Research of the Snaking Phenomenon to Improve Directional Stability of Remote Controlled Articulated Wheel Tool-Carrier

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ABSTRACT: Articulated wheel tool-carriers manufactured up to 20-25 tons of total weights are wide available on the construction equipment market and have a lot of unique advantages not accessible on Ackerman steering or truck-mounted equipment such as:
- for weight up to 20 t high cross-country mobility – comparable to heavy military tracked vehicles due to size of wheels;
- excellent manoeuvrability and keeping attachment straight ahead during turning;
- high lift capacity due to heavy axis construction;
- high pulling force;
- wide range of tools and attachments due to quick-coupling device;
- high productivity;
- high reliability and durability.
Moreover their steering systems and transmission are easy to automation due to hydraulic control systems. For those reasons they could be useful and cost effective on hazardous areas and robotised construction sites.

There is one unsolved problem, which limits the speed of operation and efficiency of using – they have poor directional stability. During straight movement the articulated tractor deviates from straight line and permanent driver correction is required. The path has oscillation shape so it is called snaking phenomenon. So in the case of remote control the speed is limited to 5-6 km/h. The higher road speed above 30 km/h of driver controlled tractor need an operator aid system that would improve directional stability of articulated tractor too. Designing such system demand perfect knowledge of snaking phenomenon arise reasons.

This paper describes tests and trials conducted on 20 tons articulated wheel loader to get answer how the snaking phenomenon is arisen. Used methods, achieved original results and their analysis are presented. It could be basis for future works on articulated tractor directional stabilisation system.

KEYWORDS: articulated tractor, high speed, identification, remote control, snaking phenomenon, steering system

1. INTRODUCTION

In Ackerman steering system thanks the geometry of suspension the stabilising force and moment appear. The steering play lets them acts independent, without the driver attention. This feature has not gets articulated steering system and snaking phenomenon always appears. It is illustrated in fig.1. It shows the travel path of articulated tractor, which is oscillating round the theoretical direction of movement. Lack of directional stability of movement caused by too high speed or too low skill and experience of driver gives growing deviation and finally the machinery is leaving road strip (permitted corridor of movement).

In order to determine all main reason of arising and growing the snaking phenomenon the experimental research was conducted. As the test object was used the loader SL -34 -weight 19,5 t and net engine power 162 kW (manufactured by Huta Stalowa Wola) in two versions of steering system, offered by manufacturer:
Type 1 – with mechanical feedback and gain $w = 1/5.5$ - applied in machines first generation;
Type 2 – with hydraulic feedback and gain $w = 1/3.2$ – operating in L-S system with
priority valve and amplifier - applied at present by almost all manufacturers of construction machines, and 2 research systems designed by authors:
Type 3 - direct working with hydraulic feedback and gain \( w = 1/6.5 \) without L-S system and amplifier;
Type 4 - direct working with hydraulic feedback and gain \( w = 1/16.2 \) without L-S system and amplifier.
As a gain “\( w \)” in steering system the inverse of number of steering wheel turns needed to realizing the full turn of frame was called.
After introduction tests [Lopatka] it was affirmed that in all steering systems the oscillations has similar period of vibration – about 2.5-3 s. From the type of steering system is depending only the value of maximum deviation amplitude and driver effort measured as angle of steering wheel revolve.
To eliminate claims that snaking phenomenon is some kind of natural frequencies or that arise because of exciting the critical speed – this values was identified.
As a next step the research of steering system acting was conducted and finally the influence of driver on machinery stability was determined.

To find them the simple test was conducted. The steering system was excited with fast steering wheel revolve and the recorded pressure in cylinder shows the oscillation with natural frequency of system. The results (fig.2) shows that period of vibration is 0.4 s and the frequency is 2.5 Hz. Compared to period 3 s of snaking phenomenon it is clear that they are not connected and snaking phenomenon is not kind of vibration related with natural frequency of steering system.

2. THE NATURAL FREQUENCY

The steering system of articulated tractor always contains 1 (in small equipment) or 2 hydraulic cylinders and moved with them 2 masses connected to front and rear part of articulated frame. The oil in the cylinder gives the spring and damping effect. So, such system always has gets natural frequencies.

![Figure 1. The snaking phenomenon of articulated tractor - speed 28 km/h - steering system - type 2](image)

3. THE CRITICAL SPEED

The critical speed characterize the vehicle mass distribution and lateral tire stiffness. During straight movement any disrupt due to different front and rear tire deformations changing him in some kind of circular movement and centrifugal force is appeared. The value of this force depends on the speed. When the centrifugal force is greater then stabilizing forces from tire stiffness the vehicle is not stable - leaving the strip and driver steering corrections is needed. The maximum value of speed when the vehicle is stable is called critical speed.

![Figure 3. The directional control response characteristics [Wong](image)]
Conducted test shows (fig. 1) that tractor is losing his stability with speed not exceed 28 km/h. Executed mathematical calculations indicated value of critical speed equal 44 km/h but credibility value can be find only in empirical way. To obtain this, the test according to [SAE] was performed. We decided for method 4 – constant speed/variable steer angle test and conducted them at a rate of 28 km/h. How to use the test results to determine the critical speed is demonstrated in fig. 3.

According to assumed guidelines, during tests were recorded:
- the change of steering wheel turn angle $\beta$;
- the lateral acceleration $a_p$ in the cab.

On the basis recorded dates the directional control response characteristics were plotted – fig. 4. It show that the tractor not achieved the critical speed and it is much more higher then developed 28 km/h.

Moreover it indicates that from critical speed point of view the loader at speed 28 km/h is stable and has got understeer characteristics. So, one may say that snaking phenomenon is not related to critical speed of vehicle.

4. THE STEERING SYSTEM OPERATION

Changing of movement direction and steering of articulated equipment is realized by turns of articulated frame with hydraulic cylinders of steering system. Each turn is related with pressure and flow changing. To know how it operates and what phenomena takes part during steering such signals as:
- pressure in both cylinder chambers;
- steering wheel angle;
- turns of articulated frame or
- length of steering cylinders;

should be measured.

In first steep the resistance of steering was determined. As a measure of resistance the pressure difference between active and passive cylinder chamber was used.

Example of recorded signals during steering on firm surface is shown in fig. 5. It indicated that after steering the system is not stable. In active chamber of cylinder after steering the pressure is higher then in passive chamber about 0,8 MPa and it correspond to the steering resistance moment equal 4 kNm. This is a residual steering moment and it appears because of oil compression in active chamber of cylinder. This moment is trying continuing the steering process but the resistance is too high. The value of this moment is depending on steering resistance and velocity of frame turning.

Example of recorded signals during steering on hard surface – loader is stand still

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When the tractor is moving the steering resistance is lowering and this residual steering moment is caused the turn of articulated frame up to time when the pressure in both chambers are equal fig.6. In these times the length of active cylinder is growing about 1-1,5 mm – fig.7. It correspond the turns of articulated frame about $\Delta \beta = 2,7^\circ$. To compensate it the driver must makes revolves of steering wheel on about 9 deg.. If he do not do it the tractor would achieve the permissible deviation $\Delta y_{\text{max}} = 0,35$ m according to [ISO], after 22 m.

The pressure measure permitted to determine forces in both – left and right cylinders – acting on articulated frame – fig.8. It shows that the frame is continually stretched – each cylinder develop the mean force about 5 kN amplitude oscillation is about 2-3 kN. This mean that joint is stretched by force about 10 kN and in this steering system has not gets any plays.

5. THE SNAKING PHENOMENON GAIN REASONS

For comparison of working efficiency of studied steering system arrangements, the time delay between signal from sensor of hydraulic steering cylinder length and signal from sensor of steering wheel turn angle was used. Analysing obtained results (fig.9,10) it is possible to affirm, that in standard arrangement the time delay is equal $\Delta t \approx 0,45$ s and it is higher then in arrangement with L-S system, where the delay is kept on level $\Delta t \approx 0,35$ s. One should pay attention that in L-S type arrangement although the signal time delay is decreased, the snaking phenomenon is more intensive and vehicle can loss their stability of movement (fig.1). This is due to considerably larger gain of steering system improving manoeuvrability and raising work efficiency during typical tasks as well as lowering the number of turns of steering wheel indispensable for realization of working cycle and the same the operator's effort.
The growth of gain in steering system as well as growth of signal delay is the main cause of increasing the snaking phenomenon. However, in essential, its scale depends on operator’s skill and predisposition.

In order to recognize the possibility of snaking phenomenon limitation by means of gain limit as well as signal delays, two direct working research systems were designed - Type 3 and Type 4. As a result of L-S arrangement elimination, the transmission time and delay was shortened in designed steering systems up to $\Delta t = 0.05$ s.

Although the signal time delay in steering system was considerable decrease (tab.1), the snaking phenomenon was limited in considerably smaller range. It should be taken in consideration that the smallest deviations from theoretical track, appear in arrangement with the smallest gain. On this bases the conclusion can be made that the operator is one of sources triggering the snaking phenomenon – limitation of possibility of his influences by gain decrease - stabilize the movement of machine, and the growth of steering system gain led to losing of stability and leaving the traffic lane.

This is completely in agreement with car research results described in [Chaczaturow] as driver behaviour. When the driver is high concentrated because of narrow corridor of travel – his reaction period is equal about 2.5-3 s. So, in this way the ma in snaking phenomenon frequency is a driver excitation frequency. At this high speed of tractor movement it is a maximum velocity of driver reaction on sensed deviations.

### Table 1

<table>
<thead>
<tr>
<th>Steering system</th>
<th>Gain in steering system</th>
<th>Signal time delay</th>
<th>Average deviation amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>1/5,5</td>
<td>0,45 s</td>
<td>27,4 cm</td>
</tr>
<tr>
<td>Type 2</td>
<td>1/3,2</td>
<td>0,35 s</td>
<td>58,4 cm</td>
</tr>
<tr>
<td>Type 3</td>
<td>1/6,5</td>
<td>0,05 s</td>
<td>18,0 cm</td>
</tr>
<tr>
<td>Type 4</td>
<td>1/16,25</td>
<td>0,05 s</td>
<td>8,1 cm</td>
</tr>
</tbody>
</table>

Because of sensed by driver lateral deviations limits their reaction and stability of movement, the research to determine possibility of improvements this sensing was conducted. In this order three position markers were situated on machine and the motion path was recorded with the digital video camera.

Two markers (A and C) were intended to marking the motion paths of the front and rear of machine (located in distance 2,5 m from joint), and third (B) – showed the operator inclination – it was fixed in axis of the joint (fig.11). They possess measuring mesh which make up white and black squares side length 5 cm, arranged in figure “chessboard”. Both the pattern and the size of elements were well-chosen on the ground of earlier conducted tests – their goal was achievement maximum legibility as well as possible to obtainment measuring accuracy, depended from resolution of recording system.
The position and distance of recording camera were carefully chosen too, in order to assure the indispensable sharpness in whole measuring range.

The analysis of registered courses of motion paths obtained with video recording method (fig.12) shows, that the rear part of machine in relation to the front gets about 30% larger values of maximum side deviations. It results mainly from lower stiffness of rear axis tires working with almost 2-times lower inflation pressure than in front one.

The character of registered courses is completely consistent but it should be noted that deviation sensed by operator (marker B) is delayed about 0,5 s in comparison with the movement of front of machine (marker C). This delay explains why the hydraulic system improvements – 9-times reducing delay in steering system – are limiting deviation only 3-times. Time delay in sensing of deviation is comparable to delay in commercial steering systems.

Dislocation the driver's seat (or future remote control sensors) from current position (close to frame joint) to the front of tractor - can be essential to accelerate the operator's reactions and to improve the stability of articulated machine movement.

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9. REFERENCES


