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# BASIC RESEARCH ON MAN-MACHINE SYSTEM IN AGRICULTURAL MACHINERY

## III. On the Tracking Characteristics of the Prctical Farm Vehicles*

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**Abstract**

As one of the series of the control experiments by human operator in our laboratory, the pursuit tracking experiment was performed using the practical farm vehicles on the roads. The results of the tracking performance were as follows:

1) Amplitude errors between the target sinusoidal line and the tracking locus of six wheeled vehicle increased as the vehicle loads both in the ascent and descent courses.

2) The phase difference of tracking locus was fully opposite between the ascent and descent course both in the cases of six wheeled vehicle and tiller with trailer. The phase led in the descent and delayed in the ascent.

3) The radius of the curvature of tracking locus of six wheeled vehicle was in proportion to the vehicle loads, and it was in inverse proportion to the target amplitude in the performance of the tiller with trailer.

4) Mean absolute errors of tracking locus had the least value against the road inclination in six wheeled vehicle, but on the contrary to it MAE had the increasing tendency with the road inclination.

5) Harmonic analysis of the tracking locus showed that the first order of the periodical elements strongly influenced the results.

6) Variances of error had the least value in the target amplitude 1.5 meters.

The system composed of human operater and the real vehicle was estimated considerably complicated affected with the various kinds of variables from out of the system and consisted of feedback and feedforward control.

## I Introduction

The results of tracking control experiments for better agricultural mechanization by human operator in the laboratory were described in the previous papers[1~2] and others. As the factors affect those human control, there were assumed as follows: input wave frequency, amplitude, wave form, controlling devices of machine, manipulated gains and operator's controlling ability and others. Among them the factor of human operator has been evident to be most important compared with other factors.

In this report factors affecting the experiments were confined to input wave length, amplitude, inclination of the road on which the test was practiced, and the kinds of real vehicle for farm use. Human operator is limited to one man.

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## II Methods of experiment and equipments

1. Architecture of the experiment

Human operator controls the vehicle and pursues the target sinusoidal wave line marked on the asphalt paved roads having different kinds of inclination in the university campus. These pursuit tests are ordinarily evaluated by the differences or errors between the target line and the pursuit line, which are calculated into various types of functions. Therefore the architecture of the experiment is comprised to relatively evaluate input and output for the system composed of the human operator and the vehicle, as the same with the previously performed experiments in the laboratory.

2. Variables affect the experiment

1) Angles of inclination of test asphalt paved road : 7, 3.5, 0 degrees.

2) Target sinusoidal lines drawn on the roads with amplitudes of 1.0~2.5 m and periods of 6~12 m.

3) Tested vehicles: mainly three axled six wheeled vehicle and ordinal power tiller with trailer respectively with the loads of 0~500 kg. Other vehicles for instances, four wheeled articulated vehicle and both front and rear wheel drived tractor as a simple approach.

The selection of period and amplitude of sinusoidal input just fit to the purposes is very important in these tracking experiments and they will decisively effect on the results of the experiments, so they were decided as follows: the minimum turning radius of six wheeled vehicle which is main object for experiments has been published 1.6 m. Then for the minimum radius of curvature of target wave being a fairly good approximation to this 1.6 m, amplitude of 1.5 m and 2.0 m have to be theoretically combined with the periods of about 12 m and 18 m respectively.

The paved roads for test being almost 4 m wide, so single amplitude must be decided 1.5 m having with the running allowance in the roadsides. Therefore we put period of input wave 12 m, and sometimes the combination of amplitude of 2 m and period of 6 m was used.

The test roads have three kinds of inclination of about 7.0, 3.5, 0 degrees. Confering the results of farm working in the inclined planes the inclination of 8 or 10 degrees is said to be the maximum slope for the demand of high precise work and high drawbar pull. Actual farm work is done on the rough roads and lands, but this experiment is on asphalt paved road. Then it can not be helped that the results of this experiment may not be just appropriate for the actual work.

Pursuiting the input target line, the path swept by the test vehicle was drawn on the surface of the road with water jet issued from the nozzle at 3~5 kg/cm$^2$ pressure made in the automatic hand sprayer mounted on the vehicle installed in the centroid of the plane shape formed with all the ground contact points of vehicle. As travelling the vehicle water jet drew the narrow band on the road. It indicated the trajectory of the varying path of the typical point of vehicle.

The loads on the vehicle were accumulated with the weight of individual body which was previously weighed to maximum 500 kg.

The speed of vehicle is one of the important factors in such a case of the tracking experiment, but in this experiment it was fixed and was regulated at nearly 1 m/sec.

Human operator is the important factor too, but in this experiment operator was limited to one man; he was familiar to the operation.

The deviation of tracking line from the base line was carefully measured, because the main purpose of this experiments was to evaluate the error between the target line and the tracking line. Sinusoidal lines respectively having three periods were marked on the road, and x axis was taken in the direction of the base line and furthermore of vehicle tracing, and the amplitude from the base line was measured on y axis perpendicularly intersected with x axis at every 0.5 m intervals on the base line from the start point. Deviation or error $\Delta y$ was calculated by subtracting the amplitude of target line from the tracking, and then the error had the plus or minus sign.

$\Delta x$ is the distance from the point where the target line intersects with the base line to the point where the tracking line crosses with the base line. $\Delta x$ having plus sign is when the cross point of tracking line with the base line advances the cross point of target line with the base line.

## III Results and discussions

The results of the experiments can be evaluated by the errors between the pass of the vehicle and the target line with the following functions.

1) Deviation from the target line (amplitude error and phase error)
2) Curvature of tracking line
3) Mean absolute error of amplitude error
4) Frequency components contained in the tracking line: harmonic analysis (phase angle and difference)[3]
5) Variance of amplitude error

1) Amplitude error ($\Delta y$)

Amplitude error is the mean value of each trials of the actual different lengths between the target line and tracking line at the points of maximum amplitude. Fig. 1 shows the relation of $\Delta y$ and vehicles' loads. In both courses as an increase of the load, $\Delta y$ increases. Especially on loading with 500 kg in the descent course a maximum error occures. It reaches 0.8 m and then this value occupies more than 53% of the target amplitude. All the errors are positive and it means the curvature of tracking line is bigger than it of target line.

Fig. 2 is about amplitude error in the case of tiller with trailer. Having no load with trailer, all the errors are negative. In descent course the absolute value of $\Delta y$ is in proportion to the increase of inclination of the road, but in ascent course in inverse proportion. It may depend upon the facts that the stroke of the steering handle of the tiller occupies only its own running course (the steering gain is 1), and then the amount of steer-handling is bigger than any other steering equipments, for instances lever handle and steering wheel. As the result the absolute peak value of $\Delta y$ is apt to diminish. When the intersected point of tracking line with the base line leads it of the point of target line—the phase of tracking leads, $\Delta x$ is signed positive. In the opposite case, it is negative. Then both in the experiments of six wheeled vehicle and tiller with trailer $\Delta x$ has the tendency of phase led in descent course and delayed in the ascent course. And as an increase of road inclination, $|\Delta x|$ increases. (Fig. 3, 4)

2) Curvature of the tracking line

Near the peak point of the amplitude tracking line, the radius of curvature can be approximated by parabola from the trace of measuring points. Both in the cases of tracking line having big or small amplitude and wave length, the radius of curvature by six wheeled vehicle has an increasing tendency as the vehicle load increases. And

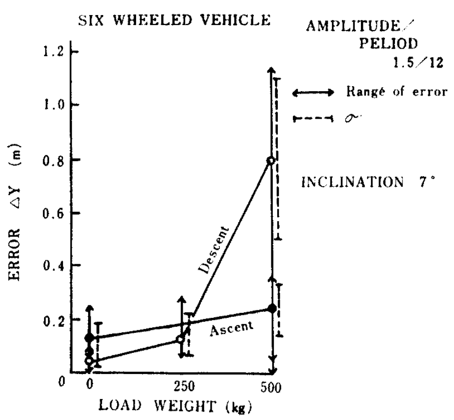


Fig. 1 The influence of vehicle load on error $\Delta y$

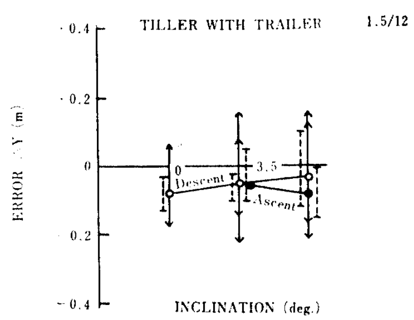


Fig. 2 The influence of road inclination on error $\Delta y$

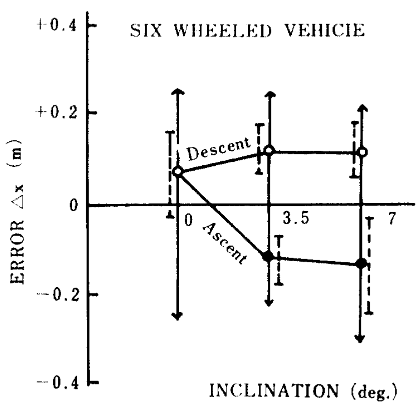


Fig. 3 The influence of road inclination on error $\Delta x$

furthermore this tendency is independent to any inclination of road. (Fig. 5) On the contrary the case of tiller with trailer is dissimilar, meaningly the radius of curvature of the tracking line is in inverse proportion to the target amplitude. This is the same tendency among descent and ascent courses. (Fig. 6) This dissimilitude in two types of vehicles may depend upon the differences of the relative positions of the centroids, steering wheels and operators' positions.

3) Mean absolute error (MAE)

Mean absolute error is defined as the summation of the absolute value of $\Delta y$ calculated throughout the course divided by the number of measuring points. This value means how large the difference between target and tracking is throughout the ex-

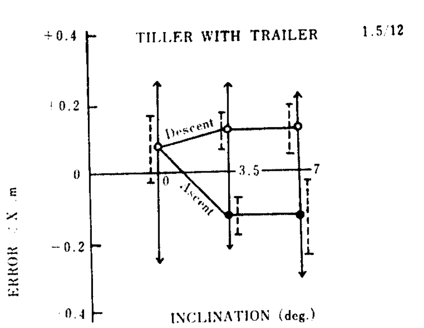


Fig. 4 The influence of road inclination on error $\Delta x$

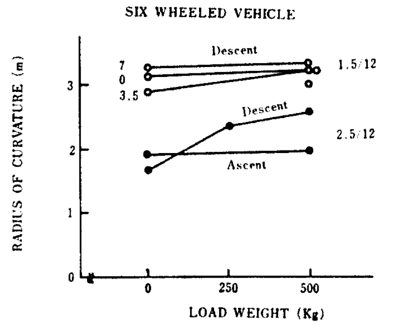


Fig. 5 The relation between vehicle load and curvature of tracking

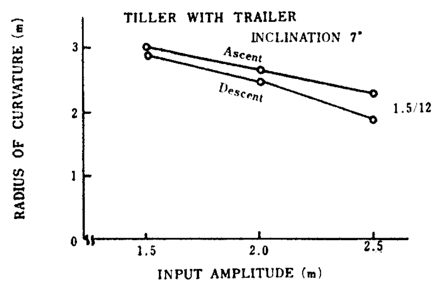


Fig. 6 The relation between input amplitude and curvature of tracking

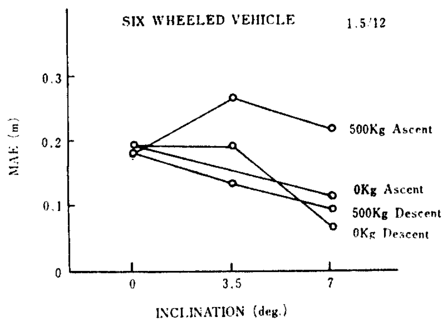


Fig. 7 The relation between road inclination and MAE of tracking

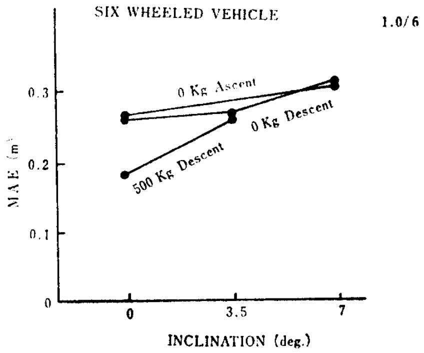


Fig. 8 The influence of road inclination on MAE of tracking

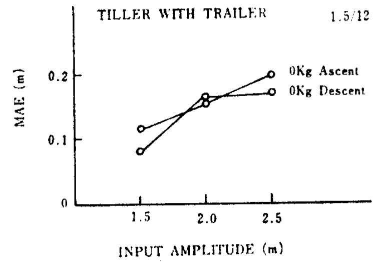


Fig. 9 The relation between input amplitude and MAE of tracking

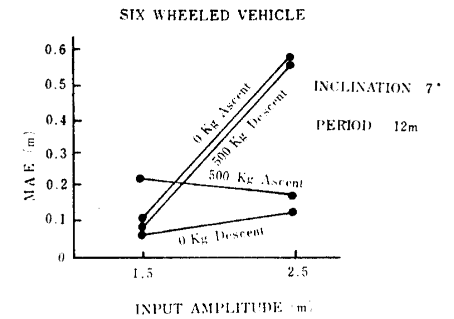


Fig. 10 The influence of input amplitude on MAE of tracking

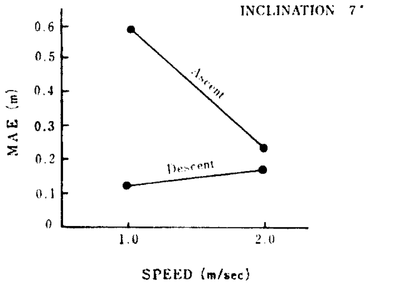


Fig. 11 The relation between vehicle speed and MAE of tracking

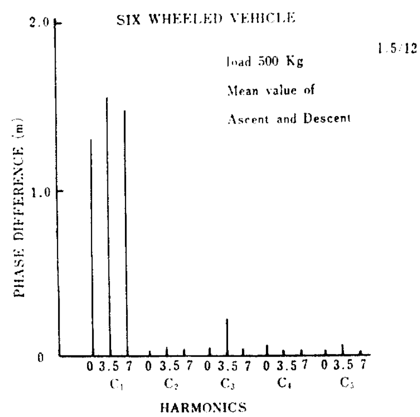


Fig. 12 Phase difference by harmonic analysis

periment. Fig. 7 and 8 indicate respectively the relations of MAE with the inclination of the road in the case of wave length 12 m, 6 m and amplitude 1.5 m, 1 m of target lines. The most significant discrepancy is found in these two cases, and the tendency is throughly inverse each other. Namely in the cases of both period and amplitude of target are smaller (Fig. 8), the tracking error is distinct in proportion to the inclination more than in the target of larger amplitude. This relates closely with the difficulty of tracking control technique. In the case of such target, MAE is not always in proportion to the inclination, but in the maximum inclination MAE is least. (Fig. 7) This reason is not clear, but to demand paying extream care in tracking control in the most steep descent is supposed. And regardless of the quantity of vehicle load, MAE has the least value in the maximum inclination.

MAE in the case of tiller with trailer is disposed to ascend with the amplitude of target increasing. In the ascent course the increasing rate of MAE is larger than in the descent. (Fig. 9)

In the case of six wheeled vehicle, the effects of the vehicle load and amplitude of input target on MAE are shown in Fig. 10. The movement of vehicle mounting with full load is quite inverse each other among both of the courses of ascent and descent. Vehicle with full load increases MAE with the amplitude increase in descent course, but in the ascent course it has an entirely inverse movement and decreases as the amplitude increasing.

On the point of quantity of vehicle load, no load has a quite inverse movement to that of full load.

As shown in Fig. 11, about the effect of the speed of the vehicle without load on MAE, in the ascent course gets MAE decreases as the vehicle speed increases, but in the descent course it increases.

4) Harmonic analysis

Harmonic analysis is suitable to express the characteristics of the continuous phenomena, especially the repeated ones and a good method to know how important the periodical elements occupied them. Phase angles and differences are the results of harmonic analysis about the amplitude of the tracking line by the method of dividing the adequate samples of the average sinusoidal wave among whole the experiments into tweleve pieces. Fig. 12 is the result of phase difference being plotted against the harmonic orders. The first order is clearly significant compared with other high orders and is large as fifteen times as others. Therefore the tracking line considerably shows faithful for the target line.

Phase angle of only the fundamental wave after harmonic analyzing the vehicle trajectory shows very clear tendency. In the ascent course the phase angle is positive, and descent course conversly has all the negative

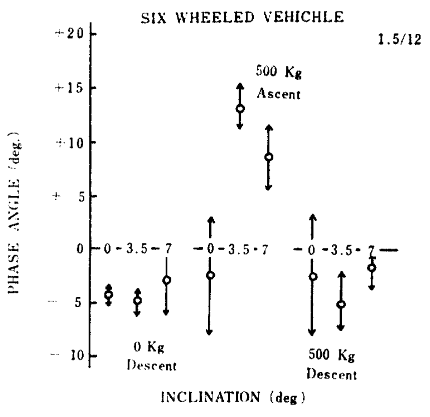


Fig. 13 Phase ancle by harmonic analysis

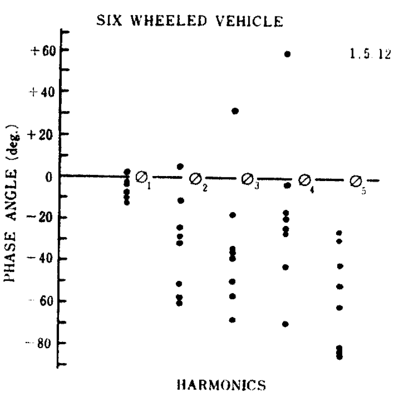


Fig. 14 Phase angle by harmonic analysis

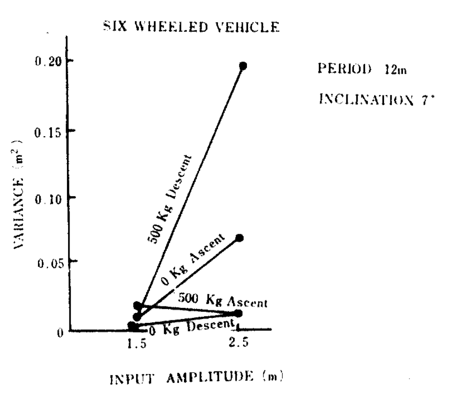


Fig. 15 The relation between input amplitude and variance of tracking

angle. This tendency is independent to the vehicle load. In descent course vehicle controlling is apt to be delayed on steering, and the ascent is forward steering. (Fig. 13)

All the phase angles are plotted against harmonic orders in abscissa without any classifications of vehicle loads, inclinations of test road and ascent or descent courses in the case of six wheeled vehicle in Fig. 14. 92% of all the plotted values of phase angle are negative among all the range of experiment. And in the fundamental wave the values almost converge to very narrow range. As the order of harmonics goes up, the deflection of the value becomes wide and the maximum value reaches minus 85 degrees in the 5th oder.

5) Variance of $\Delta y$

Variance is one of the significant and proper factor to describe the error measured as the difference between the target line and the tracking line. In Fig. 15 variance of error is expressed as the functions of target amplitude, vehicle load, ascent and descent course. Variances are apt to converge to the least value at the point of 1.5 m target amplitude, and disperse at 2.5 m amplitude. Here we can find variance in the case of descent course with full load maximum.

## IV Conclusions

To evaluate the locus of the vehicle movement the tracking experiment is the most appropriate method, refering to the technique of machine control.

In the case that human operator steers the real vehicle following the decided target, operator can forecast the target trajectory and confirm the locus of vehicle travelling. During operator trims the tracking error, he can forecast the alternation of the target. This is a kind of a feedforward control. Simultaneously he can know the amount of $\Delta x$ and $\Delta y$ and they are corrected by feedback control into as small as possible. Operator senses the technique of above-mentioned control, and then human operator and the vehicle can be estimated to be the system of learning control depended upon the feedforward and feedback control.

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# 人間―農業機械系に関する基礎的研究

## 第3報　実用車両のトラッキング特性

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### 要　　約

農用車両の操縦性能を人間工学的に把握するために簡単なシミュレータを用いた基礎実験を継続中であるが，今回は実用されるトレーラ付きティラと3軸6輪駆動車を主な対象として学内アスハァルトほ装傾斜道路上で実験をおこなった。

この実験は操縦者が供試車を操縦するとき，走行目標と実車の実走行との誤差を閉ループ的に修正しつつ，しかも目標の変化ならびに道路傾斜などの外乱を予測して操縦する開ループを兼ねたところの人間―農業機械系の制御と考えられる。

1)　系の入力となる走行目標は，片振巾 1.5$m$，波長 12$m$の正弦波を主とし，これを予め道路上に白線で描いておき，供試車の各車輪の接地点の図心にノズルを置き，搭載した噴霧機から水を噴出して路面上に走行軌跡を描かせた。

2)　目標波形と走行軌跡のx方向誤差 $\Delta$x（目標波の基線方向）とy方向誤差 $\Delta$y（x方向に直角の方向）をもって操縦性を評価した。

3)　$\Delta$yは6輪車では車両負荷重に比例して増加し，ティラでは$|\Delta y|$は道路勾配に影響を受けた。

4)　$\Delta$xは両対象機種ともに勾配の影響は降坂と登坂では全く逆の傾向を示した。

5)　走行軌跡の曲率半径は6輪車では負荷重量に比例して増大し，ティラでは目標振巾と反比例の関係をとった。

6)　振巾誤差の絶対値平均は6輪車では負荷重量の如何にかかわらず最大勾配において最小値をとった。ティラでは目標振巾に比例して登坂，降坂ともに増加した。

7)　誤差の調和解析によれば位相差，位相角ともに基本波が大きい影響を示した。

8)　誤差の分散は6輪車では入力振巾の小さい時に最小値に収斂した。