Agronomy Research **19**(S1), 896–909, 2021
https://doi.org/10.15159/AR.21.088

Improving ecological safety of agricultural off-road machines operating of sloped ground

J. Rédl[1,*] and P. Findura[2]

[1]Slovak University of Agriculture in Nitra, Faculty of Engineering, Department of Machine Design, Tr. A. Hlinku 2, SK949 76 Nitra, Slovakia
[2]Slovak University of Agriculture in Nitra, Faculty of Engineering, Department of Machines and Production Biosystems, Tr. A. Hlinku 2, SK949 76 Nitra, Slovakia
[*]Correspondence: jozer.redl@uniag.sk

Received: January 31st, 2021; Accepted: April 10th, 2021; Published: May 19th, 2021

Abstract. The goal of this article is the analysis of the specific technical properties of the agricultural machinery to prevent the ecological impacts on nature in case of a machine accident. The loss of stability and overturning of the machine is an important part of the farm safety code of practice document and the source of the ground contamination with fuel and no-bio lubricants. The main work is oriented to determine and derive the steps of prevention or prediction of dangerous states of the agricultural off-road vehicle operating on sloped ground and even applicable for heavy trucks. These steps are based on the experimental measurement of accelerations functions and implementing these into the mathematical model and following the European Union Regulations. The recommended simulation and obtained results can tell the engineers in the design process of the prototype how to accurate the technical parameters to keep the machine in a safe state while the machine is under acting the dynamic loads. Optimization of specific dimensions in the process of design can help to improve the ecological safety of the agricultural machines operating on sloped ground. Some theoretical methods are based on the Slovak National Standard STN 47 0170.

Key words: acceleration gauge, accident on slope, overturning, soil contamination, EU regulation.

INTRODUCTION

A report from Eurostat (2019) declared that the countries in the EU have a total land area and share of farmland in total land area in 2016 year 39.9% and 4.1% from EU populations are employers in agriculture. Agriculture is one of the most dangerous employment in the economy. Many researchers have been analyzed the causes of the employer's accidents. In Slovakia, the accidents rate in agriculture between 2000–2012 years period has been analyzed and has been counted the total injuries rate 12,874 and 90 was the fatal injuries (Váliková et al., 2013). The accident rates and their types in EU agricultural area have been analyzed between 2013–2019 years and in 2013 was in EU 366 fatal accidents and 135,260 non-fatal accidents (Merisalu et al., 2019). The EU farming population is predominantly self-employed, who are largely outside the scope of EU occupational safety and health (OSH) legislation. Utilizing effective communications approaches to transmit clear messages is a possible way of motivating farmer OSH adoption. The Public Health Model (PHM) of accident causation conceptualizes an accident as occurring due to multiple interacting physical and human factors while the Social-Ecologic Framework enhances the PHM by defining various levels of the social environment, which are influential on persons' OSH actions (Mc Namara et al., 2019). The national bodies for control of employer's accidents record all occurred cases. The National Labour Inspectorate in Slovakia in the 2010–2019 years period recorded 23 deadly cases, 9 hard injuries, and 2 soft injuries, and these data were processed by the Statistical Office of the Slovak Republic (2019). As a representative unit of EU we were chosen the analysis of the Estonian accident provided by Enn & Merisalu (2019). Their study aimed to analyze the dynamics of work accidents (WA) incidence by severity, gender, and lost workdays in Estonian agriculture in 2008–2017. They found in total 13 fatal work accidents have occurred, which accounts 0.8% of all the WAs (n = 1,696). The published results from the analyses about accident rates, causes, and levels of injuries were analyzed very well, but the analyses do not tell us the detailed scenes and backgrounds of accidents or possibly raised environmental damages. Several accidents arise as a consequence of agricultural machine overturns. These machines operating on sloped ground or operating on rough terrain in forestry. Wide analysis about the causes of tractors overturns and accidents from past to 2010 year has been done by Abubakar et al. (2010). A similar analysis about fatal accidents due to tractors' overturns has been published by Antunes et al. (2018). Garland (2018) published that, the harvesting machines are now being used on slopes over 100 percent (i.e. greater than 45 degrees) in varying site conditions. This should also be considered in accident reporting and analysis. As defined by Visser & Stampfer (2015) the dynamic factor reduces the slope limit where a rollover can occur. As such, loss of traction can become a significant factor and it can be deduced that most rollover accidents result from an initial loss of traction. It results in an uncontrolled gain in momentum and if followed by hitting an object, such as a stump, or a change in terrain slope, can readily result in a rollover. The basic physics with regard to retaining traction on a slope is that the gravity force pulling the machine down should not exceed the traction force that the machine can develop on the ground. Another study published by Issa et al. (2019) analyzed the influence of agricultural engineering development on the occurrences of fatal accidents in agriculture-related to farm machinery in USA. The mentioned review of accidents shows, that the fatal and other injuries of employers are the cause of the agricultural machines accidents, especially tractors overturn. To prevent machinery accidents the wide research of the operating stability is in progress. Nowadays is running intensive research, which evidence are several published research papers. The serious research has been published by Bulgakov et al. (2016), where the aim of their study was to the elaboration of the theoretical basis for the process of vertical oscillation of the combined plowing and chopping tractor-implement unit and the validation of its dynamic stability in the longitudinal and vertical plane. The research has been performed with the use of the methods of designing the analytical mathematical models of functioning of agricultural machines and machine assembly units based on the theory of tractor, the vibration theory, the theory of automatic control and dynamic stability, and the methods of computer program construction and PC-assisted numerical computation. The next research of Bulgakov et al. (2017) has been aimed on substantiate the set-up and parameters of the plowing unit with a front-mounted plow basing on the theoretical investigation of the stability of its motion in the horizontal plane. Another research published by Bulgakov et al. (2019) dealt by the investigation is a detailed examination of criteria for the stability assessment of a mechanical system used in agriculture, enabling their wide application to study the performance of the system in the case when it is affected by random forces that were not taken into account in the original model. The considered calculation methods and examples of their application make it possible to evaluate the performance of complex dynamic systems without numerical solution of complicated differential equations of the movement in the presence of external disturbances.

To prevent the possible accidental cases the European Union Commission released regulation No 167/20133, where says: 'point 11: To ensure a high level of functional safety, occupational safety, and environmental protection, the technical requirements and environmental standards applicable to vehicles, systems, components, and separate technical units concerning type-approval should be harmonized. Point 12: It is appropriate to establish the principle that vehicles must be designed, constructed, and assembled to minimize the risk of injury to the vehicle occupants and other road users.' For that purpose, manufacturers must ensure that vehicles comply with the relevant requirements set out in this Regulation. Those provisions should include, but not be limited to, requirements relating to vehicle structural integrity, systems to aid the driver's control of the vehicle, systems to provide the driver with visibility and information on the state of the vehicle and the surrounding area, vehicle lighting systems, vehicle occupant protection systems, the vehicle exterior and accessories, vehicle masses and dimensions and vehicle tires. In Chapter, I, Article 3 'Definitions', point 24, defines: 'functional safety' means the absence of unacceptable risk of physical injury or damage to the health of persons or property owing to hazards caused by mal-functional behavior of mechanical, hydraulic, pneumatic, electrical or electronic systems, components or separate technical units. The meaning of this regulation justifies the research of static and dynamic stability of agricultural off-road vehicles.

The important field of reduction of the possibilities of agricultural machinery accidents and consecutive ecological impacts is standardization. The International Organization for Standardization (ISO) released a few standards and technical reports, which deal with the safety of machinery and risk assessment. The ISO 12100 (2010) deals with the determination of the limits of machinery. Risk assessment begins with the determination of the limits of the machinery, taking into account all the phases of the machinery life. This means that the characteristics and performances of the machine or a series of machines in an integrated process, and the related people, environment, and products, should be identified in terms of the limits of machinery. Recommendations for machine manufacturers say about the inherently safe design measures. Machines shall be designed so that they have sufficient stability to allow them to be used safely in their specified conditions of use. Factors to be taken into account include:

- the geometry of the base,
- the weight distribution, including loading,
- the dynamic forces due to movements of parts of the machine, of the machine itself, or of elements held by the machine which can result in an overturning moment,
- vibration,
- oscillations of the center of gravity.

Characteristics of the supporting surface in case of traveling or installation on different sites (ground conditions, slope, etc.), and external forces, such as wind pressure and manual forces. Stability shall be considered in all phases of the life cycle of the machine, including handling, traveling, and installation, use, dismantling, disabling, and scrapping. The standard ISO 14123 (2015) deals with the reduction of risks to health resulting from hazardous substances emitted by machinery.

In Slovakia was reported the overturn of the heavy vehicle with the tank with diesel fuel. From the damaged tank has been overflowed 14,135 liters of diesel fuel and contaminating the nearby agricultural soil. Accident recovery cost was 88,662.68 Euro, Polák (2014). Streche et al. (2018) published a research paper about methods of remediation of contaminated soil with petroleum and analyzed the energy consumption of the applied method of remediation. The research about the relationship between soil contaminations due the agricultural machinery accidents is very weak. As published Visser & Stampfer (2015) for forestry machinery actual guidance on slope limits, based on either science or experience, is rare. Many guidelines refer to manufacturer's specifications, yet few of the major forestry equipment manufacturers provide slope and/or operating limits for their purpose-built machinery. Komatsu (2019) has recently published operating guidelines that indicate a slope limit of 55% when using winch assist. Also, the wheeled machines with chains or bands might have an upper limit of 45%, integral track machines up to 60%, and that tethered machines should be able to operate up to a range of 75 to 85% slope. Jucherski et al. (2005) documented that the ecological degradation of mountain areas in Poland is still significant. The situation cannot get better unless agricultural technology and engineering for mountain areas are properly developed. Currently, the lack of appropriate combined tractor-machine units and multifunctional aggregates with self-propelled tool carriers for mountain farming is especially acutely felt.

Nomenclature

$a_{1,2,3}$	translational acceleration with respect to the $_x\bar{e}_1$, $_y\bar{e}_2$, $_z\bar{e}_3$,	$\mathrm{m \cdot s^{-2}}$	q	coordinate base directions (1,2,3)	
$ag_{1,2,3}$	acceleration gauges		$\bar{r}_P$	position vector of point P	
an_q	acceleration signals from accelerations gauges, n = 1,2,3	$\mathrm{m \cdot s^{-2}}$	$\overline{r_{CG}}$	position vector of point CG	
a_{mn}	components of transformation matrix m = 1,2,3 n = 1,2,3			rotations matrix	rad
CG	center of gravity		v	velocity	$\mathrm{m \cdot s^{-1}}$
$\overline{ECG}$	computational distance	m	x_f	dislocation of center of gravity from front-end axle	m
$_{x,y,z}\bar{e}_{1,2,3}$	coordinate base directional vectors		x_r	dislocation of center of gravity from rear axle	m
g	gravitational acceleration ($\doteq 10$)	$\mathrm{m \cdot s^{-2}}$	α	angular acceleration	$\mathrm{rad \cdot s^{-2}}$
G	machine gravity vector	N	α	roll - angle produced by rotations	rad
$G_{1,2,3}$	components of gravity vector G respect to the $_x\bar{e}_1$, $_y\bar{e}_2$, $_z\bar{e}_3$,	N	α	slope angle	deg
h_3	height of center of gravity from ground	m	β	pitch - angle produced by rotations	rad

HR	distance of CG to labile stability position	m	$\beta_{1,2}$	computational angle	rad
J_2	machine moment of inertia with respect to the $_{y}\bar{e}_2$, axis	$kg \cdot m^2$	γ	yaw - angle produced by rotations	rad
KE	kinetic energy	$kg \cdot m^2 \cdot s^{-2}$	δ	computational angle	rad
$L_{1,2,3}$	dimensions of acceleration gauges dislocations	m	ε	Einstein summation parameter	
m	machine mass	kg		Euler parameters	
M_T	transformation matrix		Λ	matrix of Euler parameters	
n	index (1,2,3,4,5,6,7)		$\dot{\Lambda}$	matrix of Euler parameters derivatives	
P	any point on rigid body		ω	angular velocity	$rad \cdot s^{-1}$
PE	potential energy	$kg \cdot m^2 \cdot s^{-2}$	Ω	matrix of angular velocities	$rad \cdot s^{-1}$

MATERIALS AND METHODS

Physical model

Applied physical model include the off-road machine parameters, mounting adapter parameters, measurement devices with sensors, experimental ground parameters. The Reform Metrac is a municipal services tool carrier designed for extreme slopes and difficult terrain. The machine on the experimental ground is depicted in Fig. 1. The technical parameters of the tool carrier are in Table 1. The mounted front-end tool was mulcher Carroy the technical parameters are in Table 2. The area for the experiment was located near village Pohranice in Slovak Republic. The ground average slope angle was 17 degrees. The vegetation composition was follows: Festuca pratensis 15%, Poa pratensis 30%, Dactylis glomerata 30%, Arrhenatherum elatius 5%, Alopecurus pratensis 5%, clovers 5%, other herbs 10%. The average humidity of soil in the soil depth 10–25 cm was 19.5%. The average soil penetrometer resistance in soil depth range 0–80 cm was 2.7 MPa. On the measurement, the manoeuver with the machine was the ride along the contour line with reversible turning back to the contour line.

Figure 1. Machine Metrac H6X.

Table 1. Parameters of off-road machine

Parameters	Value
Manufacturer	Reform Werke
Type	Metrac H6 X
Engine	VM-D 754 SE
Fuel	diesel
Tyres	33×1550-15 BKT
Weight (kg)	2,370
Weight with tool (kg)	2,780
Wheel base (m)	1,995
Wheel track (m)	1,630
Center of gravity x_f (m)[1]	1,180
Center of gravity y (m)[2]	+0.007
Center of gravity h_3 (m)	0.74

[1] With respect to the front end; [2] With respect to the left side of the +*y* coordinate axis.

Measurement devices were set up for experimental measurement in-situ. For this purpose we are used the Adlink data acquisition devices which have been connected to PC through USB port. The data recording was realized in real-time. The used acceleration gauge ADXL 325EB is depicted in Fig. 2 and mounted on the machine in Fig. 3. The ADXL325 is a small, low power, complete 3-axis accelerometer with signal conditioned voltage outputs. The product measures acceleration with a minimum full-scale range of ± 5 g. It can measure the static acceleration of gravity in tilt-sensing applications, as well as dynamic acceleration, resulting from motion, shock, or vibration. The user selects the bandwidth of the accelerometer using the C_X, C_Y, and C_Z capacitors at the X_{OUT}, Y_{OUT}, and Z_{OUT} pins. Bandwidths can be selected to suit the application with a range of 0.5 Hz to 1,600 Hz for X and Y axes and a range of 0.5 Hz to 550 Hz for the Z axis. The detailed technical parameters are available at www.analog.com. The dislocations of mounted accelerations gauges are depicted on the picture 4.

Table 2. Parameters of mounted tool

Parameters	Value
Manufacturer	Dsp Production Sas
Mark	Carroy
Type	GF 2072 RE7F C6 2S
Description	mulch-laying adapter
Weight (kg)	410
Length (m)	1.0
Width (m)	2.27
Height (m)	1.10

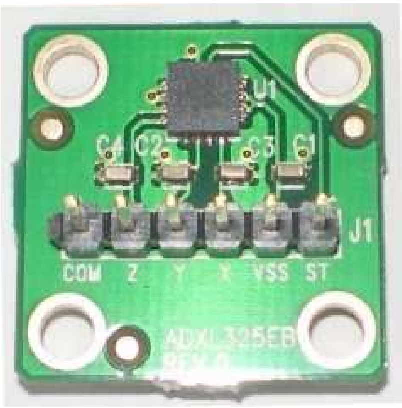

Figure 2 ADXL gauge.

Figure 3. Dislocations of sensors of acceleration on machine (is the same on the hidden part of machine).

On Fig. 4 the accelerations gauges are signed as ag1, ag2, ag3, ag4, where the measured accelerations with respect to the coordinate axes directions is an_q which means a – acclereation, n – number index for moving euquations, q – coordinate directions $_{x,y,z}\,\bar{e}_{1,2,3}$ axis with respect to the coordinate base ov machine with origin in center of gravity of machine. The determinantion of center of gravity and weigth deistribution on the machine were published by Rédl & Páleš (2017).

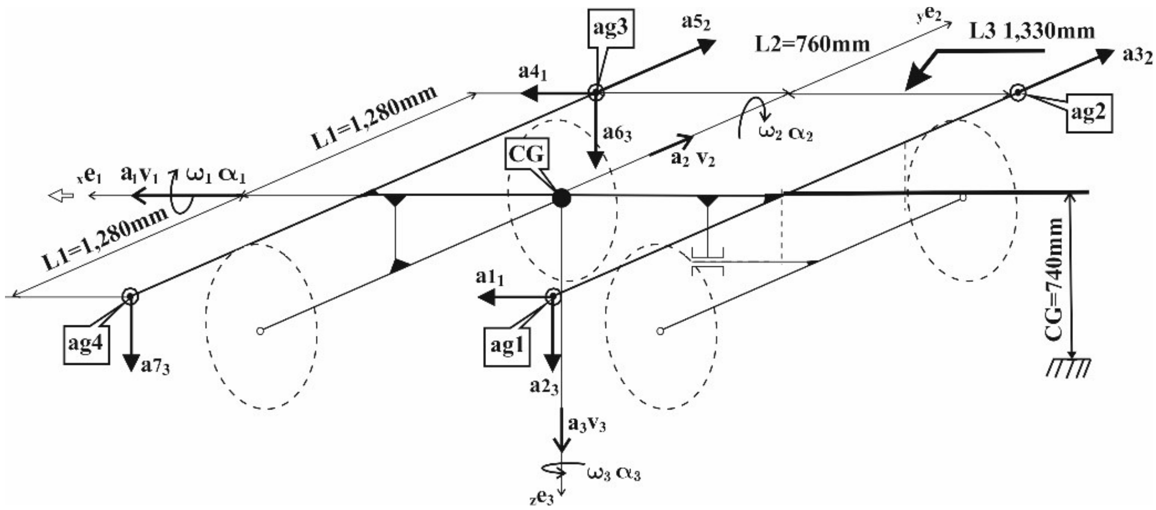

Figure 4. Model of ddislocations of sensors of acceleration on machine.

Mathematical model

Initial conditions for mathematical model are:

- neglecting the Coriolis acceleration,
- neglecting the fuel weight loss,
- neglecting the operator weight,
- neglecting gyroscopic moment of the crankshaft of motor and shafts of the mounted aggregate,
- diameter of tires are constant,
- location of center of gravity is constant with respect to the machine base dimensions.

The motion of any mass point of a rigid body in the three-dimensional space is defined with motion Eq. (1), where the mass point is a part of a rigid body, Fig. 5. The rigid body is defined as the center of gravity itself with respect to the inertial coordinate system. The position of any point *P* is defined with the position vector with respect to the center of gravity $CG \to P$.

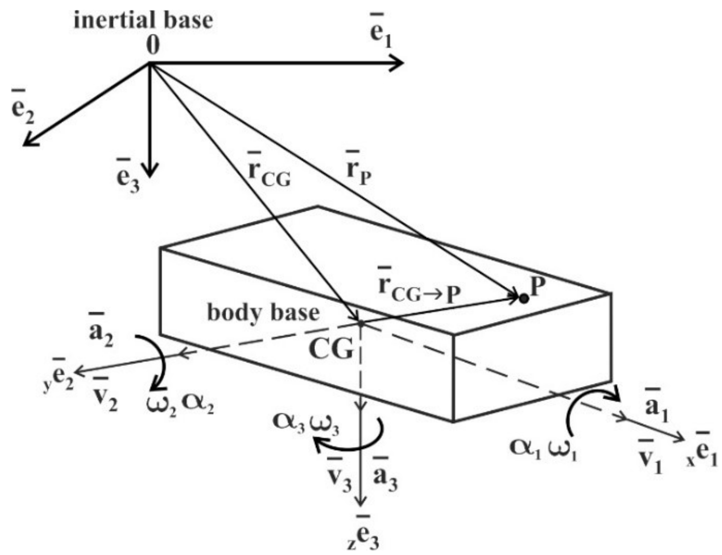

Figure 5. Rigid body in three dimensional inertial space.

$$\overline{e_i} \cdot \dot{v}^i_P = \overline{e_i} \cdot \dot{v}^i_{CG} + \varepsilon^i_{jk} \cdot \omega^j \cdot v^k \cdot \overline{e_i} + \varepsilon^i_{jk} \cdot \dot{\omega}^i \cdot \underset{CG\to P}{r^k} \cdot \overline{{}_q e_i} + \varepsilon^i_{mn} \cdot \varepsilon^i_{jk} \cdot \omega_n \cdot \omega_j \cdot$$
$$\cdot \underset{CG\to P}{r^k} \cdot \overline{{}_q e_i} + \varepsilon^i_{jk} \cdot \left(2 \cdot \omega^j\right) \cdot \underset{CG\to P}{\dot{r}^k} \cdot \overline{{}_q e_i}, \tag{1}$$
$$where\ i,j,k = 1,2,3;\ q = x,y,z$$

Where $\overline{e_i}$ is a unit vector with components $\overline{e} = \left(\overline{e_1}, \overline{e_2}, \overline{e_3}\right)$ of inertial base, $\overline{{}_q e} = \left(\overline{{}_x e_1}, \overline{{}_y e_2}, \overline{{}_z e_3}\right)$ is a unit vector of body base. For all vectors $\overline{e_i}$, $\overline{{}_q e}$, parameters ε^i_{jk} and all remained components of the Eq. (1) we used the Einstein summation convention where v is a velocity, r is a position vector, ω is an angular velocity. The point sign above the some components indicates its differentiation. Neglecting the Coriolis acceleration $\varepsilon^i_{jk} \cdot \left(2 \cdot \omega^j\right) \cdot \underset{CG\to P}{\dot{r}^k} \cdot \overline{{}_q e_i}$ and decomposition of elements with Einstein summation to its components, we got the moving equations of center of gravity with respect to the inertial base as follows:

$$a_1 = \dot{v}_1 + \omega_2 \cdot v_3 - \omega_3 \cdot v_2 - x \cdot \left(\omega_2^2 + \omega_3^2\right) + y \cdot \left(\omega_1 \cdot \omega_2 - \dot{\omega}_3\right) + z \cdot \left(\omega_1 \cdot \omega_3 - \dot{\omega}_2\right),$$
$$a_2 = \dot{v}_2 + \omega_3 \cdot v_1 - \omega_1 \cdot v_3 - x \cdot \left(\omega_1 \cdot \omega_2 + \dot{\omega}_3\right) - y \cdot \left(\omega_1^2 + \omega_3^2\right) + z \cdot \left(\omega_2 \cdot \omega_3 - \dot{\omega}_1\right), \tag{2}$$
$$a_3 = \dot{v}_3 + \omega_1 \cdot v_2 - \omega_2 \cdot v_1 + x \cdot \left(\omega_1 \cdot \omega_3 + \dot{\omega}_2\right) - y \cdot \left(\omega_2 \cdot \omega_3 - \dot{\omega}_1\right) - z \cdot \left(\omega_1^2 + \omega_2^2\right).$$

The Eqs (2) could be rewrite for six degrees of freedom where the accelerations $\alpha_1 - \alpha_6$ are obtained from experimental measurement from accelerations gauges. The dislocation of accelerations gauges are mounted on steel frame, oriented in horizontal plane of center of gravity, with dislocations depicted on Fig. 4.
For the spatial identification of rigid body with respect to the inertial base we were used the Euler parameters Λ expressed in the matrix form as follows:

$$\left[\dot{\Lambda}\right] = \frac{1}{2}[\Omega] \cdot [\Lambda], \tag{3}$$

where $\left[\dot{\Lambda}\right]$ is a matrix of Euler parameters derivatives, $[\Omega]$ is the matrix of angular velocities obtained from experiment. Solving the Eq. (3) we got the transformation matrix parameters a_{ij} where $i = 1,2,3; j = 1,2,3.$ We were created the transformation matrix as follows:

$$\left[M_T\right]_i = \prod_{i=1,2,3,..}^{n} \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}_i^T, \tag{4}$$

where the T in matrix superscript position indicates the matrix transposition on each steps $i\,to\,n$. For parameters transformation from body base to inertial base the transformation matrix $[M_T]$ has been used as follows:

$$\text{gravity acceleration vector in initial position } \left[G_0\right] = \left[T_{1,2,3}\right] \cdot \left[G\right], \tag{5}$$

$$\text{gravity acceleration vector } \left[G_i\right]=\left[M_{T(i)}\right]\cdot\left[G_0\right], \tag{6}$$

$$\text{angular velocity } \left[\Omega_{Ts}\right]=\left[M_T\right]\cdot\left[\Omega_T\right], \tag{7}$$

The differential Eqs (2) and (3) were solved numerically with application the Runge-Kutta numerical method of fourth degree as published by Rédl et al. (2015).

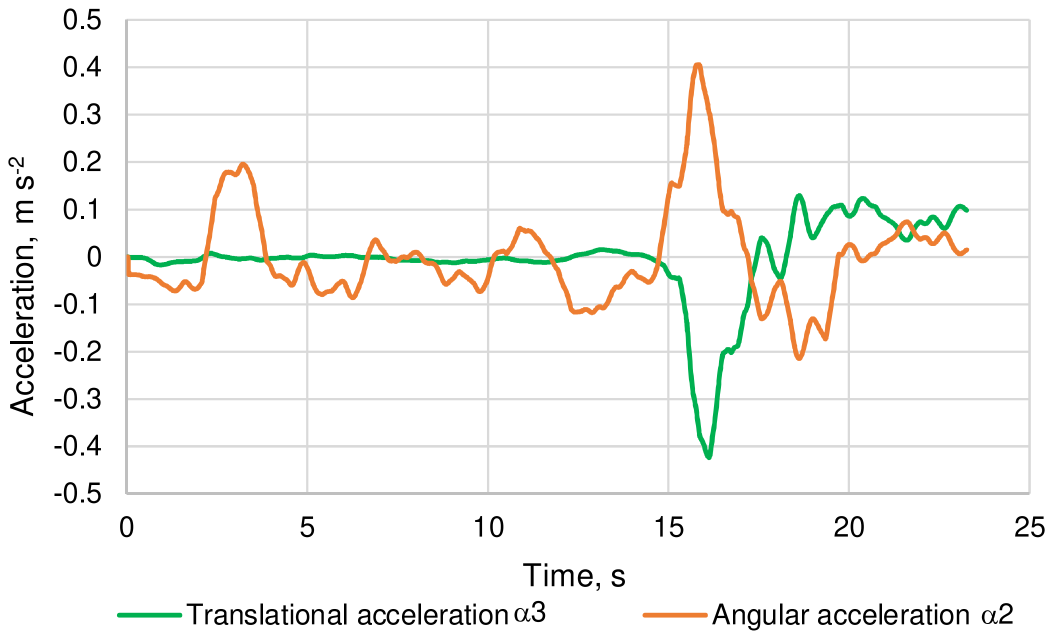

Figure 6. Machine center of gravity accelerations.

Solving the Eq. (3) we got the components of transformation matrix (4) as follows:

$$a_{11}=\lambda_0^2+\lambda_1^2-\lambda_2^2-\lambda_3^2, a_{12}=2\cdot\left(\lambda_1\cdot\lambda_2+\lambda_0\cdot\lambda_3\right), a_{13}=2\cdot\left(\lambda_1\cdot\lambda_3-\lambda_0\cdot\lambda_2\right),$$

$$a_{21}=2\cdot\left(\lambda_1\cdot\lambda_2-\lambda_0\cdot\lambda_3\right), a_{22}=\lambda_0^2+\lambda_2^2-\lambda_3^2-\lambda_1^2, a_{23}=2\cdot\left(\lambda_2\cdot\lambda_3+\lambda_0\cdot\lambda_1\right), \tag{8}$$

$$a_{31}=2\cdot\left(\lambda_3\cdot\lambda_1+\lambda_0\cdot\lambda_2\right), a_{32}=2\cdot\left(\lambda_2\cdot\lambda_3-\lambda_0\cdot\lambda_1\right), a_{33}=\lambda_0^2+\lambda_3^2-\lambda_1^2-\lambda_2^2,$$

Rotation matrix $\left[T_{1,2,3}\right]$ has the next form:

$$\left[T_{1,2,3}\right]=\begin{bmatrix}1 & 0 & 0\\ 0 & \cos\alpha & \sin\alpha\\ 0 & -\sin\alpha & \cos\alpha\end{bmatrix}\cdot\begin{bmatrix}\cos\beta & 0 & -\sin\beta\\ 0 & 1 & 0\\ \sin\beta & 0 & \cos\beta\end{bmatrix}\cdot\begin{bmatrix}\cos\gamma & \sin\gamma & 0\\ -\sin\gamma & \cos\gamma & 0\\ 0 & 0 & 1\end{bmatrix} \tag{9}$$

To derive the stability factor of machine which is operating on slope we had to determine the gravity mass vector and its components during the experiment. In the start position the machine gravity acceleration force has the form:

$$\begin{bmatrix}G_{1(0)}\\ G_{2(0)}\\ G_{3(0)}\end{bmatrix}=\left[T_{1,2,3}\right]\cdot\begin{bmatrix}0\\ 0\\ G\end{bmatrix}, \tag{10}$$

For the determination of the stable state of the machine during the maneuver on the slope we designed the model of the vehicle overturn. The geometrical interpretation of the center of gravity dislocation during the overturning is depicted in Fig. 7. The displayed overturning process is related to the manoeuver in Fig. 8.

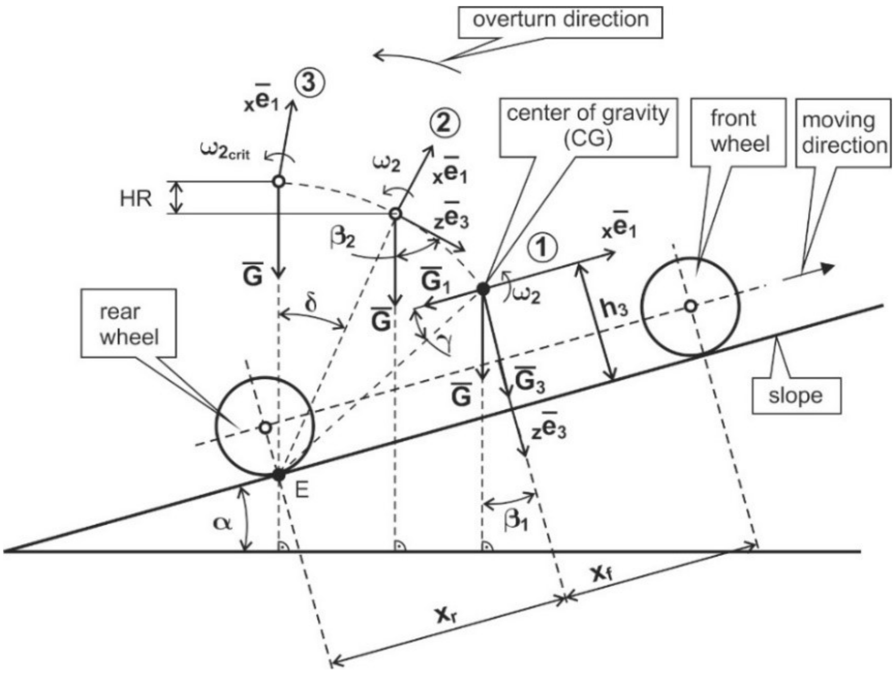

Figure 7. Machine overturning model.

The tool carrier operated on the sloped ground on the defined trajectory. The trajectory was signed with surveying rods. The duration of the maneuver was approximately 23 seconds. The maneuver was a ride along the contour line with turning to the opposite direction of the contour line. This a usual maneuver of the agricultural off-road machines operating on slopes. From experimental measurement, we got the relevant time series function of translational and angular accelerations of the center of gravity of the machine. They are depicted in Fig. 6.

RESULTS AND DISCUSSION

The overturning model has three phases. The overturning process is related to the tipping axes. The phase ① is defined with the stable condition of the ride. The phase ② is defined with the beginning of the overturning when the dislocation of the center of gravity changes due to the influence of dynamics of ride and increasing slope angle. The kinetic energy is raising as a cause of increasing angular velocity and translational velocity. The translational velocity is increasing due to the operator interaction with the sustainable velocity of the machine. The phase ③ is defined with the state of labile position. In this state, the overturning is not finished yet. The kinetic energy does not have a sufficiently high value cause to overturning the machine around the rear tipping axis. The value of angular velocity in the labile state of stability we called a critical angular velocity. Overrun of the value of critical angular velocity causes the machine to overturn inevitably and causes fatal damages to the machine. To derive the value of critical angular velocity we define the gravity acceleration vector components as follows:

$$\begin{bmatrix} G_{1(i)} \\ G_{2(i)} \\ G_{3(i)} \end{bmatrix} = [M_T] \cdot \begin{bmatrix} G_{1(0)} \\ G_{2(0)} \\ G_{3(0)} \end{bmatrix}. \tag{11}$$

Deriving the next geometrical relationships with respect to the Fig. 5 are the next:

$$G = \sqrt{G_1^2 + G_3^2}\ .$$

$$\beta_1 = \arctan\frac{G_1}{G_3},\ SH = \frac{\frac{\pi}{2} - \arctan\frac{CG_3}{x_r}}{\beta_1},$$

$$\overline{ECG} = \sqrt{CG_3^2 + x_r^2}\ , \tag{12}$$

$$HR = \overline{ECG} \cdot \left(\cos\delta - \cos\left(\frac{\pi}{2} - \beta_1 - \gamma \right) \right),$$

Kinetic energy will be:

$$KE = \frac{1}{2} J_2 \cdot \omega_2 + \frac{1}{2} \omega_2^2 \cdot \overline{ECG}^2 \cdot m, \text{ where}$$

$$m = \frac{G}{g} = \frac{G}{10} = 0.1G, \text{ and we got:} \tag{13}$$

$$KE = \frac{1}{2} \omega_2^2 \cdot \left(J_2 + 0.1G \cdot \overline{ECG}^2 \right),$$

where J_2 is the moment of inertia of machine about the ${}_Y e_2$ axis and has the value $J_2 = 943.36\ kg.m^2$.

Consumption of kinetic energy (13) from state ① to state ② will be $KE = HR \cdot G$. If the position of center of gravity is on the labile position its means that the line $\overline{ECG}$ is perpendicular on the plane of slope and lays on the tipping axis. The center of gravity has the potential energy:

$PE = m \cdot g \cdot \Delta h$, where $\Delta h = \overline{ECG} - \overline{ECG} \cdot \sin(\beta_1 + \gamma)$ and after some corrections we got:

$$PE = G \cdot \overline{ECG} \cdot \left(1 - \sin(\beta_1 + \gamma) \right). \tag{14}$$

The labile stability will change when the condition $KE \geq PE$ will be satisfied with the range of critical angular velocity $\omega_{2_{Crit}}$. With combination of Eq. (13) and (14) we got the critical angular velocity:

$$\omega_{y_{crit}} = \sqrt{\frac{2G \cdot \overline{ECG} \cdot \left(1 - \sin(\beta_1 + \gamma) \right)}{J_2 + 0.1G \cdot \overline{ECG}^2}}\ . \tag{15}$$

The stability is failure when $\omega_2 \geq \omega_{2_{Crit}}$. For other tipping axes the mathematical procedures are identical. The critical angular velocities for analyzed machine maneuver are depicted in Fig. 9.

From Figs 6 and 9 we can detect that the turning maneuver starts around 15 seconds. When the machine running along the contour line, the rear tipping axis is inactive. After this moment the rear tipping axis became active (machine front end goes in front of the slope) and lateral tipping axes became active. The machine starts turning. The dynamic forces acting on the vehicle on rounding especially the inertial centrifugal force. Between 15 seconds and 20 seconds, the rear tipping axis became active. In this position of the machine is a high risk of overturning around the rear overturning axis. Also, the left and right tipping axes are activated as is shown in Fig. 8. The most dangerous state occurs in the critical angular velocity of lateral tipping axes. The critical angular velocity reaches the value when the angular velocity reaches this value the possibility of overturning around the lateral axis very high. If the active stability control device is mounted on the machine, the pitch angular velocity is indicated the possible risk of overturning as published by Rédl et al. (2014). Eliminating the risk of the overturning of the machine will increase the operating and ecological safety of agricultural machines.

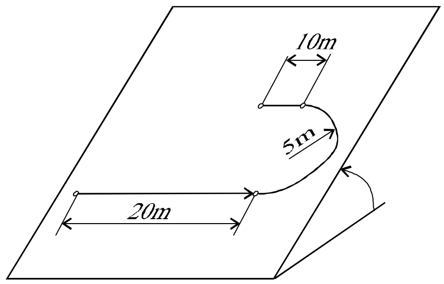

Figure 8. Maneuver.

Prediction of the tractor overturn is the serious problem in the agricultural machinery. The mathematical models created by Previati et al (2014) are able to estimate the rollover limit of a farm tractor. The rollover phenomenon is investigated by considering the static stability of the farm tractor on a sloped surface. The authors derived three mathematical models to understand the basic features of the rollover mechanism. The models are able to predict the (static) rollover limit for any orientation of the farm tractor with respect to the slope. The effects of tyre stiffness (vertical and lateral) and nonsymmetrical implement positioning are analyzed also. The limitation of presented model is fact that the models did not actuated by real technical function. From this point of view is usable for prediction of static states of overturns.

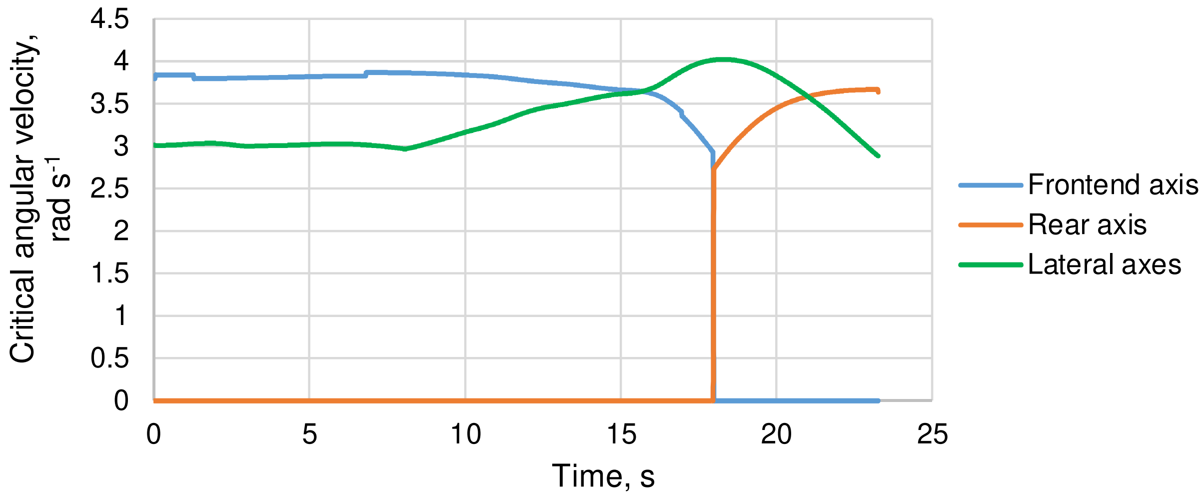

Figure 9. Critical angular velocity.

Bietresato & Mazzetto (2018) stated that unstopped overturning must be avoided at all to prevent serious damages to people and things near the facility, due to the dangerous condition of having a relevant mass in a not-controlled motion within an enclosed area. Reporting of the agricultural damages and the outflow of the fuel or other technical liquid due to machine accident is very lack. Kogler et al. (2015) determined that the information content of accident reports, because of insufficient information about the accident-causing human-machine interaction, does not suffice to derive or develop further sustainable preventive measures. The reporting of the soil contamination is missing.

The Slovak standard STN 47 0170 defines the mathematical background of determination of allowed operating slope angle for agricultural machines. The developed mathematical model based on the Slovak standard enables the prediction of the dangerous states of the machine during the maneuver.

CONCLUSION

The study presenting the nowadays actual problems about the dangerous consequences of agricultural machines overturn and the ecological impact on the agricultural soil. We designed the mathematical model for the determination of critical angular velocity which has a major influence on the dynamic stability of the agricultural machine operating on sloped ground. The mathematical model is based on the Slovak national standard STN 47 0170. We realized the experimental measurement with an agricultural machine on defined land parameters and slope. Designed mathematical model processed the measured technical function of the acceleration of the center of gravity of the machine. The derived geometrical relationship of the center of gravity dislocation allows determining the critical angular velocity related to the active tipping axis. Carrying out the experimental measurements for certain maneuvers for certain operating conditions we able to implement the boundary ranges of critical angular velocities into the active stability control devices and eliminated the machine accidents. That improve also the ecological safety of agricultural machines operating on the sloped ground.

REFERENCES

Abubakar, M.S., Ahmad, D. & Akande, F.B. 2010. A Review of Farm Tractor Overturning Accidents and Safety. *Pertanika J. Sci. & Technol.* **18**(2), 377–385.

Antunes, S.M., Cordeiro, C. & Teixeira, H.M. 2018. Analysis of fatal accidents with tractors in the Centre of Portugal: Ten Years Analysis. *Forensic Science International Volume* **287**, June 2018, Pages 74–80. https://doi.org/10.1016/j.forsciint.2018.03.048

Analog.com ADXL 325 Data Sheet [Internet 25.03.2021], available from:
https://www.analog.com/media/en/technical-documentation/data-sheets/ADXL325.pdf

Bietresato, M. & Mazzetto, F. 2018. Increasing the safety of agricultural machinery operating on sloping grounds by performing static and dynamic tests of stability on a new-concept facility. *Int. J. of Safety and Security Eng.* **8**(1), 77–89 . DOI: 10.2495/SAFE-V8-N1-77-89

Bulgakov, V., Adamchuk, V. -Arak, M., Nadykto, V., Kyurchev, V. & Olt, J. 2016. Theory of vertical oscillations and dynamic stability of combined tractor-implement unit. *Agronomy Research* **14**(3), 689–710.

Bulgakov, V., Adamchuk, V., Nadykto, V., Kistechok, O. & Olt, J. 2017. Theoretical research into the stability of motion of the ploughing tractor. *Agronomy Research* **15**(4), 1517–1529, 2017. https://doi.org/10.15159/AR.17.069

Bulgakov, V., Kaletnik, H., Goncharuk, T., Rucins, A., Dukulis, I. & Pascuzzi, S. 2019. Research of the movement of agricultural aggregates using the methods of the movement stability theory. *Agronomy Research* **17**(5), 1846–1860. https://doi.org/10.15159/AR.19.189

Enn, A. & Merisalu, E. 2019. Dynamics of work accidents incidence by severity, gender and lost workdays in Estonian agricultural sector and sub-sectors in 2008–2017. *Agronomy Research* **17**(4), 1617–1629. https://doi.org/10.15159/AR.19.169

Eurostat. 2019. Agriculture, forestry and fishery statistics 2019 edition, Luxembourg: Publications Office of the European Union, 2019 ISBN 978-92-76-13193-9, https://doi:10.2785/798761, KS-FK-19-001-EN-N

Garland, J.J. 2018. Accident reporting and analysis in forestry: guidance on increasing the safety of forest work. *Forestry Working Paper* No. 2. Rome, FAO.

Issa, S.F., Patrick, K., Thomson, S. & Rein, B. 2019. Estimating the Number of Agricultural Fatal Injuries Prevented by Agricultural Engineering Developments in the United States. *Safety* **5**(63). doi:10.3390/safety5040063

ISO 12100. 2010 Safety of machinery - General principles for design - Risk assessment and risk reduction.

Jucherski, A., Golka, W. & Eymontt, A. 2005. Agricultural engineering in the ecological mountian farms. *Rural Areas and Development* **3**(2005).

Kogler, R., Quendler, E. & Boxberger, J. 2015. Analysis of occupational accidents with agricultural machinery in the period 2008–2010 in Austria. *Safety Science* **72**, 319–328.

Komatsu report 2019. www.komatsu.com. Available at: https://home.komatsu/en/ir/library/annual/pdf/KMT_AR19E_spread.pdf. Accessed 08.10.2020.

Mc Namara, J., Griffin, P., Phelan, J., Field, W.E. & Kinsella, J. 2019. Farm health and safety adoption through engineering and behaviour change. *Agronomy Research* **17**(5), 1953–1959. https://doi.org/10.15159/AR.19.151

Merisalu, E., Leppälä, J., Jakob, M. & Rautiainen, R.H. 2019. Variation in Eurostat and national statistics of accidents in agriculture. *Agronomy Research* **17**(5), 1969–1983. https://doi.org/10.15159/AR.19.190

Polák, R. 2014. Report on the extraordinary deterioration of water quality on the locality Dolné Saliby on 12.3.2014 no. 3368-8818/326/2014 Dom. Hydropol, Rudolf Polák s.r.o. Rajská l, 81108 Bratislava.

Previati, G., Gobbi, M. & Mastinu, G. 2014. Mathematical models for farm tractor rollover prediction. *Int. J. Vehicle Design,* Vol. **64**, Nos. 2/3/4.

Rédl, J. & Páleš, D. 2017. Algorithm of determination of centre of gravity of agricultural machine with error estimation. *Mathematics in Education, Research and Applications* **3**(2), 95–103. doi: https://doi.org/10.15414/meraa.2017.03.02.95-103

Rédl, J.-Váliková, V. & Antl, J. 2014. Design of active stability control system of agricultural off-road vehicles. *Research in agricultural engineering* **60**, 77–84. ISSN 1212-9151

Rédl, J., Váliková, V., Páleš, D. & Antl, J. 2015. Application of numerical integration in technical practice. *Math. Educ. Res. Appl.* **1**(1). doi: http://dx.doi.org/10.15414/meraa.2015.01.01.12-17

Regulation (EU) No 167/2013 of the European Parliament and of the Council of 5 February 2013 on the approval and market surveillance of agricultural and forestry vehicles.

Váliková, V., Rédl, J. & Antl, J. 2013. Analysis of Accidents Rate of Agricultural Off-Road Vehicles. *Journal of Central European Agriculture* **14**(4), 1303–1316. doi: 10.5513/JCEA01/14.4.1348

Visser, R. & Stampfer, K. 2015. Expanding Ground-based Harvesting onto Steep Terrain: A Review. *Croatian Journal of Forest Engineering* **36**(2), 321–331.

Statistical Office Of The Slovak Republic, 2019, https://slovak.statistics.sk/

STN 47 0170. 2001. Agricultural tractors and machinery. Gradeability test metods. Safety of work. *Slovak office for standardization* 2001. Poľnohospodárske stroje a traktory. Stanovenie svahovej dostupnosti. Bezpečnosť práce. (in Slovak).

Streche, C., Cocârţă, D.M, Istrate, I. & Badea, A.A. 2018. Decontamination of Petroleum-Contaminated Soils Using the Electrochemical Technique: Remediation Degree and Energy Consumption. *Sci. Rep*. **8**(1), 3272. doi: 10.1038/s41598-018-21606-4