SIMULATION CALCULATION OF TRACTOR-POTATO PLANTER COMBINATION MODEL

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ABSTRACT
The paper presents a concept of mathematical model, which may be used for analyzing the behavior of tractor – agricultural machine combinations at the preliminary design stages. The model is based on 2D so called bicycle models (two-wheeled) that are often referred to in the literature, but it is significantly modified because third axle was added. The model has been applied to a tractor – potato planter combination. The measurements of behavior tractor - potato planter combination during traffic were conducted to model parameters identification. Obtained results permit evaluate influence value of combination tractor – potato planter parameters on its traffic stability.

Keywords: agricultural machine, simulation, motion stability

1. INTRODUCTION

It is evident from statistical data that many serious accidents take place during the transfer of agricultural machines to the working site and during their movement while working. Nearly every third fatal accident in agriculture is caused by driving over, hitting or catching by vehicles and moving machines. The most serious effects occur in accidents during transport and those related to manoeuvring with tractors and machines (nearly 30% of all fatal accidents). One may assume that at least some of these accidents are caused indirectly by the design features of agricultural machines which unfavourably influence their traction properties.

Research concerned vehicles steerability and stability simulation were conducted for a long time. However the results were rarely transferred into the agricultural machine field. It demands taking into consideration specificity of agricultural machine construction and its combination with tractor on the one hand. On the other hand it demands analysis of machine behavior on diverse grounds (field ways, fields) possesses complex and changeable properties (Saarilahti 2002)

2. MODEL DESCRIPTION

As the result of increasing of computer possibility very complex, nonlinear models of vehicle start occur. But important disadvantage of a model with many degrees of freedom is great deal of data needed to circumscribe vehicle features. It is especially essential as the model is appropriated to using on preliminary design stage, when many data lack. Lacked and uncertain data decrease accuracy of results obtained by simulation and put usefulness of expenditure of work connected with model building in question.

In that case we made an attempt construct comparatively simple model with few degrees of freedom. Such models can be met in various publications concerned control of vehicle dynamics both transverse and longitudinal (Grzegożek 2000; Ślaski, Mac, and Szczepaniak 2000; Harada and Harada 1999).

The model is based on 2D so called bicycle models (two-wheeled) that are often referred to in the literature (Feng and He 2005**;** Börner and Isermann 2006), but it is significantly modified because third axle was added.

Attempt is made to apply the model to the tractor – potato planter combination (Fig. 1). Semimounted potato planter is attached to tractor by lower pull rod of 3 point linkage. Potato planter is equipped with castoring wheels. It necessary to emphasize that potato planter revolution with reference to tractor round Z axis normal to road surface is impossible.

Figure 1: Tractor – potato planter combination during field works

During deriving the model following assumptions were made:

- combination movement has constant longitudinal speed v_x,
- flexibility of engine mounting and seats are passed over,
- articulated joints clearances are passed over,
- turning angles, slip angles of wheels and of vehicle are so little to formulas $\sin(\Psi)\approx \Psi$ and $\cos(\Psi)\approx 1$ can be accepted.

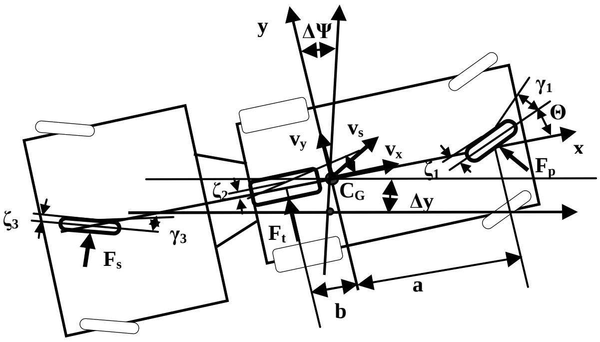

Figure 2: Three wheel 2D model of tractor – potato planter combination; symbols are described under model system of equations (1)

Proposed model has seven degrees of freedom: lateral displacement of combination center of gravity, combination rotation angle, lateral displacements of front and rear tractor wheels, slip angle of tractor's front and rear wheels, turning angle of castoring wheels. The longitudinal speed and tractor driven wheel turning angle are the input data.

System of equations (1) was obtained on the basis of Newton equation of dynamics and Kieldysz theory (Chatschaturov, 1976, Karnopp 2004) describing rolling of pneumatic wheel (Szczepaniak and Grzechowiak 2006).

$$\begin{cases} \dot{v}_y = \dfrac{c_{\xi_1}}{M}\zeta_1 + \dfrac{c_{\xi_2}}{M}\zeta_2 + \dfrac{m\left(\kappa^2 + a_k^2\right)}{M\left(a_k + b_k\right)}\ddot{\theta}_k - v_x\dot{\Psi} \\ \ddot{\Psi} = \dfrac{ac_{\xi_1}}{I_{zz}} * \zeta_1 - \dfrac{bc_{\xi_2}}{I_{zz}} * \zeta_2 - \dfrac{c}{I_{zz}}\dfrac{m\left(\kappa^2 + a_k^2\right)}{\left(a_k + b_k\right)}\ddot{\theta}_k \\ \dot{\zeta}_1 = -v_y - a\dot{\Psi} + v_x\Theta + v_x\gamma_1 \\ \dot{\zeta}_2 = -v_y + b\dot{\Psi} + v_x\gamma_2 \\ \dot{\gamma}_1 = -\dot{\Psi} - \dot{\Theta} - v_x a_1\left(\zeta_1 + \dfrac{K_{\delta_1}}{c_{\xi_1}}\gamma_1\right) \\ \dot{\gamma}_2 = -\dot{\Psi} - v_x a_2\left(\zeta_2 + \dfrac{K_{\delta_2}}{c_{\xi_2}}\gamma_2\right) \\ \dddot{\theta}_k = -\dfrac{v_x k_k}{K_{\delta_k}}\ddot{\theta}_k - k_k\dfrac{\left(a_k + b_k\right)^2}{m\left(\kappa^2 + a_k^2\right)}\dot{\theta}_k - k_k v_x\dfrac{\left(a_k + b_k\right)}{m\left(\kappa^2 + a_k^2\right)}\theta_k \end{cases} \quad (1)$$

where Ψ – combination rotation angle [rad], v_y and v_x – components (lateral and longitudinal) of velocity of combination center of gravity [m/s], ζ_1, ζ_2 – side displacement front and rear tractor wheels [m], γ_1, γ_2 – slipping angle front and rear tractor wheels [rad]. Θ – mean turning angle of driven wheels [rad], θ_k – turning angle of castoring wheels [rad], a – distance from front tractor axle to combination center of gravity [m], b – distance from rear tractor axle to combination center of gravity [m], c – distance from potato planter axle to combination center of gravity [m], M – combination mass [kg], m – castoring wheels mass [kg], I_{zz} – combination moment of inertia with respect to vertical axis [kg*m^2], $c_{\xi 1}$, $c_{\xi 2}$ – coefficients of lateral stiffness of tractor tires [N/m], $K_{\delta 1}$, $K_{\delta 2}$, $K_{\delta k}$ – cornering coefficients of tractor and potato planter wheels [N/rad], a_1, a_2 – coefficients of deflected tires curvature [m^{-2}], a_k – distance from castoring wheel pivot axis to its center of gravity [m], b_k – distance from the castoring wheel pivot axis to its center of gravity [m], k_k – coefficient of castoring wheel sidewall stiffness [kg/rad].

3. CONDUCTED TEST AND SIMULATION

The identification experiment was carried out to estimate exact values of combination model parameters. The investigation was aimed at getting data about combination behavior during execute various maneuvers (change traffic lane, pass, turning with various radii) and at loads acting on combination wheels. During the measurements ISO recommendations were applied.

The modern, specially worked out apparatus kit was using during test (figure 3). It contains among other things sensor for simultaneous measurement of wheel position and orientation and microwave sensors for speed and distance measurement (Sparrer 2003). All loads (forces and moments) acting on tractor wheels and its angle velocity were measured too.

Figure 3: Testing equipment on the tractor front wheel: a) velocity sensor, b) system for measure of driven wheel position

Tractor tires property investigation was made too. The series of measurements of lateral, longitudinal, side and cornering stiffness of tires were carried out.

Obtained data was used to parameters identification of tractor - potato planter combination model.

4. MODEL IDENTIFICATION

The identification was made by minimization of loss function describing estimation error of model output (Szczepaniak 2008). Identification problem was reduced to single criterion minimization task. It can be solved by means of many procedures available for example in Matlab system (Coleman, Branch, and Grace 1999). It was assumed, that objective function describing estimation error should be non-negative function of estimated parameters:

$$F_{critt}(par) = \frac{1}{n}\sum_{k=1}^{m}\sum_{i=1}^{n}\alpha_k\left(y_{mk}(t_i) - y_{pk}(t_i)\right)^2 \qquad (2)$$

where n – number of simulation steps, *par* – vector of identified parameters of model, t_i – moments of simulation and measurement steps, y_m – *m* dimensional vector of model state parameters obtained out of simulation, y_p – *m* dimensional vector of model state parameters obtained out of identification experiment, α_k – weights of state parameters.

Properties of objective function (2) are difficult to determine because to it's calculate system of model equations (1) should be solved. In that case three different algorithms available in Matlab were tested:

- Nelder-Mead method (*fminsearch* function in Matlab) – finds minimum of unconstrained multivariable function using derivative-free method,
- *fmincon* – finds minimum of constrained nonlinear multivariable function,
- *lsqnonlin* – solves nonlinear least-squares (nonlinear data-fitting) problems:

$$\min_x f(x) = \frac{1}{2}\left(f_1^2(x) + f_2^2(x) + \cdots + f_m^2(x)\right) = \frac{1}{2}\|F(x)\|_2^2 \qquad (3)$$

Test of selected optimization methods effectiveness was conducted by means of numerical experiment, on the basis results obtained out of computer simulation. Optimal values of identified parameters were known owing to using the same model as standard model and identified model. Beside the problems connected with measurement inaccuracy and model simplification were avoided. Used approach makes possible minimize identification error to zero during the test. It allows to comparison and evaluation of proposed optimization methods efficiency.

As the result of carried out numerical experiment it turned out that the procedure *fmincon* is the worst. The best is the procedure *fminsearch* (Nelder Mead method).

After numerical test and optimization method selection proper identification of model parameters was started.

The identification was carried out by means of minimization of function (2) on the basis comparison values of model state parameters such as lateral velocity or combination rotation angle obtained from simulation and from measurements. Vector of identified parameters included: I_{zz}, $K_{\delta1}$, $K_{\delta2}$, $K_{\delta k}$, κ, k_s, $c_{\xi1}$, $c_{\xi2}$, a_1, a_2.

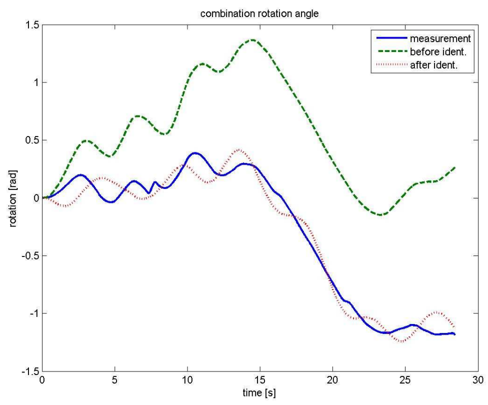

Figure 4: Charts of combination rotation angle (Ψ) obtained from measurement and from simulation before and after identification

5. FORECAST SIMULATION

After getting correct parameters values of model tractor – potato planter, model can be used to forecast simulation conducting. It enables constructors to describe influence of the parameters on combination behaviour.

In the real construction we can change one of the parameters only with simultaneously change another one. For example: we can change location of combination axle only together with change centre of gravity location and moments of inertia. Using the model we can model such changes too of course. But we can estimate influence of only single parameter on machine behaviour. It facilitates constructor decision concerning selection of changed parameters.

Sampled analyses of tractor – potato planter combination behaviour are presented. The legends enclosed to the charts show values of the changed parameters.

On the figures 5 and 6 we can see changes of combination trajectories caused to changes of distance between combination center of gravity and tractor front axle.

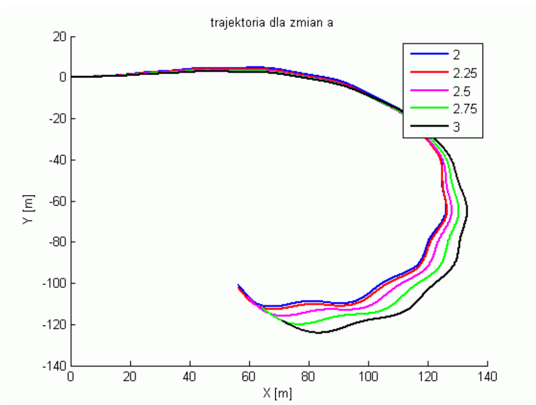

Figure 5: Changes of combination trajectory for various distances from front tractor axle to combination center of gravity (the distances values are shown on the legend [m]) during ride along a circle

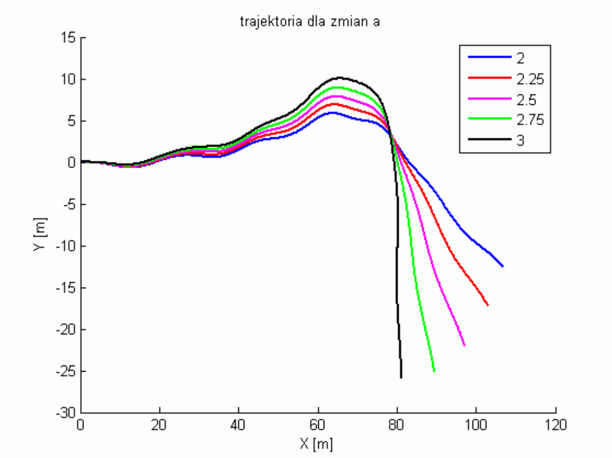

Figure 6: Changes of combination trajectory for various distances from front tractor axle to combination center of gravity (the distances values are shown on the legend [m]) for cornering

We can check, that according to expectation (potato planter wheels are castoring wheels) change only distance betweeen axle of potato planter and combination center of gravity doesn't influence on motion of the vehicle significantly (figure 7).

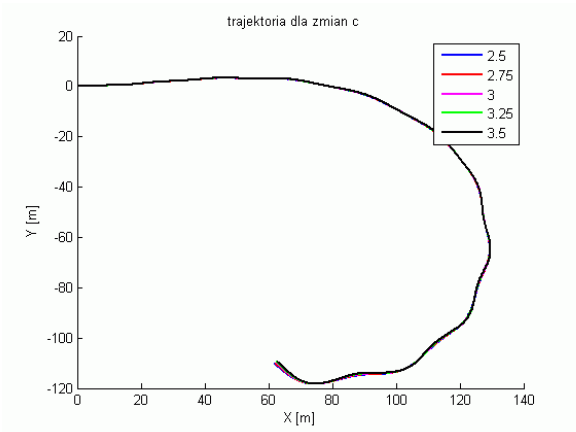

Figure 7: Changes of combination trajectory for various distances from potato planter axle to combination center of gravity (the distances values are shown on the legend [m]) during ride along a circle

The location of centre of gravity has especially influence on combination behaviour. Its shift means simultaneous change of distances from both tractor axles and planter axle. The positive value showed on the legend means forward shift (figure 8).

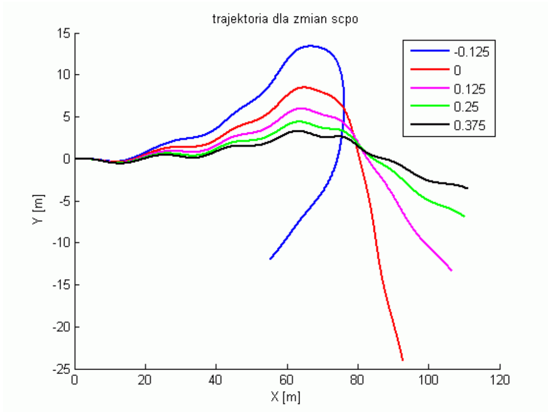

Figure 8: Changes of combination trajectory for various combination center of gravity position (the shift values are shown on the legend [m], positive values mean forward shift) for cornering

We can see that back shift center of gravity is able to result in stability loss (blue line).

Test of interactions between individual model parameters is important too. The figures 9 and 10 show the influence of tractor front axle tires lateral stiffness on adequately front and back tractor tires side displacement.

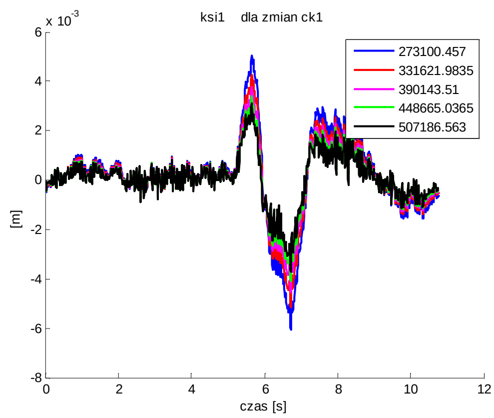

Figure 9: The changes of lateral displacement of tractor front axle tires (model variable ζ_1 [m]) for various values of lateral stiffness of tractor front axle tires $c_{\xi 1}$ [N/m] (see legend)

According to expectations less displacement occurred for bigger tires stiffness. It is visible especially during changes of tires displacement direction.

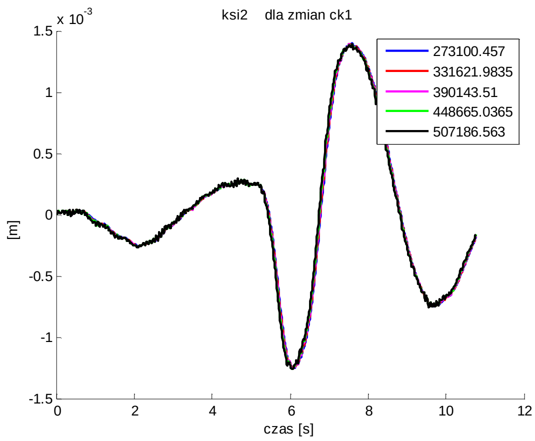

Figure 10: The changes of lateral displacement of tractor back axle tyres (model variable ζ_2 [m]) for various values of lateral stiffness of tractor front axle tires $c_{\xi 1}$ [N/m] (see legend)

Figure 10 shows that change of tractor front axle tires stiffness doesn't influence significantly on behaviour of back axle tires.

Similarly, change of lateral stiffness of back axle tires causes changes of dislacements only for back axle tires (figures 11 and 12).

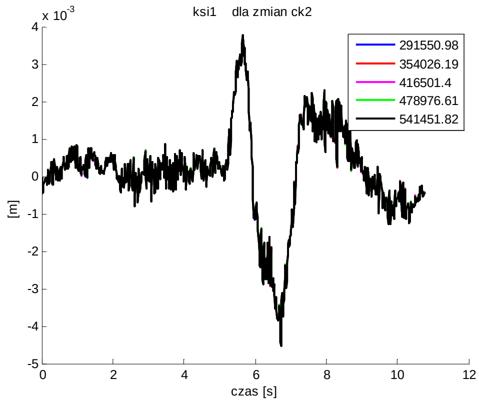

Figure 11: The changes of lateral displacement of tractor front axle tires (model variable ζ_1 [m]) for various values of lateral stiffness of tractor back axle tires $c_{\xi 1}$ [N/m] (see legend)

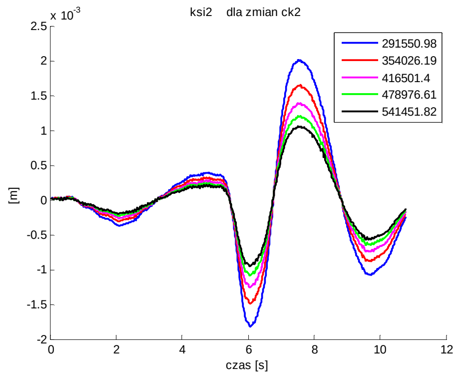

Figure 12: The changes of lateral displacement of tractor back axle tires (model variable ζ_2 [m]) for various values of lateral stiffness of tractor back axle tires $c_{\xi 1}$ [N/m] (see legend)

On figure 12 we can see that bigger stiffness of back axle tires cause less lateral displacement of this axle tires, The differences are less than for tires of front axle. It is caused probably by bigger pressure on tractor back axle.

6. CONCLUSIONS

Our long-term goal of presented work is providing agricultural machine constructors with tools (adequate models) making possible machine traffic on the diverse ground simulation on the relatively early stage of designing, before prototype construction. It will allow taking into consideration construction properties influence on agricultural machine way of motion, particularly on motion stability.

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