac{L_{ht}}{F_{nd}L_{hd} + KL_{ht}} = \frac{L_{hd}}{KL_{hd} + F_{nd}\left(L_{hd} + \frac{w_1(w_1 + r\sin\alpha)}{r\sin^2\alpha\cos\alpha}\right)} \tag{A7}$$

Inverting this expression gives

$$F_{nd}\frac{L_{hd}}{L_{ht}} + K = K + F_{nd}\left(\frac{L_{hd} + \frac{w_1(w_1 + r\sin\alpha)}{r\sin^2\alpha\cos\alpha}}{L_{hd}}\right) \tag{A8}$$

Now, this expression is simplified and the right hand side of the remainder, which stems from Cowell & Makanjuola (1966), is rewritten to their notation while the left hand side is extended by L_s

$$\frac{\frac{L_s}{L_{ht}}}{\frac{L_s}{L_{hd}}} = \frac{l_2 + \frac{w_1(w_1 + r\sin\alpha)}{r\sin^2\alpha\cos\alpha}}{l_2} \tag{A9}$$

We observe that

$$l_2 = s_b + \frac{w_2}{\tan\alpha} \qquad (A10)$$

and that

$$w_1 + r\sin\alpha = w_2 \qquad (A11)$$

and, according to Cowell & Makanjuola (1966),

$$\psi = \frac{\left(s_b + \frac{w_2}{\tan\alpha} + \frac{w_1 w_2}{r\sin^2\alpha\cos\alpha}\right)}{l_2}\theta \qquad (A12)$$

Thus, Eqn (A9) can be rewritten

$$\frac{\alpha}{\beta} = \frac{\psi}{\theta} \qquad (A13)$$

Since this expression is true, our assumption is also true.

Thus, the expressions given by Cowell & Makanjuola (1966) and Makanjuola & Cowell (1970) for the distance it takes a heavily overdamped and laterally disturbed implement to return to 10 % of its initial disturbance are equivalent to the corresponding expressions in I.

Hillside operation

Makanjuola & Cowell (1970) predicted the lateral drift for an implement with a real hitch point to be (using their notation)

$$\chi_d = \frac{W_I l_1 \sin k}{N + D} \qquad (A14)$$

while study I gives the expression

$$L_s = \frac{L_{hd} m_i g \sin\gamma}{K + F_r} \qquad (A15)$$

Makanjuola & Cowell (1970) assumed that the angle between the tractor's plane of symmetry and the resulting hitch force is small. Making this assumption, Eqn (A15) can be rewritten

$$L_s = \frac{L_{hd} m_i g \sin\gamma}{K + F_{nd}} \qquad (A16)$$

In study I the centre of gravity was assumed to coincide with the centre of resistance. If this assumption also is made for the implement described by Eqn (A14), then Eqns (A14) and (A16) are equivalent.

For the virtual hitch point situation, Makanjuola & Cowell (1970) give

$$\chi_d = \frac{W_l l_1 l_2 \sin k}{N l_2 + D\left(l_2 + \frac{w_1(w_1 + r\sin\alpha)}{r\sin^2\alpha\cos\alpha}\right)} \tag{A17}$$

while the expression in I is

$$L_s = \frac{L_{hd} m_i g \sin\gamma}{K + \frac{L_{hd}}{L_{ht}} F_r} \tag{A18}$$

However, Makanjuola & Cowell (1970) assumed that the angle of the resulting force was small and in I the centre of gravity was assumed to coincide with the centre of resistance. Making these assumptions common, (A17) and (A18) can be rewritten

$$\chi_d = \frac{W_l l_2 \sin k}{\frac{N l_2 + D\left(l_2 + \frac{w_1(w_1 + r\sin\alpha)}{r\sin^2\alpha\cos\alpha}\right)}{l_2}} \tag{A19}$$

and

$$L_s = \frac{L_{hd} m_i g \sin\gamma}{K + \frac{L_{hd}}{L_{ht}} F_{nd}} \tag{A20}$$

Since the two numerators are equivalent, the two expressions are equivalent if the two denominators are equal. Let us assume that they are

$$K + \frac{L_{hd}}{L_{ht}} F_{nd} = N + D\left(1 + \frac{w_1(w_1 + r\sin\alpha)}{l_2 r\sin^2\alpha\cos\alpha}\right) \tag{A21}$$

Noting that different notations are used on the left and right hand sides, this can be simplified to

$$\frac{L_{hd}}{L_{ht}} = 1 + \frac{w_1(w_1 + r\sin\alpha)}{l_2 r\sin^2\alpha\cos\alpha} \tag{A22}$$

But this is equivalent to Eqn (A9) which earlier was proven to be true. Thus it has been shown that the expressions given by Makanjuola & Cowell (1970) for the lateral drift on a hillside are equivalent to the expressions given in I.

APPENDIX B. Errata

The following errors in the published papers have been found by December 10th 1992. Three references in paper II were published with minor errors. They should read:

[13] **Payne, P.C.J.; Tanner, D.W.** The relationship between rake angle and the performance of simple cultivation implements. Journal of Agricultural Engineering Research 1959, **4**(4): 312-325

[16] **Söhne, W.** Einige Grundlagen für eine landtechnische Bodenmechanik (Some basic principles for an agricultural soil mechanics). Grundlagen der Landtechnik 1956, **7**: 11-27

[17] **Möller, N.** Conventional coulters for small grain drilling. Department of Agricultural Engineering and Rationalization, Agricultural College of Sweden, Report No 28. Uppsala, Sweden, 1975