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Evaluation of Turnability of Tracked Vehicle

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Abstract

Rice combine harvester is one of the typical agricultural machines developed in the process of rice production in Japan. Recently 5 kinds of turning methods have been introduced in which 3 of them have already been applied to commercial machines while the other 2 are subjected to experimentation for future commercialization. In this paper, the turning methods were evaluated from different viewpoints in terms of smooth turning with less energy and less disturbance of the top soil in paddy fields with emphasis placed on (1) energy conservation, (2) safety and (3) automation.

Discipline: Agricultural machinery
Additional key words: rice cultivation, top soil disturbance, operation efficiency, harvesting operation, turning method

Introduction

Various types of tracked vehicles are used not only in agriculture and forestry but also in the field of construction machinery and military operations because of their outstanding mobility and maneuverability especially in rough terrain. Current trend of tracked vehicle is characterized by the use of rubber track equipment which is environment-friendly. This condition is important for practical applications in agricultural machines such as rice combine harvester and construction vehicles like bulldozers and excavators.

Turning methods that are currently used can be classified into 5 systems:

(1) Pivot turn system

In this system, the vehicle turns with one track being operated while the other is not operated and/or braked. Both tracks are in full contact with the ground surface (no control of contact area of tracks)[7].

(2) Pivot turn system with control

Basically this system is the same as the pivot turn system, except that the contact length with the ground surface of the braked track is shortened to reduce the turning motion resisting moment[2,4,6].

(3) Spin turn

Since both tracks are operated in opposite directions during the turning motion, shortening of the turning radius and completion of the turning motion can be achieved quickly and smoothly. As a consequence however, more power is consumed[1].

(4) Soft turn

This system has been recently applied to commercial machines. Both tracks are operated in the same direction but the speed is different. As a result, the turning radius is larger, but top soil disturbance is reduced when the vehicle is turning[1].

(5) Turntable method

In this system, turning takes place by using a turntable and not by the running gear. Operator's safety can be secured in addition to smooth turning motion. Typical application of this system can be seen in excavators, one of the construction machines[3,5].

Among the turning systems listed above, systems (1), (3) and (4) have already been applied to commercial machines. The other 2 systems (2) and (5) were proposed by the author, but they are not practically applied yet. In this paper, the evaluation of the 2 turning systems which the author proposed was discussed in terms of practical use in agriculture and comparison with pivot turn system as standard basis.

Pivot turn system

As stated earlier, the contact length of the braked track is shortened to reduce the turning motion resisting moment, as shown in the following equation

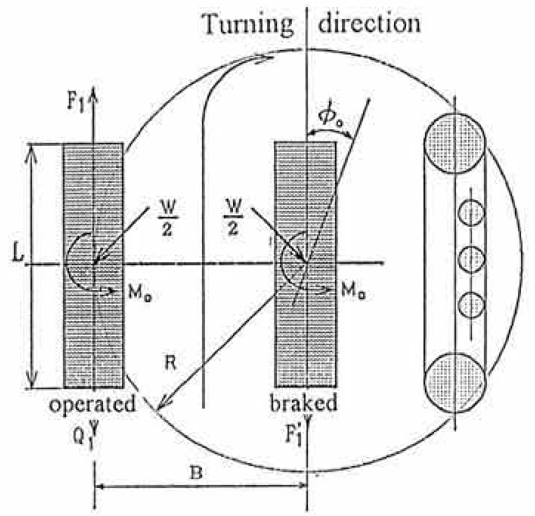

Fig. 1. Conventional pivot turn system without control

for braked track (Fig. 1).

$$M_0 = \frac{1}{4}\mu P_1 bL^2, \quad P_1 = \frac{W}{2bL} \tag{1}$$

$$M_0 = \frac{1}{8}\mu WL \tag{2}$$

where L : ground contact length of braked track (m),
b : ground contact width of braked track (m),
W: load acting on both tracks (N),
μ : coefficient of friction between the track and ground surface,
μ_0: coefficient of rolling resistance of the track,
R : turning radius (m).

Assuming that F_1 is the driving force of the operated track and F_1' is the frictional resistance for the tracks, the rolling resistance of the operated track, Q_1, can be expressed as:

$$Q_1 = \frac{W}{2}\mu_0. \tag{3}$$

For a braked track, the rolling resistance $Q_2 = 0$, since it is not moving. Considering the momental balance at point O, $(F_1 - Q_1) = 2M_0$, then, the driving force required for turning can be expressed as:

$$F_1 = \frac{\mu WL}{4B} + \mu_0\frac{W}{2}. \tag{4}$$

The work required for turning, E_0(J) can be expressed

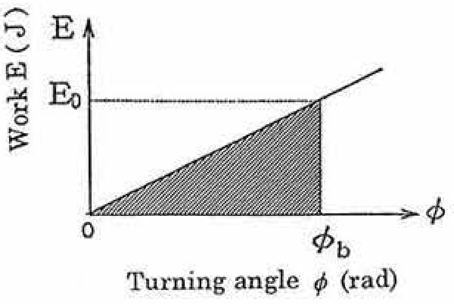

Fig. 2. Relationship between the work requirement and the turning angle for pivot turn system without control

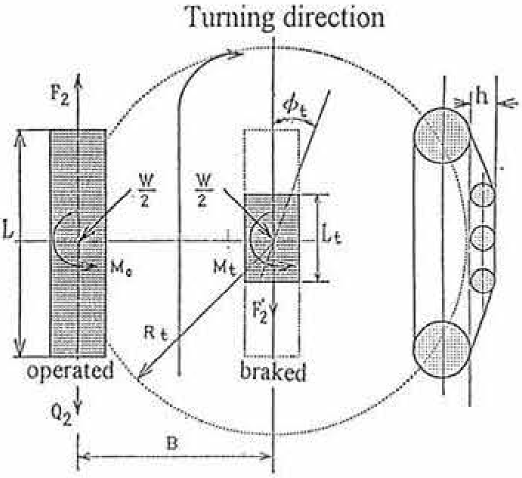

Fig. 3. Pivot turn system with control of contact length of track

by using the turning angle ϕ_0(rad) as follows:

$$E_0 = F_1 R\phi_0 = \left(\frac{\mu WL}{4B} + \mu_0\frac{W}{2}\right)R\phi_0. \tag{5}$$

Fig. 2 shows the relationship between the work required for turning E_0(J) and the turning angle ϕ_0(rad). It can be concluded that the work required for turning increased proportionally with the increase of the turning angle of the track.

Pivot turn system with control

Fig. 3 shows a schematic representation of a pivot turn system with control of the contact length from L to L_t for braked track in turning motion. Turning motion resisting moment under this condition becomes

$$M_1 = \frac{1}{8}\mu W L_t. \quad \dots\dots (6)$$

For the driving force F_1, it is expressed as shown below:

$$F_1 = \frac{\mu W(L + L_T)}{8B} + \mu_0 \frac{W}{2}. \quad \dots\dots (7)$$

The work required for turning in this system E_t(J) can be derived by using the turning angle of track ϕ_t(rad).

$$E_t = \left(\frac{\mu(L + L_t)}{8B} + \frac{\mu_0}{2}\right) W R_t \phi_t + \frac{1}{2} Wh \quad \dots\dots (8)$$

where L_t: controlled ground contact length of track (m),
R_t: turning radius of pivot turn with control (m).

In the above equation, the second term on the right-hand side, (Wh)/2, indicates the work required for lifting the braked track up to the height, h, where the time for this controlled motion was relatively short and the height, h was very small compared to the contact length. Fig. 4 shows the relationship between the work required for turning, E_t(J) and the turning angle of track ϕ_t(rad). It is obvious that in this system, a braked track is controlled to shorten the ground contact length and reduce the turning motion resisting moment. Therefore the work, (Wh)/2, is required as soon as the turning motion starts. However once the turning motion proceeds, the work required increases with a comparatively lower rate than in the pivot turn system previously described.

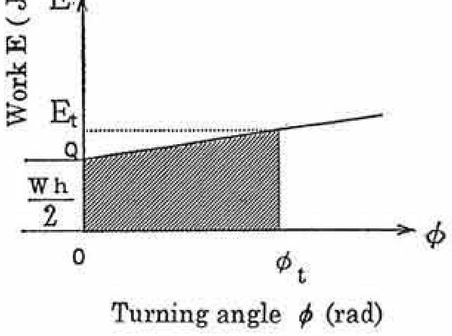

Fig. 4. Relationship between work requirement and turning angle for pivot turn system with control

Comparison between pivot turn system and pivot turn system with control

It was already demonstrated based on the equations presented earlier that the shortening of the ground contact length must be within a limited range sufficient to support the load acting on the braked track to be more effective in reducing the turning motion resisting moment and to improve the turnability of the tracked vehicle. Actual mechanism for practical application was also proposed through the prototype vehicle used in the experiment (Fig. 4).

Pivot turn system with control can be recommended for reducing the turning motion resisting moment. However the additional controlling unit which must be installed will also increase the machine price. Therefore a comparison of the cost/performance of the machines should be made for evaluation. Fig. 5 shows a graph of the relationship between the work required for turning and the turning angle for both pivot turn system and the system with control. Improvement of turnability can be achieved by the following methods: (1) by shortening the length OQ = (Wh/2) in E-ϕ graph as much as possible or (2) by lowering the slope OP in E-ϕ graph as much as possible.

For method (1), either W or h or both W and h must be reduced for actual use. For method (2), controlled ground contact length of track should be minimized as much as possible, which can be mechanically determined using the value of height, h. In Fig. 5, point P is the intersection point of 2 lines of the work graphs of the 2 turning systems (pivot turn and that with control). The turning angle ϕ_b corresponding to the point P indicates the boundary turning angle to determine which turn system should

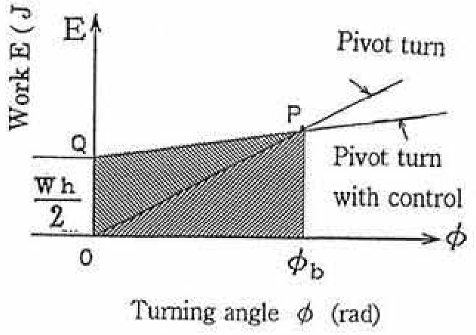

Fig. 5. Comparison of the work between pivot turn system with control and the one without control

be applied.

In conclusion, (a) the pivot turn system can be recommended when the vehicle is turned or steered in the range where the turning angle is less than ϕ_b, however (b) the pivot turn system with control of the contact length should be used when the vehicle needs to turn or to be steered over a range where the turning angle exceeds ϕ_b. The value for the boundary turning angle ϕ_b can be determined by the measurement during the field test for practical application. The equation for estimating the value of the turning angle ϕ_b can be derived as follows: Let 2 equations (5) and (8) be equal: $E_0 = E_t$.
Then,

$$\left(\frac{\mu L}{4B} + \frac{1}{2}\mu_0\right) W\phi_0 R = \left(\frac{\mu(L+L_t)}{8B} + \frac{\mu_0}{2}\right) WR_t\phi_t + \frac{1}{2}Wh.$$

In the above equation, $\phi_0 = \phi_t = \phi_b$,

$$\phi_b = \frac{h}{\frac{\mu}{2B}\left(LR - \frac{L+L_t}{2}R_t\right) + \mu_0 (R - R_t)}. \quad \text{(9)}$$

The boundary turning angle ϕ_b can be expressed as the function of (L, L_t, R, R_t, B, h, μ, μ_0):

$$\phi_b = f(L, L_t, R, R_t, B, h, \mu, \mu_0).$$

Considering the non-dimensional values shown below and substituting them in the above equation, ϕ_b can be rewritten as:

$$\phi_b = \frac{h}{\frac{\mu}{2B}LR\left(1 - \frac{1+K_1}{2}K_2\right) + \mu_0 R(1 - K_2)}. \quad \text{(10)}$$

If $R = R_t$, then $K_2 = 1$. Rearranging equation (10)

$$\phi_b = \frac{h}{\frac{\mu}{2B}LR\left(1 - \frac{1+K_1}{2}\right)} \quad \text{(11)}$$

Calculation for practical application

The estimation of the value for ϕ_b using the following data taken from the actual commercial machine (combine harvester) is shown here:
$h = 50$ mm, $\mu = 0.7$, $L = 1{,}040$ mm, $K_1 = 0.3$, $B = 900$ mm, $R = 1{,}100$ mm, $L_t = 312$ mm (assuming that $L_t/L = 1/3$).

Determination of lifting height, h

With the lifting action of track, the load acting on the track is concentrated on the central part and the contact pressure beneath the track increases as shown below.

$$p = \frac{W}{A} = \frac{W}{bL} \rightarrow p_1 = \frac{W}{bL_t}. \quad \text{(12)}$$

The contact pressure of the track in relation to the sinkage is shown using the equation

$$p = kz^n \quad \text{(13)}$$

where k and n: constants for soil specified.
It can be rewritten by combining the above equations as:

$$z = \left[\frac{W}{kbL_t}\right]^{\frac{1}{n}}. \quad \text{(14)}$$

Considering this equation, the lifting height of track, h should be larger than the track sinkage, z. Therefore the following condition should be satisfied for determining the degree of height, h: $h < z$.
Using the data shown above and assuming that the controlled contact length of the track is $L_t = 312$ mm, the contact length of the track is shortened to 1/3 from its original length. Using the above data and substituting them into equation (11), the following can be obtained consequently: $\phi_b = 0.16$ (rad) = 9.17° (degree).

Results and discussion

It was estimated from the calculation that the value of ϕ_b was approximately 9°. However this value may change depending on the soil conditions, since it can increase with an increase of the value of the frictional coefficient at the interaction between the soil and the track. Table 1 shows the values of ϕ_b obtained for various kinds of ground surface, in which the vehicle was operated for testing.

It appears that the value of the boundary angle, ϕ_b can be changed depending on the surface condition of the ground, which is likely to affect the coefficient of friction beween the track and the ground surface. Normally since the frictional coefficient

Table 1. Value of ϕ_b for various kinds of ground surface

Kind of ground surface	Value of ϕ_b (°)
Concrete	10
Hard sandy soil (almost equal to the level for the introduction of the combine harvester for harvesting after drainage)	14
Hard grassland	15

for a concrete surface is higher, the value of ϕ_b for a concrete surface is smaller than the others.

Conclusions

In this paper a pivot turn system with control of the contact length of track was evaluated and compared with the conventional pivot turn without any control system of track's contact length. The boundary turning angle (ϕ_b) was used as one of the measures to determine the range in which the controlled pivot turn system should be applied using the example of calculation for the rice combine harvester and the experimental results of the test vehicle constructed specifically for this purpose on various kinds of ground surface. The results can be practically applied to the automatic guidance control of the combine harvester when it travels along the rice plant row during harvesting operation under a certain steering angle. In this case the boundary turning angle can be used for the steering control regardless of whether the pivot turn system is activated. Only when the value of the actual steering angle exceeds the value of the boundary turning angle ϕ_b, should the pivot turn system with control be activated. On the other hand, the average steering angle can be calculated based on statistical analysis to determine how much the rice plant row fluctuates in an actual paddy field. Based on the results of this survey, a decision can be made for the equipment of the pivot turn system with control. In addition, the concept of controlled pivot turn system is suitable for larger scale machines like bulldozers, to drastically reduce the turning motion resisting moment.

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