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Study on the Development of a Precision Control Method for Semi-Trailed Agricultural Machinery for Tracing the Track of the Tractor

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Abstract

A new steering control method for wheel systems of agricultural machinery to enhance the follow-up performance with a tractor was developed to improve the operability of semi-trailed agricultural machinery. The basic concept of this control method is the alignment of the turning radius of tractor and machine for a constant turn, and a formula was derived for expressing this geometrical relationship. Based on this formula, a control method was developed which uses the steering angle of the wheel system of an agricultural machine as a variable for the steering angle of the tractor's front wheels and the angle of traction. Thereafter, this control method was applied to the in-line type prototype test trailer and a commercially available roll baler and running tests were conducted. The results showed a significant improvement in the follow-up performance of the trailer and roll baler attached to the tractor. However, since the need to measure the steering angle of the tractor's front wheels is difficult for practical application, the steering angle of the tractor's front wheels was estimated and the estimated values were used for the control for application to the commercially available roll baler. The results of this test showed that the same level of follow-up performance could be achieved as when the steering angle measured for the tractor's front wheels was used and that applications were possible. It was also confirmed that by the addition of a compensation coefficient for a slope to the estimated figures, a high follow-up performance could be achieved even on sloped grassland.

Discipline: Agricultural machinery
Additional key words: semi-trailer, steering control method, roll baler

Introduction

Semi-trailed agricultural machinery is widely used for forage harvesting and transport. This system is selected because part of the agricultural machine mass can be supported by the wheel system of the machine. As a result, large mass machines can be easily handled and attachment to a tractor is relatively simple. However, the follow-up performance of this type of machine with the tractor is inadequate as seen in the off-tracking when turning and improvements in operability and maneuverability are necessary.

In recent years, mechanisms for steering the wheel systems of agricultural machines in accordance with the angle of traction (refraction angle at the hitch point) have become commercially available to improve the operability of manure spreaders and sugar beet harvesters. The so-called link method enables to obtain uniform tracks of the tractor and the machine for a constant turn. However, for driving states in which the turning radius changes constantly, such as zigzag driving or a 90° turn (referred to as the non-constant turning state), no significant improvement is expected in the follow-up performance because the control is passive. Since ordinary

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agricultural machines often perform this type of non-constant turning, it is necessary to solve this problem in order to improve the operability of semi-trailed agricultural machinery.

Under these circumstances, examination of an active steering control method (referred to as active precision control method) for a single axle, 2-wheel agricultural machine using the actual steering angle of the tractor's front wheels in addition to the angle of traction was initiated to develop a method for high-precision follow-up by semi-trailed agricultural machinery of a tractor's driving track even in a non-constant driving state. In this report the method for deducing the basic equality to control the system and the results of driving tests for a test trailer, used as a model of agricultural machine are presented. A commercially available roll baler to which this control method was applied for a driving system with the agricultural machine attached in the straight rear of the tractor (referred to as the in-line format) is described.

Deducing the basic equality to control the system[2)]

1) Turn under constant radius circle

The conditions of the tractor and agricultural machine state when the machine is steered so that the constant turning radius is aligned are shown in Fig. 1 as the 2-wheel model. The A and B points in Fig. 1 are arbitrary points on the central line of the tractor and machine and the system is designed to make the tracks of these 2 points uniform for a constant radius circle.

The following equation is derived when a perpendicular line is drawn from the central point T of the machine wheels to OP and a triangular shape is formed by point T, point P and the perpendicular line.

$$\tan(\phi+\theta)=\frac{\ell_h+\ell_t\cos\phi}{R_r-\ell_t\sin\phi} \quad \cdots\cdots\cdots\cdots\cdots\cdots \ (1)$$

In this equation, ϕ is the angle of traction, θ is the steering angle of the machine wheels, ℓ_h is the distance from the center of the tractor's rear wheels to the hitch point, ℓ_t is the distance from the hitch point to the machine wheels and R_r is the turning radius.

When $\tan(\phi+\theta)=(\tan\phi+\tan\theta)/(1-\tan\phi\tan\theta)$ is used to rearrange this equation, the following equation is derived.

$$R_r(\cos\phi\tan\theta+\sin\theta)=\ell_t+\ell_h(\cos\phi-\sin\phi\tan\theta) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \ (2)$$

Also, since points A and B are located on the perimeter of the same circle with the radius $(R_r^2+\ell_a^2)^{1/2}$, when the distance from point A to the tractor's rear wheels is defined as ℓ_a, the following equation is derived.

$$\ell_a^2-\ell_b^2-\ell_h^2=2\,\ell_b\,(\ell_h\cos\phi-R_r\sin\phi) \quad \cdots\cdots\cdots (3)$$

When R_r is eliminated using equations (2) and (3), the equation showing the relationship which provides the alignment of the tracks of points A and B for a constant radius circle is derived.

$$\theta=\tan^{-1}\frac{\ell^2-\ell_b^2-\ell_h^2+2\,\ell_b\,\ell_t}{(-\ell_a^2+\ell_b^2+\ell_h^2)\cos\phi+2\,\ell_b\ell_h}\times\sin\phi \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \ (4)$$

Furthermore, when the equation is simplified using the approximations of $\sin\phi\approx\phi$ and $\cos\theta\approx 1$, the following is derived.

$$\theta=(\ell_a^2-\ell_b^2-\ell_h^2+2\,\ell_b\,\ell_t)\,\phi/(-\ell_a^2+\ell_b^2+\ell_h^2+2\,\ell_b\ell_h) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \ (5)$$

In this equation, ℓ is the wheel base of the tractor and is defined as $\ell=-R_r\tan\delta$. Now, δ is the steering angle of the tractor's front wheels.

2) Non-constant turning state

The plane movement of the tractor and agricultural machine is considered assuming the absence of side

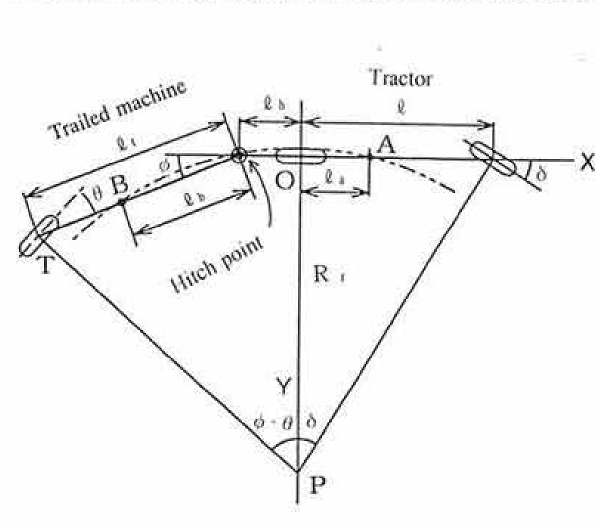

Fig. 1. Concept of development of steering method
Radii at point A and at point B are the same.

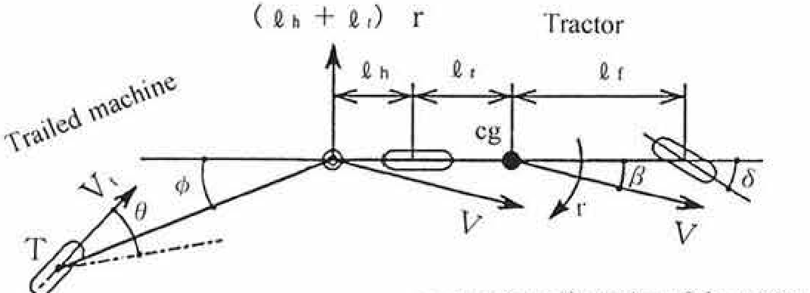

Fig. 2. Model used for the tractor and trailed machine

slip of the wheels. In Fig. 2, when the line which connects the hitch point and the T point, in the center of the machine wheels, is the base, since the traveling speed of the tractor and the machine in the direction of this line is aligned, the following is derived.

$$V_t\cos(\phi-\theta) = V\cos(\phi-\beta) - (\ell_r+\ell_h)r\sin\phi \quad \text{.............................} (6)$$

Next, when the speed element which intersects the base line is considered and the drawing angle ϕ representing the change of speed $\dot{\phi}$ is determined, the following is derived.

$$\dot{\phi} = \frac{V_t\sin(\phi-\theta) - (\ell_r+\ell_h)r\cos\phi - V\sin(\phi-\beta)}{\ell_t} - r \quad \text{.............................} (7)$$

In this equation, V_t is the traveling speed of the agricultural machine, V is the tractor driving speed, r is the tractor yaw angular velocity, β is the side slip angle at the tractor's center of gravity position and ℓ_r is the distance from the tractor's rear wheels to the center of gravity.

β and r in the absence of side slip of wheels are represented by $\tan\beta = \ell_r \tan\delta/\ell$ and $r = V\tan\delta\cos\beta/\ell$. Then the equation is rearranged by deriving V_t from equation (6) and substituting it in equation (7) and the following is derived.

$$\dot{\phi} = V\{-\ell\phi - (\ell_h+\ell_t)\delta - \ell\theta\}/\ell\ell_t \quad \text{.................} (8)$$

Meanwhile, by substituting $R_r = -\ell/\tan\delta$ in equation (2), further simplifying and determining the relationship between the target angle of traction ϕ_t and the tractor front wheels' steering angle necessary for obtaining identical trajectories of points A and B, the following is derived.

$$\phi_t = \{(\ell_b+\ell_h)^2 - \ell_a^2\}\delta/\ell\,\ell_b$$

At this point, in order to provide a control for aligning ϕ with ϕ_t, a feedback technique is applied in which the ϕ changing speed ($\dot{\phi}$) is expressed by the following equation.

$$\dot{\phi} = \alpha(\phi_t - \phi)$$

The target steering angle θ_t of the agricultural machine necessary for achieving this feedback is indicated by the following equation.

$$\theta_t = (\alpha - k_2)\phi/k_2 - (\alpha k_1 + k_3)\delta/k_2 \quad \text{............} (9)$$

In this equation, $k_1 = \{(\ell_b+\ell_t)^2 - \ell_a^2\}/2\ell\ell_b$, $k_2 = V/\ell_t$ and $k_3 = V(\ell_h+\ell_t)/\ell\ell_t$.

Based on the equation, the target steering angle of the machine wheels for aligning the track in a non-constant turning condition is determined. The machine wheels should be controlled for steering to meet the target steering angle.

Test trailer overview and driving test[2,3]

1) Test trailer overview

Fig. 3 shows the test trailer prototype attached to the tractor. The sizes of the steering angle of the tractor's front wheels, the angle of traction and the steering angle of the trailer's wheels are measured by potentiometers installed at relevant positions. Based on the values of the angles determined by potentiometers, ON-OFF of the electromagnetic, hydraulic direction control valve is controlled via a relay and the hydraulic cylinder expands and becomes contacted to drive the trailer wheels. In the test, a control program was run which uses interruptions

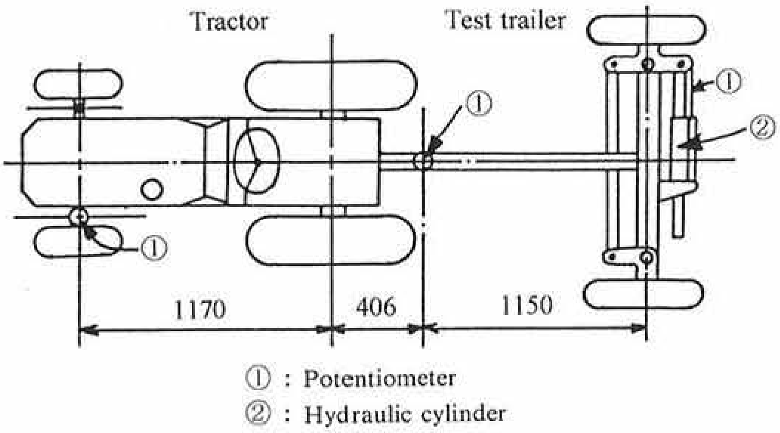

Fig. 3. Test trailer and tractor

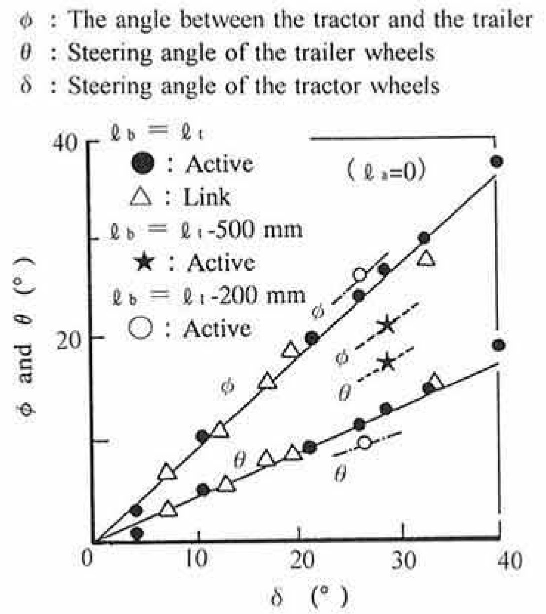

Fig. 4. φ, θ/δ characteristic diagrams
Trailer wheel control system was applied.

every 10 ms based on an interval timer built into the control computer in order to maintain a constant control interval. The cylinder used for steering the trailer wheels is a bilateral rod type cylinder with an internal diameter of 30 mm, a rod diameter of 16 mm and a stroke of 250 mm.

2) Driving test results using the test trailer

In the driving test, drops of water are left on the surface at set points to draw the track and the tracks are compared to align the tracks of the tractor and trailer. Tests of a constant radius circle with the tractor side point set in the rear wheel center and the trailer side point set in the trailer wheel base center when the control was applied, were carried out. Based on the results obtained, while a track offset of 8.5 cm and 26 cm occurred for steering angles of 18° and 31°, respectively for the tractor's front wheels, there was almost no off-tracking when the control was applied. Fig. 4 shows a comparison with the calculated values for cases in which a constant radius circle is driven with different actual steering angles for the tractor's front wheels and measurements of the angle of traction and the steering angle of the trailer's wheels are taken. The link indicated in the figure corresponds to the case when the link method is used for control with the target steering angle based on equation (5) being determined and applied for actual control. The wavy line and alternate long and short dash line in the figure show the results of driving when the trailer side setting point position changed in the active precision control method and in both cases, the calculated values and the measured values agreed well.

Next, Fig. 5 shows a comparison between the active precision method and absence of control and steering control by the link method for a turning track when a 90° angle turn is performed through an abrupt turn of the handle by the operator driving the tractor on a flat concrete street surface. The driving speed at this time is 0.38 m/s, the points at which the system attempts to align the track when the control is applied correspond to the center of the tractor's rear wheels for the tractor and the center of the machine wheels for the machine and a neutral zone of ±1° is set for the angle of traction when control is applied. When there is no control, once the 90° turn begins, the trailer cuts to the inside and the track for the setting point goes way off

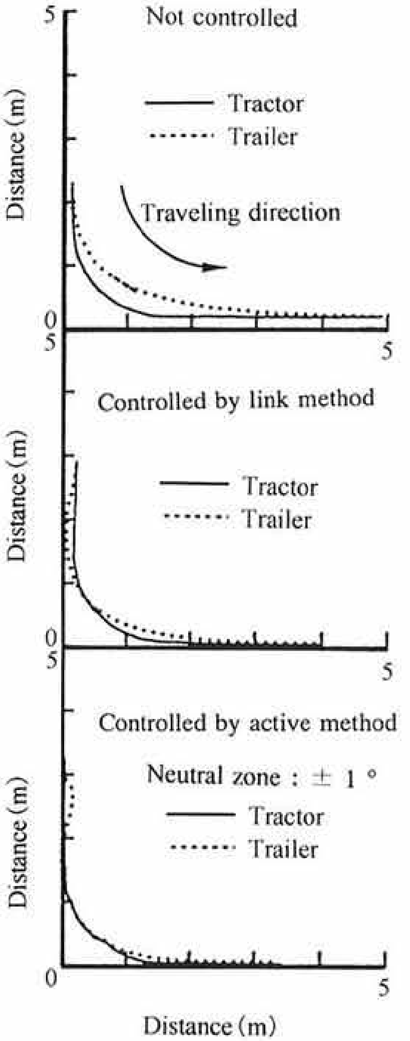

Fig. 5. Top view of trajectories in 90° turn
Traveling velocity is 0.38 m/s.

course. Furthermore, the trailer track is not aligned with the tractor track even after reverting to a straight course. When the link method control is applied, the track is not as far off as without any control, but even though the control is set to align the tracks for a constant radius circle, in the first part of the circle, the trailer crosses outside of the tractor's track and for the latter half of the circle, it crosses inside of the tractor's track. In contrast, when the newly developed active precision control method is used, while there is a slight amount of crossing on the inside by the trailer initially, the follow-up performance is excellent afterwards. The return to a proper track after the tractor reverts to a straight course is also quick. The reason why some crossover to the inside at the beginning of the turn is observed with the active precision control method is that since the tractor and the trailer are controlled to follow the same turning circle with the same turning point, when the tractor's front wheels are adjusted, the trailer's wheels are turned to be on the turning track which matches the angle of the tractor's adjustment although the trailer is still on the tractor's straight course track.

These results show that the introduction of the active precision control method significantly improves the follow-up performance of a semi-trailed agricultural machinery attached to a tractor.

Application of control sytem to a middle-sized commercialized roll baler and tests[4)]

Based on the results obtained with the test trailer and in order to study the suitability of the active precision control method, a middle-sized roll baler available in the market with a pick-up width of 1 m and a bale-forming chamber diameter of 90 cm was retooled for steering control and used in driving tests as well as field work. The tractor selected for these tests had an engine output of 22 kW, a wheel base (ℓ) of 1.79 m, a distance from the rear wheels to the hitch point (ℓ_h) of 0.96 m, a distance from the baler hitch point to the wheels (ℓ_t) of 1.76 m and a distance from the hitch point to the center of the baler pick-up device (ℓ_b) of 0.995 m. Also, steering of the baler wheels was handled by a hydraulic cylinder and oil was supplied by a hydraulic unit (with an output of 2.4 L/min when the tractor PTO base rotation is 540 rpm) built in the baler. The points at which the control system attempted to align the track corresponded to the center of the rear wheels ($\ell_a = 0$) on the tractor side and to the center of the pick-up device on the baler side.

In Fig. 6, a comparison of the results is shown for the absence of control and a model of link method control for the track when a 90° turn is performed at a speed of 1.65 m/s on a flat concrete surface. As in the case of the test trailer, the track alignment is off to the greatest extent for the absence of control and the amount of dislocation decreases in the link method and then in the active precision control method. Even when bales weighing nearly 140 kg are loaded in the bale-forming chamber and a 90° turn is performed, the follow-up performance using the active precision control method shows almost no change. In field work as well, excellent follow-up performance is achieved. Furthermore, by applying a control process, since the risk of interference of

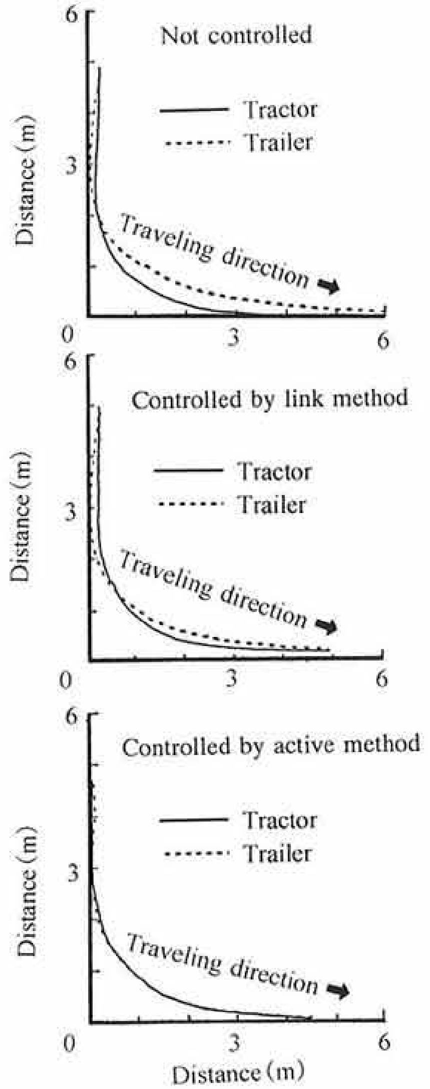

Fig. 6. Top view of trajectories in 90° turn (in-line type roll baler of real size)
Traveling velocity is 1.65 m/s.

the tractor with the baler is reduced even with larger angles of traction and a smaller turning radius, the turning performance is also enhanced in addition to the better follow-up performance.

Improvement of the control method and effect[1]

The active precision control method as described thus far involves the measurement of the steering angle of the tractor's front wheels using a potentiometer and applying control based on the results of measurement. This method requires that sensors be attached to the tractor for measurement of the steering angle of the front wheels or the rotary angle of the handle, and this requirement is not suitable for practical use. Therefore, instead of a method which measures the steering angle, a method which uses estimates of the actual steering angle from the angle of traction and the angular velocity of the angle of traction was examined.

In equation (8), the angular velocity of the angle of traction was determined from the angle of traction and the steering angle of the tractor's front wheels or the steering angle of the machine wheels. This equation (8) can be derived as follows.

$$\phi = -k_2\phi - k_2\theta - k_3\delta$$

Note that $k_2 = V/\ell_t$ and $k_3 = V(\ell_h + \ell_t)/\ell\ell_t$. In this case, ϕ and θ are determined and ϕ can be calculated as the change in $\dot{\phi}$ measured over time. Therefore, the actual steering angle of the tractor's front wheels necessary for control can be estimated by the following equation.

$$\widetilde{\delta} = -(\dot{\phi} + k_2\phi + k_2\theta)/k_3 \quad \text{......................(10)}$$

When the relationship expressed in equation (10) is substituted in equation (9), it is assumed that the target steering angle corresponds to the measured steering angle ($\theta_t = \theta$) and the equation is simplified. As shown in the following equation, it is possible to determine the target steering angle from the angle of traction and the angular velocity of the angle of tractiom.

$$\theta_t = \frac{\ell_a^2 - \ell_b^2 - \ell_h^2 + 2\ell_b\ell_t}{-\ell_a^2 + \ell_b^2 + \ell_h^2 + 2\ell_b\ell_h}\phi - \frac{\ell_t}{V} \times \left[1 - \frac{2\ell_b(\ell_h + \ell_t)V'}{\alpha\ell_t\{(\ell_b + \ell_h)^2 - \ell_a^2\}}\right]\dot{\phi} \quad \text{....(11)}$$

Here, α is the feedback gain, V is the actual driving speed and V′ is the fixed speed value input in advance.

This revised control method is referred to as the "new active precision control method" in contrast to the original "active precision control method", and Fig. 7 shows a comparison of this method applied to the previously described roll baler for a track resulting from zigzag driving over a flat concrete surface with the absence of control, link method control and active precision control. For this control application, the feedback gain is set at 0.84 and V′ at 1.2 m/s with a driving speed of 1.7 m/s. Also, the angle of traction neutral zone for control is set at ±1°, and the driving speed is set by inputting

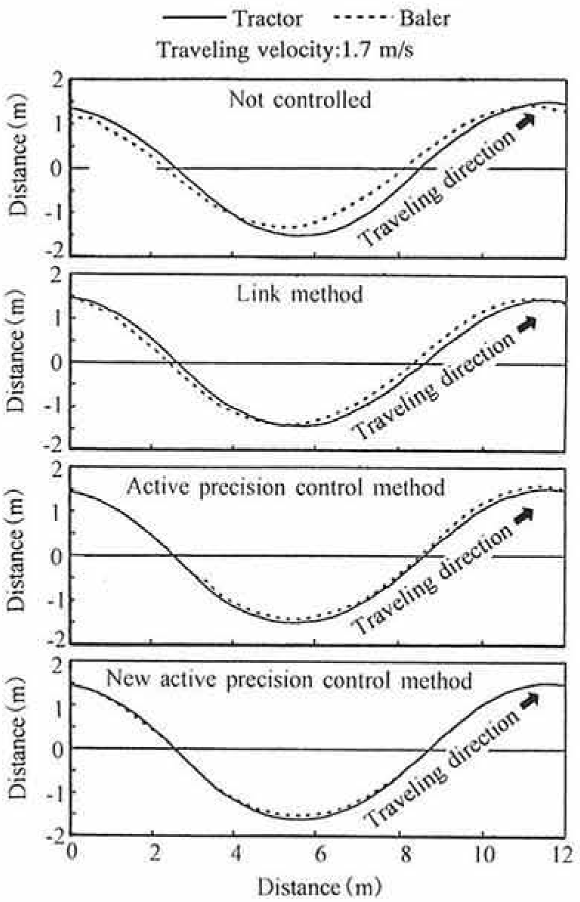

Fig. 7. Top view of trajectories in zig-zag running test

a value which is compatible with the defined driving zone in order to simplify the control device. Without any control, the dislocation is 52 cm (maximum) and for the link control method, the maximum track dislocation is 23 cm with phase delay. By comparison, the active precision control method and the active precision control method based on the estimation of the steering angle gave a maximum dislocation value of 10 cm and 7 cm, respectively. It is thus obvious that the track follow-up performance can be achieved at the same levels as with the active precision control method, and considering the lack of requirement for special work on the tractor itself, this method is highly suitable.

When work is being conducted on sloped grassland, since the agricultural machinery slips towards the valley side of the slope, the work performance deteriorates compared to flat land. To alleviate this shortcoming, a sensor which detects the slope angle is attached to the machine and if this angle is used as compensation to equation (11) for the application of steering control to the machine wheels, it is possible to achieve an excellent follow-up performance and work results even on sloped grasslands. Specifically, the following equation is used to determine the steering angle.

$$\theta_t = F_1\phi - F_2\dot{\phi} - F_3\omega \quad \text{.............................(12)}$$

In this equation, F_1 and F_2 are the coefficients of $\dot{\phi}$ and ϕ in equation (11), ω is the slope angle and F_3 is the compensation coefficient based on the slope.

When a driving test was conducted on an 8° slope using a roll baler (with a bale diameter of 100 cm) to which this slope compensation had been applied, the results showed that while a dislocation of about 7 cm occurred in the absence of control or without slope compensation, there was practically no dislocation when slope compensation with F_3 fixed at 0.3 was applied. Also, when a zigzag traveling test was applied to the same land, while the track dislocation between the tractor and the baler was nearly 20 cm without any control, a maximum value of about 5 cm was maintained when the control was applied. These results emphasize the value of this technique for improving the follow-up performance of the machine on sloped land.

Conclusion

(1) For semi-trailed agricultural machinery, a method for controlling the steering of the machine wheels based on the angle of traction and the steering angle of the tractor's front wheels was developed in order to improve the follow-up performance with the tractor.

(2) The basic approach for the control technique was to obtain identical values for the turning radius of the tractor and the machine wheels for a constant radius circle and a theoretical equation was introduced. Furthermore, the effectiveness of this approach was verified using a test trailer.

(3) To align the tracks for a non-constant radius turn, the active precision control method which provides a steering control based on the following equation using the angle of traction and the steering angle of the tractor's front wheels was developed, and this control method was applied to a test trailer and a commercially available roll baler for driving tests. The results showed that this control method improved the follow-up performance of the machine with the tractor.

$$\theta_t = (\alpha - k_2)\phi / k_2 - (\alpha k_1 + k_3)\delta / k_2$$

(4) The active precision control method was further improved by estimating the steering angle of the tractor's front wheels and using these values in the following equation to determine the steering angle for the machine wheels based on the angle of traction and the angular velocity of the angle of traction. This improved method which is referred to as the active precision control method based on the estimation of the steering angle was applied to the roll baler for driving tests. The results showed that the follow-up performance reached levels similar to those obtained with the active precision control method. Also, this control method was suitable for practical use because it does not require the installation of sensors for measuring the actual steering angle of the tractor's wheels or other changes.

$$\theta_t = \frac{\ell_a^2 - \ell_b^2 - \ell_h^2 + 2\ell_b\ell_t}{-\ell_a^2 + \ell_b^2 + \ell_h^2 + 2\ell_b\ell_h}\,\phi - \frac{\ell_t}{V} \times \left[1 - \frac{2\ell_b(\ell_h + \ell_t)V'}{\alpha\ell_t\{(\ell_b + \ell_h)^2 - \ell_a^2\}}\right]\dot{\phi}$$

Additionally, the follow-up performance can be further enhanced by applying a compensation coefficient for sloped grassland.

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