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The Influence of Front Linkage Geometry on Tractor-implement Interaction

R. G. THOMPSTONE;* P. A. COWELL†

Tractor front linkages pose special problems for soil engaging implements. This paper examines the effect of linkage geometry on stability in the longitudinal-vertical plane of implements supported by a depth wheel. Two unstable zones for the location of the virtual hitch point are identified. The theoretical analysis is verified by soil tank experiments using a half scale mouldboard push-plough.

1. Introduction

Linkages for mounting implements on the front of tractors have been marketed for a number of years. Although comprehensive literature is available to assist in the design of rear linkages, no comparable theoretical framework has been published for front linkages. It is the purpose of this paper to develop guidelines for the design of front linkages, particularly when used with soil engaging implements. The analysis is restricted to a consideration of the longitudinal–vertical plane only and implements whose depth is controlled by a support wheel.

2. Development of tractor front linkages

The earliest front linkages were of lightweight design for use mainly with forage and hay-making equipment, which could be operated in conjunction with rear mounted equipment for multi-operation single pass working. They were supplied as bolt-on kits being manufactured principally by companies independent of the tractor manufacturers, and followed the traditional Ferguson design of two lower links with a single acting hydraulic power lift and a manually adjustable length top link.

Attempts were made to mount other implements on the front of tractors such as steerage hoes, small dozer blades and other specialist implements. These were usually mounted on their own special linkages and sub-frames, which did not readily lend themselves to interchangeability. By contrast, the lightweight continental front linkages referred to above, were equipped with ball ends to take standard Category 1 or Category 2 implement pins, and implements could easily be modified to fit by using conventional "A" frames.

Front linkage kits often include a mechanical power-take-off driven from the front of the engine crankshaft. The direction of p.t.o. shaft rotation has been one of the main blocks to standardization, but standards for the dimensions of the attachment points on front mounted implements have now been introduced.[1] As with rear linkages, the location of the mounting points on the tractor is left to the tractor designer who thereby chooses the geometry the linkage adopts when an implement is attached.

Tractors have not generally been designed with front linkages in mind, and since the front axle is centrally pivoted, it is necessary to mount the front links on a substantial

* R. G. Thompstone, Writtle Agricultural College, Chelmsford, Essex, UK
† P. A. Cowell, Silsoe College, Silsoe, Bedfordshire, UK

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Notation

- D horizontal soil force acting on the implement, N
- F resultant force exerted by the tractor on the implement in the longitudinal-vertical plane, N
- L horizontal component of force exerted on the implement by the lower links of the tractor, N
- R resultant force exerted on the implement by the soil and gravity in the longitudinal-vertical plane, N
- U force exerted on the implement by the top link, N
- V soil reaction exerted on the implement support wheel, N
- W resultant vertical force exerted on the implement by the soil and gravity, N
- h implement mast height, m
- x moment arm of resultant vertical soil and gravitational force on the implement about the cross-shaft, m
- y moment arm of the horizontal soil force acting on the implement about the cross-shaft, m
- α angle between forces F and R, degrees
- β angle between forces V and R, degrees
- θ angle of the top link to the horizontal, degrees

sub-frame, bolted to the sides of the tractor. With lightweight non-soil engaging equipment, the geometry of the linkage does not matter greatly since the implements being used operate above ground level and only require the linkage to lift the implement for transport and turning, and to lower it into work. If any form of height control is required, then this may be achieved by physically restraining the travel of the lower links, usually by adjustable length chains.

There are a number of potential advantages that can be derived from the front mounting of ploughs, and when, in the late 1970s heavier and more robust front linkages were introduced in France to carry the topping units of multi-row sugar beet harvesters, it was on these heavier linkages that push-ploughs were first tried.

As rear mounted implements have become bigger, they have become more difficult to lift and tend to destabilize the tractor. The problem has been made much worse by the increased popularity of reversible ploughs. If a front plough can be used in conjunction with a rear mounted plough, smaller and lighter implements can be used for the same number of furrows per pass. Also, mounting of cultivating implements on front linkages opens up the possibility of multi-operation single pass cultivation.

With rear-wheel-drive-only tractors it is generally disadvantageous to carry the full weight of an implement on the front because it causes weight transfer from the rear axle to the front, so reducing tractive capacity. Four wheel drive tractors with power steering suffer no such drawback, and advantage can be taken of the fact that when both front and rear mounted implements are used together there is less need for the large amount of front end ballast normally required to provide front end stability, steerability and traction.

The geometry of the linkage in the vertical plane is important because it affects the angle of entry of the implement, its stability in work and, perhaps more importantly, the effect of the resultant force on the tractor itself.

At first sight it may be thought that the principles of design of front linkages must be

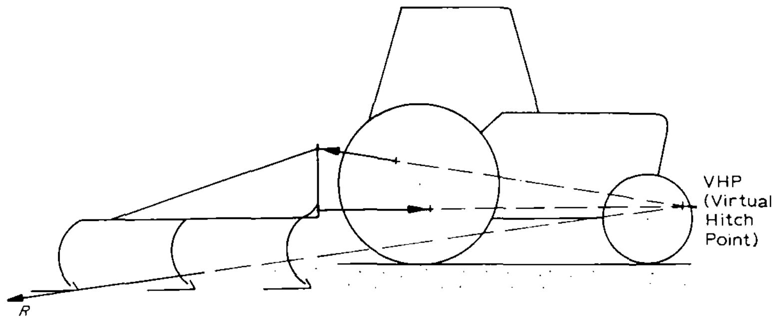

Fig. 1. External forces acting on a rear mounted implement with unrestrained lower links

similar to that of rear linkages. Closer examination shows that there are a number of quite fundamental differences. With rear mounted implements the linkage converges forward when viewed in side elevation (*Fig. 1*). When the lower links are unrestrained the implement penetrates until the resultant soil and gravitational force R acting on the implement passes through the point of convergence of the links.[2] This must be so because to be in equilibrium R must be concurrent with the forces in the top and lower links.

Implements such as mouldboard ploughs and mole ploughs have a preferred direction of travel and any deviation from the equilibrium position causes large restoring forces to be induced on the implement opposing the deviation. This linkage arrangement is therefore inherently stable. The point of convergence of the links is the instantaneous centre of rotation of the implement (ICR). Since the resultant R passes through the same point it is also commonly referred to as the virtual hitch point (VHP).

In a dynamic situation, such as the plough entry, implements so mounted (linkage unrestrained) follow an exponential path to equilibrium, the rate of response being determined solely by the distance from the front share to the ICR.[3]

With front linkages it is common to have the point of convergence of the linkage behind the plough, which results in a dynamically unstable hitch. There are two common arrangements in practice, one in which the linkage consists of a pair of unconstrained lower links with a single rigid top link, and one in which the two lower links are constrained and the top link is telescopic or is replaced by a chain.

The linkage geometry is arranged so that the plough is seeking to penetrate but is prevented from doing so by a support wheel at the front of the plough. This support force may be substantial and reduces the total load carried by the wheels of the tractor, with a consequent loss of tractive efficiency. The magnitude of the support force depends on the location of the point of convergence or instantaneous centre of rotation (ICR) of the linkage, so it is important for designers to know quantitatively how these two are related.

If the wheel support required to hold the implement in position turns out to be negative the linkage will be unstable.

This paper examines the effect of ICR location on the support force offered by the front wheel of the implement and the conditions for linkage stability. In all subsequent analyses the tractor and implement are approximated by a two dimensional model in the vertical plane.

3. Force analyses of current systems

3.1. *Constrained lower links and telescopic top link*

With this system the depth of the front of the implement is controlled by a wheel, while the depth of the rear of the implement is controlled by limiting the travel of the lower

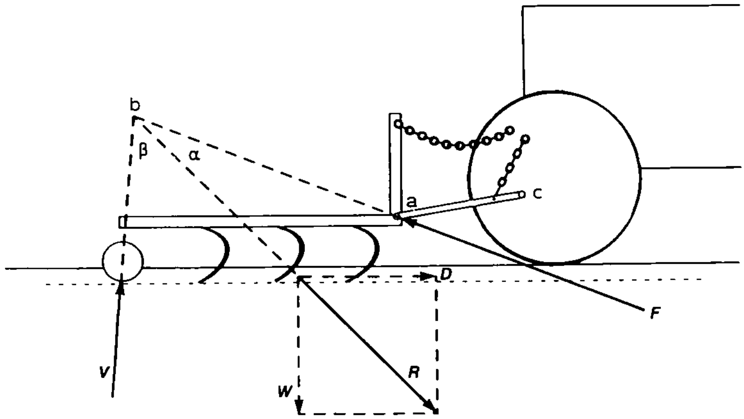

Fig. 2. External forces acting on a front mounted implement, constrained lower links with telescopic top link

links (*Fig. 2*). The implement is hinged about the lower link implement pin, a, about which it pivots as the tractor and implement pass over undulating ground. No force is taken by the top link while the implement is in work, but it comes into tension when the implement is raised out of work.

The draft force D and the resultant of the vertical soil and gravitational forces action on the implement W can be combined to form force R. Two other forces act on the implement, the reaction force F between the implement and the tractor, and the depth wheel support force V. V is the resultant of the vertical ground reaction and the rolling resistance of the wheel and is regarded as positive in the upward direction.

For any given implement working in a soil at a certain combination of depth and forward speed, forces W, D, and hence R are determined in magnitude, direction and position and are unaffected by the hitch geometry. The magnitude of the wheel reaction V will be greatly influenced by hitch geometry, but its line of action will not. V must always pass through the wheel centre and its direction is determined by the normal ground reaction and rolling resistance. Since rolling resistance increases with the normal reaction, the direction of V will be affected only to a limited extent. For the purpose of this analysis, therefore the direction of V is assumed to be constant and uninfluenced by the geometry of the hitch.

The forces V and R intersect at a point b. The third force, F, must also pass through this point for the three forces to be in equilibrium. F must also pass through the implement attachment pin a. With the directions of the three forces thus established, if the magnitude of R is known, then a force triangle can be constructed and values for V and F found.

Forces F and V are dependent on the design of the linkage. The magnitude and direction of force F will be altered by moving the location of the pin a, but will not be influenced by the location of the tractor to lower link attachment, pin c.

3.2. *Rigid top link and unconstrained lower links*

In this arrangement the implement is mounted on a three point linkage which is free to move in the vertical plane, and is supported by a wheel at the front (*Fig. 3*). The point of

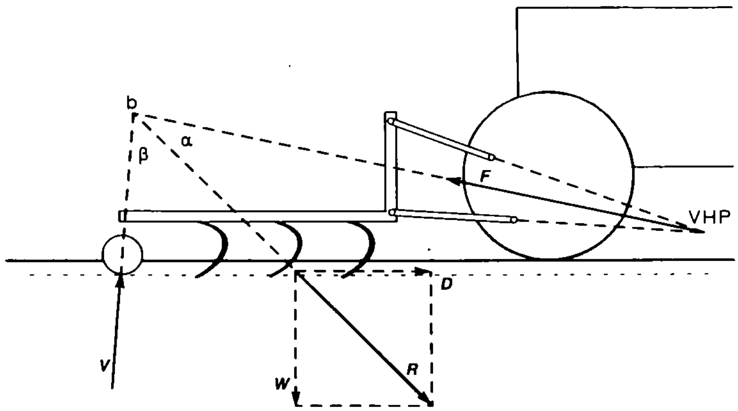

Fig. 3. External forces acting on a front mounted implement with unrestrained links

convergence of the top and bottom links is the instantaneous centre of rotation of the implement (ICR).

R is the resultant of the horizontal soil force *D* and the net vertical soil and gravitational force on the implement *W*. Since the links of the hitch are freely pivoted at both ends and are unrestrained, any forces arising in them must pass through the end pivots and be concurrent at the ICR. They may thus be represented by a single force *F* acting through the ICR.

The implement now has three forces acting on it, *R*, *V* and *F* which at equilibrium must all be concurrent at b. Since *F* passes through the ICR this point may also be regarded as a virtual hitch point.

With this system therefore, the geometry of the top and lower links in the vertical plane determines the location of the ICR which, in turn, determines the direction and magnitude of the force *F*.

4. Relationship between *V*, *R* and the location of the ICR

The resultant force *R* and, within the limits of assumption in this analysis, the line of action of wheel support force *V* are both unaffected by the geometry of the hitch. However, the magnitude of *V* depends on the line of action of the resultant force *F*, which is determined by the hitch geometry and is therefore under the control of the designer. Too large a value of *V* reduces the potential tractive capacity of the tractor, while a negative value (not possible in practice) indicates that the implement cannot penetrate and the linkage is unstable in that position.

Fig. 4 illustrates the relationship between *V*, *R* and *F*. For a given soil/implement situation, *R* and β may be regarded as given. The support force *V* is a function of α, the angle between *F* and *R*.

From the geometry of the triangle

$$\frac{V}{\sin\alpha}=\frac{F}{\sin\beta}=\frac{R}{\sin[180-(\alpha+\beta)]}=\frac{R}{\sin(\alpha+\beta)}$$

Therefore

$$V=\frac{R\sin\alpha}{\sin(\alpha+\beta)} \tag{1}$$

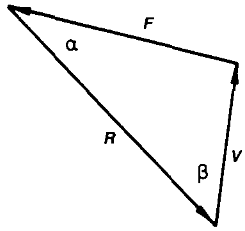

Fig. 4. F, V and R may be represented by a triangle of forces

and

$$F = \frac{R \sin \beta}{\sin (\alpha + \beta)} \tag{2}$$

Assuming for any given situation that R and β are constant, the reaction of the support wheel V is a function of α, which is determined by the choice of the location of the ICR. *Fig. 5* illustrates how V varies with α. When α is zero, that is when the ICR lies along R, V is zero. As α increases, V increases up to $180° - \beta$. Between $180° - \beta$ and $180°$, V is negative, which indicates that the support wheel will tend to lift and the implement and linkage will be unstable. For α beyond 180° the cycle repeats itself. *Fig. 5* also illustrates the zones of location of the ICR for stable operation.

Eqn (1) shows that the support force V depends on angle α, and it will be the same for all points on straight lines emanating from the point of intersection b. This is illustrated in *Fig. 6.*

For a free linkage to support the implement totally without the need for a support wheel the ICR must be located along the line of action of R.

5. Stability

Fig. 7 shows two stable zones for the location of the ICR, namely d and e, and two unstable zones, f and g. If the ICR lies to the left of the line of action of R, the moment

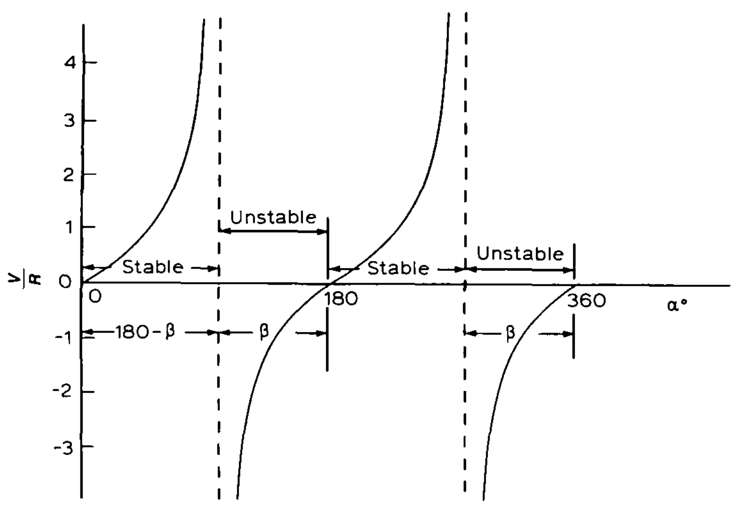

Fig. 5. Illustration of the range of α for stable operation

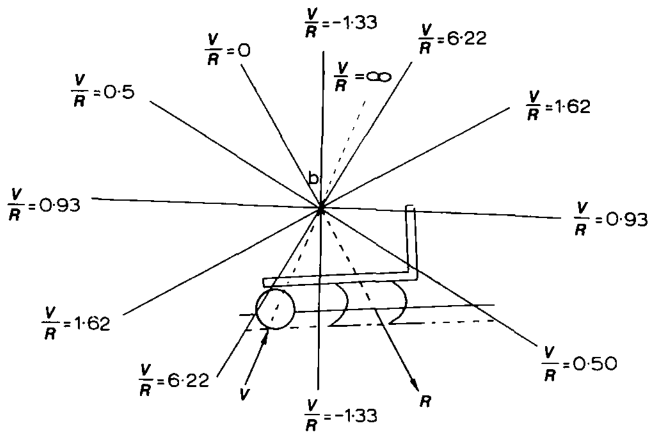

Fig. 6. Illustration of typical values of $\frac{V}{R}$ *as determined by location of ICR*

exerted by *R* about the ICR is clockwise, and for an ICR to the right of the line it is anti-clockwise. If the ICR lies to the left of the line of action of *V*, the moment exerted by *V* about the ICR is anti-clockwise, and for an ICR to the right of the line it is clockwise. Thus, in stable zones d and e the moments counter-balance each other. In unstable zone f they combine to produce an anti-clockwise couple which results in the implement adopting a tail high position. In unstable zone g the moments combine in a clockwise direction to produce tail down instability. In the latter case the tractor attempts to climb over the implement. It is necessary, therefore, in practice, to ensure that the ICR is located sufficiently far from the boundary lines to eliminate the possibility of its crossing into a zone of instability. This can occur with implements of different mast height, weight, and draft force.

Although this analysis defines a necessary condition for stability it does not explore the situation consequent to a movement of the linkage. For example, as soon as the

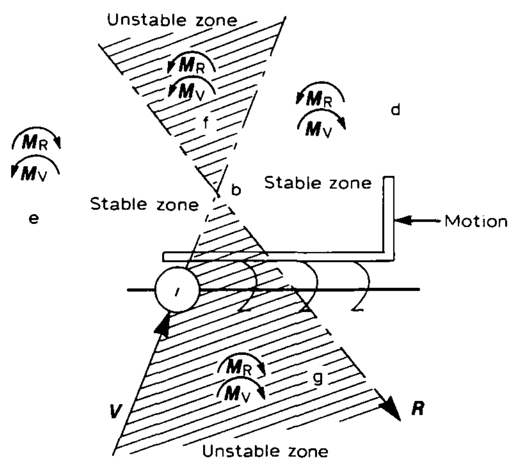

Fig. 7. Illustration of stable and unstable zones for the location of the ICR of the implement

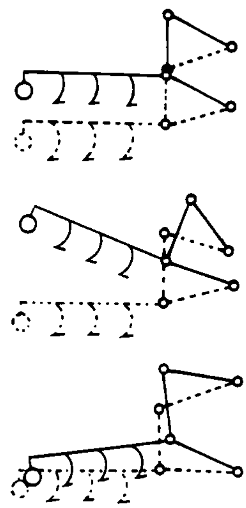

Fig. 8. Effect of linkage configuration on implement clearance in the raised position

implement begins to move large changes can take place in R, particularly its vertical component, and the zones of stability will alter. Similarly the location of the ICR moves after the implement has been displaced. For example, when the ICR is in zone g it will move down away from b as the implement moves, and similarly when it is in zone f it will move up away from b. A full analysis of these situations is beyond the scope of this paper.

6. Ground clearance in the raised position

When the linkage is parallel, the implement is lifted parallel to the ground and clearance is constant along the length of the implement (*Fig. 8*). If the links converge rearwards then the front of the implement is raised more than the rear, the amount depending on the degree of linkage convergency. Such convergence will also reduce the lift capacity of the linkage. Convergence forwards of the links causes the rear of the implement to be lifted more than the front and results in problems of clearance at the front of the implement.

7. Angle of entry into work

To aid rapid entry of a soil engaging implement to full working depth, the implement should be lowered onto its points. This is easily achieved with a rear mounted implement with linkages that converge forwards to the ICR. With front mounted implements, however, with the ICR to the rear, the implement is lowered onto its heel rather than its points (*Fig. 8*), and must rely on its weight to pull it into work.

The requirements for the angle of entry conflict with those for clearance in the raised position and could be most easily solved by a linkage in which the length of the top link could be varied as the linkage is raised.

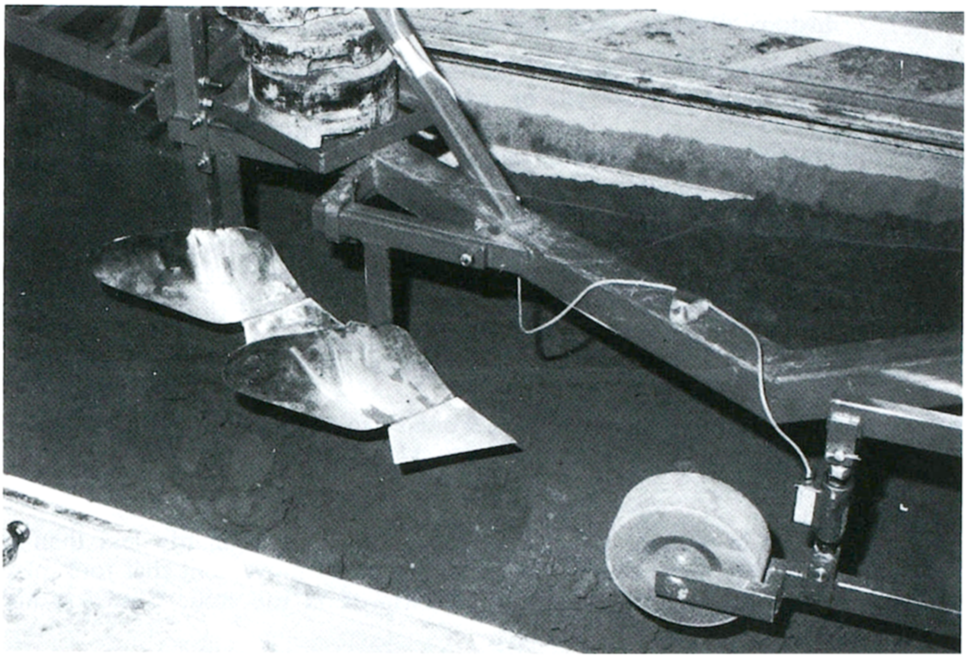

Fig. 9. Experiments were conducted with a half scale plough in the soil tank

8. Experimental verification

In order to verify the theoretical analysis a series of tests was carried out with a half scale mouldboard plough in the Silsoe College soil tank (*Fig. 9*). The plough was mounted on a linkage whose geometry could be adjusted over a wide range. The front depth wheel was instrumented so that force V could be measured. The linkage was attached directly to a sub-frame which was mounted on the soil tank carriage unit through a single octagonal ring dynamometer. This dynamometer enabled the magnitude and position of the resultant force acting in the longitudinal-vertical plane to be established.

R was initially determined by removing the front depth wheel and restraining the linkage to hold the implement at the correct depth. Separate experiments were carried out to determine the coefficient of rolling resistance of the support wheel to establish the angle of V to the vertical. From this information it was possible to determine angle β. Subsequent experiments were carried out at the same depth and speed.

Since R and β remain constant for a given plough depth and speed, irrrespective of the hitch geometry, predictions of the value of V can be made for various linkage configurations using Eqn (1).

A series of tests was conducted with the linkage unrestrained. V was measured experimentally and compared with its predicted value.

9. Experimental results

Tests were carried out with the linkage in 14 different configurations. The locations of the ICR in each case are illustrated in *Fig. 10,* and the results are summarized in Table 1.

Reasonably good agreement was obtained between the predicted and experimental

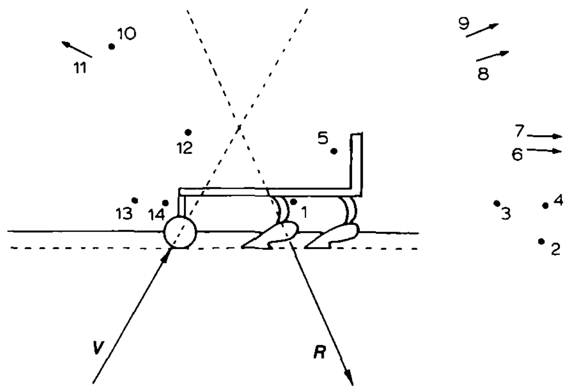

Fig. 10. Illustration of the different locations of ICR of the implement as used in experimental work. The results are summarized in Table 1

values of *V*, though in general the actual values of *V* were slightly less than those predicted. This probably arose due to the inevitable slight movement that took place at the linkage between its position when being measured in the static condition and its position when pushing the plough.

In tests 10, 13 and 14, the linkage was found to be unstable, although the respective ICR's were to be found in the stable zone e (*Fig.* 7). In the case of 13 and 14, the ICR approached rather closely to the boundary line through *V*. Any slight rearward tilting of the plough causes the linkage to lower and the ICR to come into the unstable zone g. The linkage then collapses with the implement tail down. In case 10, any slight forward tilting of the plough causes the ICR to move upwards and cross into unstable zone f. The linkage then collapses with the tail of the implement up.

A similar case of instability was found in the field with a full scale chisel plough mounted on the front of the tractor with a forward converging linkage.

Table 1

Comparison of predicted and experimental values of depth wheel support force *V*

Test no.	*Angle α, deg*	*Predicted V, kN*	*Actual V, kN*
1	8	0·37	0·29
2	45	1·56	1·38
3	50	1·70	1·50
4	51	1·78	1·53
5	52	1·80	1·10
6	61	2·27	1·99
7	65	2·28	1·97
8	82	3·02	2·50
9	87	3·54	2·48
10	215		Unstable
11	219	1·43	1·62
12	252	2·61	2·89
13	281		Unstable
14	292		Unstable

10. Operation with restrained links and automatic control

One alternative approach to controlling the depth of the implement is to remove the support wheel and restrain the lower links, in the same manner as with draught or position control for rear mounted implements.

Such an arrangement would give added vertical load on the tractor and improve overall tractive efficiency. If the depth of the implement was to be controlled by a draught control system, it is interesting to consider whether any special problems would arise. Draught control systems usually sense the force in the top link or the combined force in the lower links. *Fig. 11* shows the external forces acting on the implement.

The force exerted by the top link (in the absence of vertical acceleration) is

$$U\cos\theta = \frac{Wx}{h} + \frac{Dy}{h} \tag{3}$$

Since

$$D + U\cos\theta = L$$

$$L = D\left(1 + \frac{y}{h}\right) + \frac{Wx}{h} \tag{4}$$

With rear mounted ploughs the equivalent equations are:

$$U\cos\theta = \frac{Dy}{h} - \frac{Wx}{h} \tag{5}$$

and

$$L = D\left(1 + \frac{y}{h}\right) - \frac{Wx}{h} \tag{6}$$

Thus the forces in both the top and lower links are greater with front mounted implements than with similar rear mounted implements.

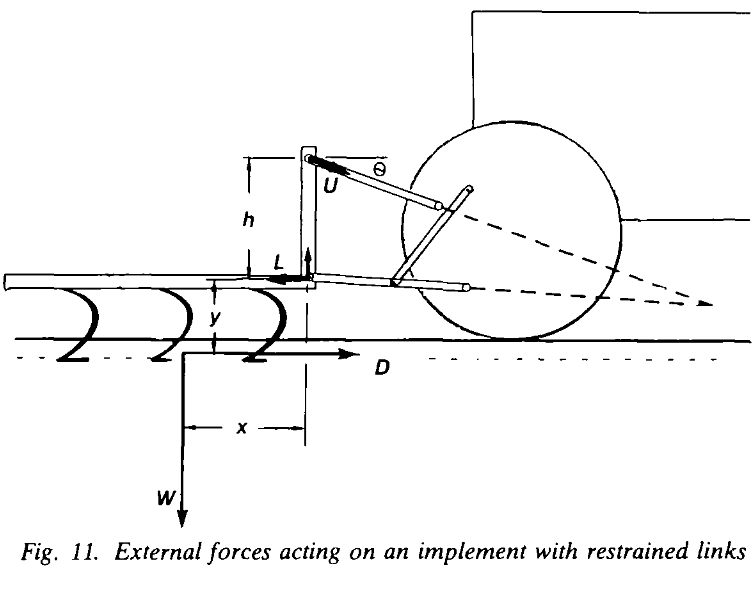

Fig. 11. External forces acting on an implement with restrained links

For top link sensing, the sensitivity to a change in draft force is given by

$$\frac{\partial(U\cos\theta)}{\partial D}=\frac{y}{h}\quad\text{(typically 1, since } y\simeq h\text{)}\tag{7}$$

and for lower link sensing by

$$\frac{\partial L}{\partial D}=1+\frac{y}{h}\quad\text{(typically 2)}\tag{8}$$

These sensitivities are the same for both front and rear mounted implements. However, since the linkage forces are much greater in the front mounted case, the changes occurring due to draught or depth variations represent a much smaller percentage of the total sensed force.

11. Conclusions

The analysis in this paper relates to soil engaging implements mounted on a three point linkage on the front of a tractor, operating as a free linkage with depth wheel, or with a non-rigid top link and restrained lower links.

For stable operation in these cases, the location of the instantaneous centre of rotation (ICR) must be arranged so that the implement is trying to penetrate but is held at the working depth by a support wheel running on the ground surface or by restraining the lower links. In the case of a non-rigid top link the instantaneous centre of rotation is replaced by the point of attachment of the lower links to the implement.

Two zones may be identified for the location of the ICR in which the linkage becomes unstable. They are bounded by two straight lines which intersect at a node b above the implement, one lying along the line of action of the support force offered by the depth wheel and the other lying along the line of action of the resultant soil and gravitational force acting on the implement. These zones lie in the regions generally above and below the implement.

If the ICR is located in the unstable zone above the implement, then as the tractor moves forward the linkage collapses in nose-dive mode. If the ICR is located in the unstable zone below the implement, the linkage collapses in the tail-down mode.

The load carried by the support wheel depends on the location of the VHP within the stable zones, more particularly, the angle α made by the line joining the ICR to the node of intersection b. The smaller the angle α, the less is the support force generated by the support wheel.

The load carried by the depth wheel represents a reduction in the potential load carried by the tractor wheels, so the greater it is the less the overall tractive efficiency.

The location of node b depends not only on the position of the support wheel but also on the weight of the implement and the soil forces. It is important, therefore, to ensure that the ICR is placed sufficiently far away from the anticipated zones of instability to preclude the possibility of linkage collapse.

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