DYNAMIC PROBLEMS OF HITCHING MOUNTED PLOUGHS

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The linkage of the mounting equipment transfers the forces acting on a plough in work onto the tractor, and accordingly the correct setting of the plough also has an influence on the dynamic equilibrium of the plough itself. The investigation of the plough can usually be based on the average forces with which the constructed equilibrium of a simple swing-plough demonstrates the main points of the investigation (Fig. 1).

To the weight E, acting in the centre of gravity, we add the vertical component of the average soil reaction force and the frictional resistance at the landside. The resultant of these forces is the P_1 force, which would turn the plough around the hitching point with a moment $M_1 = P_1 p$. Because the hitch point, as a link, is not able to transfer a moment, the equilibrium of the plough is accomplished by using the force K, which acts on the sole, and whose $M_2 = K . k$ moment is in the case of equilibrium always equal to the moment aforementioned. The force K is, therefore, the function of the M_1 moment and as this M_1 is, furthermore, the function of the position of the hitching point, a suitable dimensioning of the hitching is very important from the view-point of the tractor performances.

The hitching point must be positioned in such a way that it should have, also in the worst circumstances, a minimal M_1 moment, which keeps the plough in the soil, but the K reaction force should not be too great.

The equilibrium in the horizontal plane may similarly be constructed where the R_{xz} component of the soil reaction force has a moment $M_3 = R_{xz} z$ on the hitching point. This is counterbalanced by the moment of the landside $M_4 = Cc$. The side force is, therefore, also the function of the hitching point position.

As in the three-point linkage the hitch point is movable at will, the desired force distribution on the plough may be realized by an adequate arrangement of the links. A detailed analysis of the forces is shown on a free mounted plough on a three point linkage (Fig. 2).

Let us first regard the equilibrium of the plough in the vertical plane which lies in the travelling direction. Adding the R_{xy} component to the weight of plough E, and then to this the friction of landside and sole, one gets a partial resultant, whose influence line intersects the line of the supporting force at the wheel. After adding these we obtain the resultant of the vertical forces acting on the plough, which must always go through the π_1 pole, named the virtual hitch point. For ploughs without wheel, the support is made by the sole. The free mounted plough penetrates into the soil only if the partial resultant of weight, soil resistance force and friction goes over the π_1 pole, namely, it has a clockwise moment (on Fig. 2). This moment forces the plough to pene-

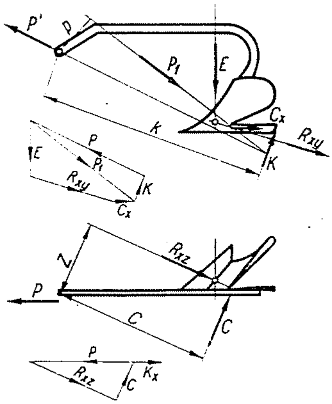

Fig. 1. Forces, acting on a simple swing plough on the vertical and horizontal plane of travel

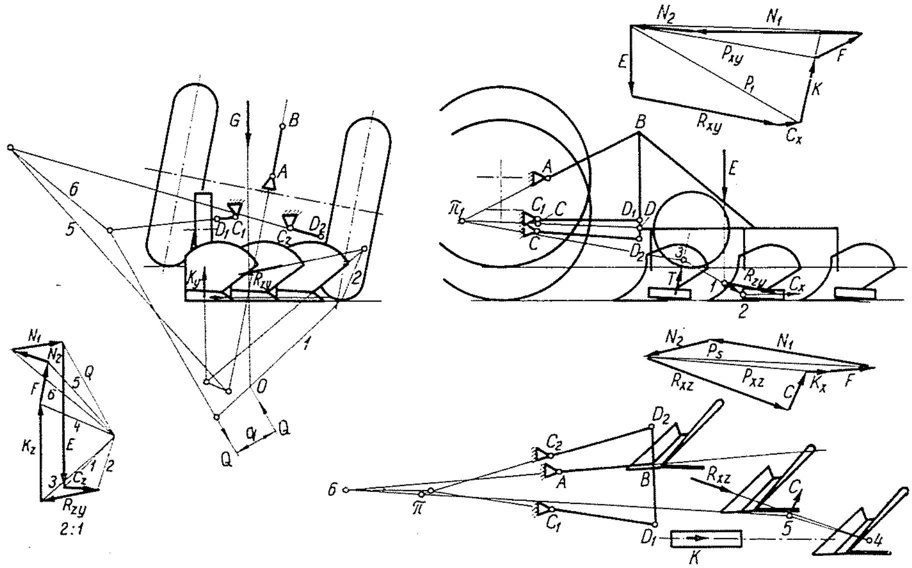

Fig. 2. Investigation of the forces acting on a plough, mounted with a three-link-hitch, by force and catenary polygons

trate into the soil and it always raises a support force with which the influence line of the tractive force will go through the virtual hitch point and in this way the condition of equilibrium will be realized.

The tractive force, acting on the virtual hitch point, is transmitted to the tractor by the three-point linkage and may easily be decomposed into the three directions of the linkages.

In the horizontal plane the construction may be similarly done. To the R_{xz} soil reaction force we add the rolling resistance at the wheel and the side force at the landside. The moment of the P_2 resultant, arrived at from the soil reaction force and the rolling resistance, is counterbalanced by the moment of the C side-supporting force at the landside. The value of the C force is, therefore, the function of the moment of the P_2 on the π_2 pole. In that case when the values of soil reaction and soil resistance are constants, the value of the force C may be changed also transferring the π_2 pole (by turning the hitching axle of the plough). If on the horizontal projection the direction of the upper link does not cross the π_2 pole, then we bring the P_{xz} resultant to meet the direction of the upper link and the line which connects this point of intersection with the π_2 pole is regarded as a Culmann auxiliary line and by this the resultant can be decomposed to the desired directions.

After constructing the force polygon in the vertical and horizontal plane of travel, we may also draw the projection of forces in the plain perpendicular to them, with which the values of the forces in the connecting rods can be determined. This is made more practical by drawing a catenary polygon with the forces got in the previous drawings. (On the figure the scale of forces was duplicated to the previous falls.)

We add to the E weight of the plough, acting in the centre line, the C_z projection of the side supporting force and the R_{yz} component of the soil reaction. Further, the establishment of the forces in the links and at the wheel will be determined with a force polygon, knowing the directions of the forces.

In the case of a closed force polygon, however, quite often the catenary polygon remains open. This means, that in the vertical plane perpendicular to the direction of travel there is a counter-clockwise resultant moment, whose value is determined by the product of A catenary force and q distance. This moment which is transferred onto the tractor with the hydraulic linkage, not drawn in the figure, enlarges the land side loading of the tractor reducing the, by the slope of the tractor already lessened, land side wheel load.

To completely estimate the forces in the linkage we have to make a construction in all three planes. As the pull of a plough and the tractor wheel loadings are mainly determined by the force distribution in the vertical plane of travel, for the study of the additional loadings of the driving axle, a construction in this only plane is sufficient. A hitch with controlled plough is analyzed on such a simplified sketch (Fig. 3).

The effect of a hydraulic control may best be seen then, when first we make a construction with a π pole, which is the intersection of the directions of the upper and lower links. According to what had been done before, we can get the value of supporting force K. If we want to diminish this force employing a hydraulic control, the influence line of the P' force has to be more inclined. The moment, which results from the difference of the two

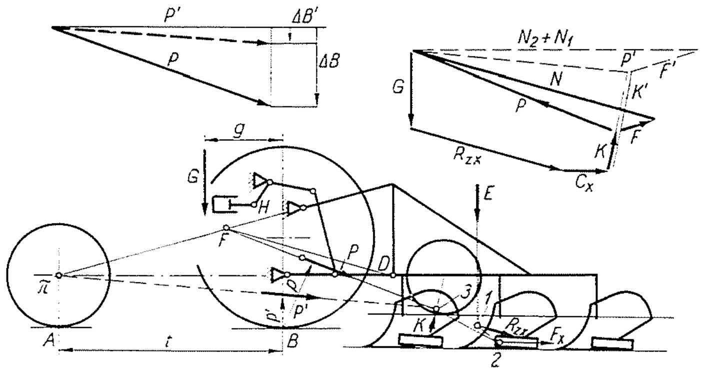

Fig. 3. Presenting the effect of plough control in a force polygon

moments $M = P'p' - Pp$ may be used for the additional loading of the driving axle. Estimating the forces in the hydraulic controlled rods, the influence line of the P tractive force will intersect the direction of the upper link and this point will then be connected with the D hitching point between the lower links and the plough. The P force will then be decomposed into the mentioned FD line and the direction of the upper link.

The force- and position-controlled hydraulic equipments work according to this principle. In the force-control system, where the plough works without the supporting wheel, the depth of ploughing is controlled by the pressure of a spring located in the upper link. The pressure of the spring is increased by the tractive force, consequently a deeper ploughing will be greater. At the various antislip equipments the depth control is governed by a gauge wheel, but the pressure in the hydraulic cylinder, which is less than that needed to lift the plough, lessens the supporting force at the wheel, and so with a part of the forces acting on the plough, the loading of the driving axle is increased.

The graphical analysis of the hitching shows that by laying the position of the hitch point backward, the additional load of the tractor driving axle may be increased. This can be realized by two means, namely, making the upper or the lower link more inclined. The resulting effect is the same in both cases and it is possible to achieve this also by making the beam of the plough shorter. However, this last requirement is already fulfilled by another point of view, stability.

The increase of tractive efficiency has its reason in a more inclined tractive force, but this is limited by the excessively lessened supporting force, at which the plough comes out of the soil. Another limiting factor is the unloading of the first axle. Writing the following equation, the maximal distance between the contact point of the rear wheel with the soil and the influence line of the tractive force may be determined (Fig. 4):

$$M_B = At + PP - Gg = 0$$

from where:

$$P_{\max} = \frac{Gg - A_{\max} t}{p_{\max}}$$

can similarly be calculated at the given conditions of minimal distance too,

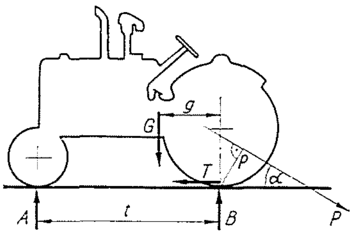

Fig. 4. Study of influence lines of forces acting on the tractor

which is needed for a certain tractive force, if we join the resistances and the peripheral force into a single equation:

$$Gf + P\cos\alpha + fP\sin\alpha = T = KB$$

$$Gf + P\cos\alpha + f\sin\alpha = K\left[G\frac{t-g}{t} + P\frac{P}{t} + P\sin\alpha\right],$$

from which:

$$P_{\min} = t\left[\frac{\cos\alpha - K\sin\alpha}{K} - \frac{G}{P}\left(\frac{t-K}{t} - \frac{f}{k}\right)\right].$$

For a given motor HP, the tractive efficiency of an universal tractor is determined by the loading of the rear wheels and the K coefficient of traction. Introducing a $\lambda = \frac{A}{B}$ coefficient, which gives the weight distribution on the axles, we can get a direct relationship between the dinamic weight distribution and the tractive efficiency.

The rolling efficiency may be calculated as follows:

$$\eta_g = \frac{P}{T} = 1 - \frac{P_g}{T} \quad (T = kB),$$

where

P = horizontal force on the drawhook,
T = tractive force depending on the load capacity of the soil,
P_g = rolling resistance,
B = vertical loading of the driving axle,
k = coefficient of traction for the wheel.

With additional load to the drive axle (ΔB), the rolling efficiency will be different too:

$$\eta_g' = 1 - \frac{P_g + f\Delta B}{T + k\Delta B}.$$

The loss, as a result of the slip at the driving wheel, may be calculated according to Svirchevskij with the following expression:

$$\eta_s = 1 - a\frac{P}{G} - b\left(\frac{P}{G}\right)^c,$$

where

G = the weight of the tractor,
a, b, c = empirical constants.

Adding the mechanical efficiency to these two losses, the tractive efficiency may be calculated as the product of the three efficiencies

$$\eta_v = \eta_M\left[\frac{P}{T}\left(1 - a\frac{P}{G} - b\left(\frac{P}{G}\right)^c\right)\right].$$

Economic operation allows only a minimal slippage, when the straight starting part of the slip curve may be regarded and according to this, the last member of the expression is to be neglected:

$$\eta_v = \eta_M\left(\frac{P}{T} - a\frac{P^2}{TG}\right).$$

Expressing the forces with the axle loads:

$$\eta_v = \eta_M\left[\frac{kB - f(A + B)}{kB} - a\frac{(kB - f(A + B))^2}{kB\,(A + B)}\right],$$

and then dividing both numerator and nominator, at the first member with B, at the second with B^2:

$$\eta_v = \eta_M \left[1 - \frac{P}{K}(1+\lambda) - a\,\frac{(k-f-\lambda)^2}{k(1+\lambda)} \right],$$

we may express the tractive efficiency as a function of the axle load distribution, assuming, that the mechanical efficiency and the coefficients of rolling and traction are constants.

Differentiating the function of efficiency according to λ we can get at the zero value the optimal λ, at which the resulting efficiency has a maximum

$$\lambda_{\text{opt}} = \frac{k}{\sqrt{f^2 + \frac{f}{a}}} - 1\,.$$

Substituting into the function of η_v the $\lambda = 0$ and $\eta_v = 0$ values, we may also draw the $\eta_v = f(\lambda)$ function. And since the tractive performance is

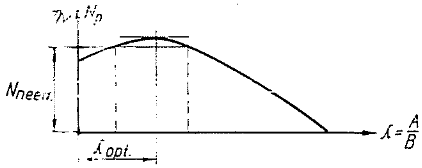

Fig. 5. The possible traction power in the function of the axle load distribution

the product of the motor output and the tractive efficiency, we may also draw the tractive performance in the function of the axle load distribution, $N_P = f(\lambda)$ (Fig. 5).

Making use of the quotient of the front and rear axle loads, we may also express the theoretically possible tractive performance as the function of the position of the hitching point. To express this, let us examine the forces

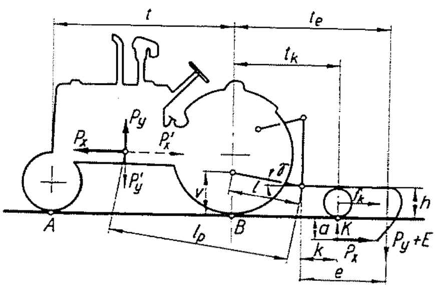

Fig. 6. Analytical method for the investigation of the axle load distribution

acting on a mounted plough with support wheel and without hydraulic control (Fig. 6).

Let us write the moments of the forces, acting on the plough, on the contact point of the support wheel and the soil. (We take the application point of the soil reaction force in the centre line of the plough and we neglect the rolling and sliding resistances.)

$$M_K = P_y(e - k) - P_x a + P_y(k + l_p \cos\gamma) - P_x(h + l_p \sin\gamma) = 0$$

from where:

$$P_y = P_x \frac{a + h + l_p \sin\gamma}{e + l_p \cos\gamma} .$$

Similarly writing on the contact point of the rear wheel of the tractor the moment of the forces acting on the tractor:

$$M_B = P'_x (h + l_p \sin\gamma) - P'_y (l_p - 1) \cos\gamma = 0$$

in which substituting one of the previously obtained forces $|P'_y| = |P_y|$

$$M_B = P_x\left[(h + l_p \sin\gamma) - (l_p - 1)\cos\gamma \frac{a + h + l_p \sin\gamma}{e + l_p \cos\gamma}\right],$$

the change of the M_B moment may be expressed as the function of the l_p distance to the π pole at a constant P_x horizontal force. Representing the M_B function, we get a hyperbola, but the λ in the function of l_p is a hyperbola, too. We can, therefore, join the two diagrams with the help of l_p. Increasing the value of l_p, λ decreases and intersects the abscissa axis when the front axle is zero, as a result of M_B. Comparing the diagrams of λ and M_B it can be established that with increasing P_x and the resultant of the vertical forces, the zero point of the function will be removed to the greater values of the l_p pole distance and that the decrease of the wheel distance has the same effect.

If we draw the change of the tractive performance in the function of λ also beside the previous one, we get a direct relation between the theoretical possible tractive performance of the tractor and the weight transferring effect of the mounted plough. The maximum of the performance curve gives the optimal value of λ_t, with which the best M_B moment may be determined (Fig. 7).

Let us analyse, on a numerical example, the different effects of a free and controlled mounted plough on the performance of the tractor to show the advantage of the hydraulic control system.

The possible peripheral force of the wheel is, in a limitation case, equal to the tractive and rolling resistances:

$$T = P_x + V_g .$$

The peripheral force is the product of the dynamical wheel loading and the coefficient of traction, whose value on heavy land may be 0.4—0.5 at a slip of 15—20% and the rolling resistance is taken into consideration in both cases with 15%.

The values, determined by a six-component non-planar balance are taken as the basis of the tractive resistance, to eliminate the effect of the

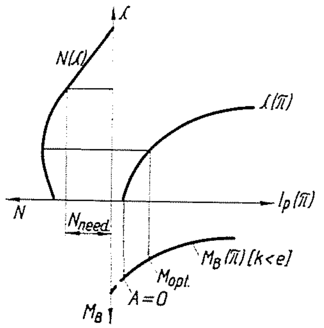

Fig. 7. The relationship between the traction power, axle load distribution and the axle load transferring moment M_B

plough construction. Dividing the horizontal component of the soil reaction by the cross section of the furrow $p_x = \frac{P_x}{F}$, we get the specific soil resistance, which is independent of the plough construction. At the same time the quotient of the section of the furrow gives the specific plough resistance $P = \frac{P}{E}$, which is influenced not only by the construction, but also the condition and setting of the plough.

Comparing the different systems of mounted ploughs we can take the p_x as the starting point of the investigation, which has a value of 15—30 on light, 20—50 on middle and 45—60 kg/dm^2 on heavy soils. The weight of the tractor is uniformly taken as 2,000 kg, the weight of the plough 380 kg, and the coefficient of traction $k = 0$.

At a free — during work from the hydraulic independent — mounting system, the moment around the virtual hitch point is counterbalanced by the force of the sole. The support wheel has a loading only at the sinking of the sole. If the force at the support is great, the additional loading of the drive axle lessens, therefore, at this comparative investigation we took the force at the wheel as zero and the frictional resistance at the landside as $C_x = 40$ kg in both cases. The vertical component of the soil reaction also influences the load of the driving wheel, and if we take, to make the calculation simple, this force for each sock as 25 kg, we get at the controlled system, capable for greater tractive performances, a less inclined influence line for the resultant of the soil reaction.

Finally let us assume that the investigation is made at the limit of the tractor's tractive performance with a differential locking device, consequently the furrow and land side wheels are able to produce the same peripheral force (Fig. 8).

Taking the contact point of the soil reaction as the centre line, the influence line of the received resultant passes in controlled system through the contact point of the plough and the lower links, in the independent system,

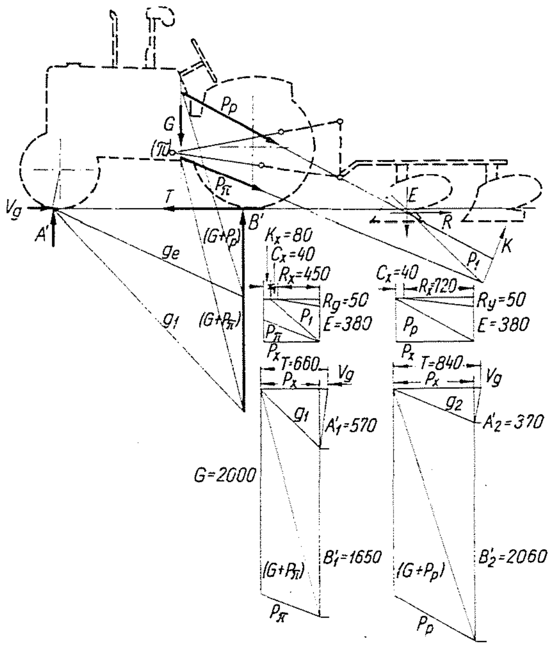

Fig. 8. Graphoanalytic comparison of the free and hydraulic-controlled mounted ploughs

however, also regarding the supporting force, through the virtual hitch point. Knowing the vertical loading of the plough ($E + R_y$) and the influence lines of the forces, the construction of the force polygon gives a horizontal soil reaction of $R_{x1} = 450$ kg in the free, and $R_{x2} = 720$ kg in the controlled system. We may, taking into consideration the rolling resistances, also draw the polygon of the forces acting on the tractor, which gives the dynamic axle load distribution. The line, which cuts out in the force polygon the axle load distribution is obtained, connecting the intersection of the resultant of tractive force — tractive weight and the influence line of the supporting force in the driving wheel, with the contact point of the first wheel and the soil.

According to the design, the static load of the driving axle ($B = 1{,}260$ kg) has been increased by the free mounted system to a dynamical axle load 31% greater ($B_1 = 1{,}650$ kg), while at the hydraulic control, the increase was 63.5% ($B_2 = 2{,}060$ kg). Under the same conditions the maximal tractive force is 27% greater, which enables, assuming a 20 cm deep and 60 cm wide ploughing, a tractor, which reached without hydraulic control its limit of tractive performance upon a soil of $p_x = 37.5$ kg/cm^2 specific resistance, will be able to plough controlled on a soil of $p_x' = 60$ kg/cm^2 specific resistance and *that means a 60% increase of the tractive force.*

Furthermore, it is possible, knowing the dynamic axle load distribution, to determine also the minimal tractor weight required to for ploughing in the future, the weight of the tractor can be regarded as the function of the furrow cross-section.

Assuming a k coefficient of traction and introducing three factors the dynamic weight of the tractor may be expressed as a function of the furrow cross-section:

$$G_{\text{whole}} = \frac{p_x F a}{\beta \varkappa \gamma},$$

where

p_x = specific soil resistance,
F = furrow cross-section (given by the agriculture),

$$a = \frac{T}{R_x},$$

(which indicates the advantage, provided by the total or partial mounting)

$$\beta = \frac{B'}{B},$$

(quotient of the loading of the rear axle at stillstand and work, — which shows the difference between the free and controlled systems)

$$\gamma = \frac{B}{G_T} \sim 0.625,$$

(quotient of the static drive axle load and the weight of the tractor, — a factor, which represents the position of the centre line).

The expression made from the factors gives a linear relation between the weight of the tractor and the horizontal component of the soil resistance force:

$$\frac{G}{R_x} = \frac{a}{K\beta\gamma},$$

from which the corresponding tractor weight for given p_x values can always be calculated for the desired furrow cross sections (Fig. 9).

The (α, β) factors in the expression are obtained graphically. According to the construction shown in Fig. 8, with $k = 0.4$, the values of the factors are in the free system $\alpha = 1.47$, $\beta = 1.4$; in the controlled: $\alpha = 1.17$, $\beta = 1.64$.

The minimal tractor weight with socks ($F = 6\ cm^2$), on heavy soil ($p_x = 60\ kg/dm^2$) comes to about 1,620 kg in the free, and 980 kg in the controlled

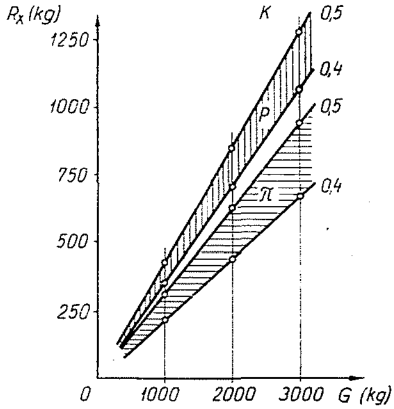

Fig. 9. The relationship between the weight of the tractor and the soil resistance force at the limit of ploughing possibility

system. Therefore, for ploughing economically, with the most common two-furrow plough, a total weight of 3,240 kg, respectively 1,960 kg is needed (plough, driver incl.), which shows, that the further decrease of tractor weight — required from the point of view of agriculture — may be realized by using an adequate control system.

Summary

The graphoanalytic investigation of the free and hydraulic-controlled mounted ploughs shows that the hydraulic control profoundly improves the traction power of universal tractors. The method based on expressing the load transferring effect of hitching is completed by a numerical example.

Literature

1. GALAMBOS, J.: Az egyetemes traktorok vonóképességének növelése függesztett munkagépekkel. Mezőgazdasági Gépesítési Tanulmányok 1961 No. 6. Mezőgazdasági Kiadó, Budapest.
2. GETZLAFF, G.: Über die Bodenkräfte beim Pflügen bei verschiedener Körperform und Bodenart. Grundlagen der Landtechnik. Heft 3 (1952)
3. SKALWEIT, H.: Über die gegenseitige Abhängigkeit von Schleppergewicht und Pflugfurche. Landtechnische Forschung **11**, 1 (1960)
4. ГУСЯЦКИЙ, М. Л.: Некоторые основные вопросы теории навесных агрегатов. Механизация и электрификазия социалистического сельского хозяйства. **2** (1956)

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