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Innovative system for monitoring the tip over stability of mobile excavating machines on a tracked undercarriage

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INTRODUCTION

Tip over stability is one of the most important factors affecting safe operation of an excavator. In order to avoid tipping over, the operator should comply with a series of producer recommendations or standards.

According to current practice, excavator producers determine the so called tipping loads for different positions of the work-tool. The user, on the other hand, chooses the work tool for the excavator, e.g. a bucket, taking these loads into account. It is required that the bucket volume with the material in it, does not exceed 75% of the tipping load at selected position of the tool. This procedure conforms with ISO 10567 recommendations. The 25% surplus is saved due to possible additional tipping moments resulting from dynamic forces, that might occur during excavator operation. From the literature (Dudczak, 2000) it is known, that very high dynamic forces can be observed e.g. when the manipulator is stopped rapidly while lowering (boom and arm extended).

According to ISO 10567, the tipping load for a given position of the manipulator is considered to be the one at which the machine changes to the unstable position. It is the state in which for the considered tipping line, the resultant tipping moment acting on the machine is equal to the resultant moment that acts against tipping (counter-moment).

Experiments show that a safety factor, a 25% level according to ISO 10567, effectively protects the excavator from tipping over during work, as long as it operates on stable flat ground. In case of operation on slopes or non-stable ground, meeting the standard requirements does not guarantee safety. In such cases the operator has to rely on his experience and skills.

The majority of producers state that their excavators are able to overcome slopes reaching up to 30-35 degrees. Placing an excavator on such steep slope is possible only after fulfilling some requirements. While driving on a slope, the manipulator has to be in a strictly defined position and has to be positioned in the direction of movement. While driving, the excavator should not be subjected to lateral tilt over 10 degrees.

Producers' guidelines concerning excavators operating on slopes are in most cases imprecise. Most usually they define only the slope inclination in the longitudinal direction of the machine. Rotation of the body of the machine is then possible in the range of +/-90 degrees relative to the position when the manipulator is directed towards the top of the slope. Apart from that, it is recommended to work at low speeds, accelerations and decelerations.

The requirement to operate at zero lateral inclination is impossible to implement in real life. In real life conditions, such inclination is always possible even if the operator does not realize it. The excavator operating on a theoretically flat surface can stand on a rock or other obstacle, which can lead to significant lateral inclination. In case of excavators on rails, lateral inclination can result directly from the track camber. It can reach even 6 degrees. The highest track camber in Poland is 7.2 degrees (180 mm rail height difference).

From the presented analysis it can be concluded that the operator does not have to worry about the tip over stability as long as he or she operates on stable flat ground and with bucket volume complying with standards. When the machine stands on sloping or soft ground, the operator has to take special care, as even short moments of inattention may lead to an inappropriate decision. Therefore installation of a system for monitoring of the tip over stability seems highly helpful. It can help the operator in many situations to make a proper decision. This system can be even indispensable when using an oversized bucket or long reach boom.

Although the above conclusion on the need for monitoring tip over stability was formulated for single bucket excavators, in many cases it is also correct for other mobile mining machinery and mobile earthmoving machinery. For example, the articulated mine bucket loaders can be mentioned here. These types of loaders are usually characterized by small track widths, which is very unfavorable from the point of view of tipping stability. As a result, they can often lift the boom with the load to its full height only provided that they are standing on a flat surfaceor when they do not remain in a position that allows turning with a small turning radius.

TYPICAL SYSTEMS FOR MONITORING THE TIP OVER STABILITYAVAILABLE ON THE MARKET

A classic device for monitoring tip over stability of excavators is GKD TECHNIK LTD product named ”1TMI – Total Moment Indicator” shown in Fig. 1. It shows the level of load in the bucket as a fraction of nominal load in real time. Overloading is indicated by a light flashing next to an exclamation mark. The level of use of the nominal bucket load is in this case the measure of tip over stability surplus. System 1TMI does not take into account the influence of the slope on excavator's stability. GKD TECNIK LTD has also more sophisticated systems in their offer, having more advanced functions such as e.g. „2RCI – Rated Capacity Indicator”.

Fig. 1 Device 1TMI for monitoring the nominal load use
Source: (Gkdtechnik.com, 2017)

Another company offering such systems is Prolec Ltd. One of their interesting products is a device called PMERail. It is designed for use with excavators on rails. These are particularly vulnerable to tipping over due to lower wheel base than in tracked machines. PMERail informs the operator about the current use of the nominal bucket load, however 100% of nominal tip over load is defined as 75% of tipping load for certain manipulator position. The operator's PMERail panel is illustrated in Fig. 2 and Fig. 3.

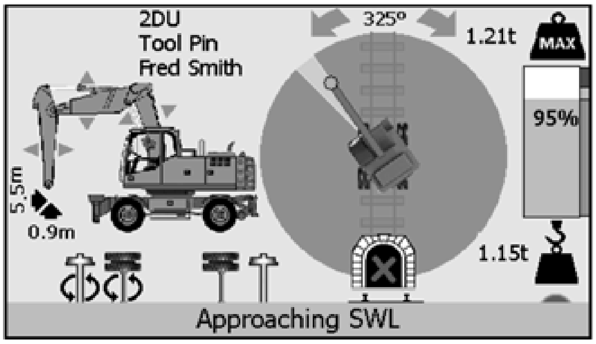

Fig. 2 Exemplary view of the operator's panel of PMERail system. Description in the text
Source: (Prolec Ltd., 2014)

In the Fig. 2 a situation is shown when the load does not exceed nominal value. The operator is informed about the use of 95% of nominal load and that all manipulator movements are safe, the system presents safe movement directions by green arrows. In Fig. 3 a situation is presented when nominal bucket load has been exceeded. The system shows information that the bucket maximum load has reached 105% of nominal value and that the up and down motion of the first part of the boom, as well as motion up of the second part of the boom and the arm is dangerous, which is indicated by red arrows on the display. Optionally some Prolec Ltd systems allow automatic blocking of dangerous motions of the manipulator in order to eliminate the possibility of an erroneous action of the operator.

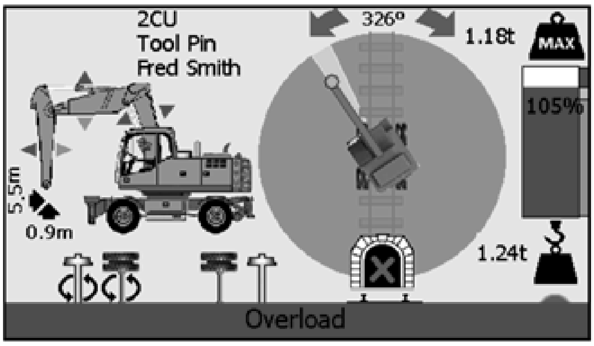

Fig. 3 Exemplary view of the operator's panel of PMERail system. Description in the text
Source: (Prolec Ltd., 2014)

All commercially available systems for monitoring tip over stability known to the authors are based on the measurement of oil pressure in the chambers of hydraulic cylinders supporting the boom. The measured pressure makes it possible to determine the moment of force with which the manipulator acts on the vehicle in order to overturn it. This moment is compared by the system with the permissible one. The permissible load however depends on the ground inclination and relative position of some parts of the machine. They must therefore be measured by the system continuously. In addition, in order to properly calculate the permissible loads the system must be provided with the location of the particular tipping edges of the machine. The currently available systems assume that the tipping edges do not change their location. However, under actual operating conditions this may not be the case (see Figure 4).

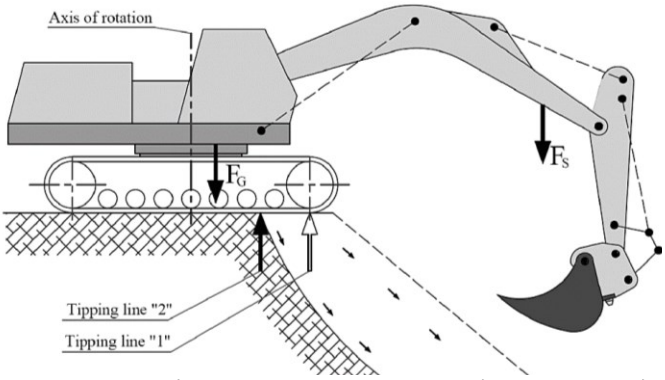

Fig. 4 Displacement of tipping edge as a result of a landslide of a slope

CONCEPT OF A NEWSYSTEM FOR MONITORING OF THE TIP OVER STABILITYIN MOBILE MACHINES ON TRACKED UNDERCARRIAGE

The systems described in Part 2 are not capable of precise calculation of tip-over stability surplus when its tipping lines are other than previously assumed. Shifting of tipping line positions can take place due to ground: instability, unevenness, low stiffness or inhomogeneity.

Addressing above mentioned drawbacks of other solutions, the authors have decided to develop a new type of system, without these shortcomings. It was assumed that the new system should determine stability surplus based on actual pressure distribution beneath the tracks. Knowing the pressure distribution it would be possible to check whether the tipping lines did not shift their position.

The system for measurement of pressure distribution under the tracks is however expensive and difficult to integrate into the machine, therefore a compromise solution has been adopted. It was assumed that the system will be based on measurement of normal loads at the vehicles supporting rollers. Such solution implicated the necessity to include in the algorithm, the values of track tension and measured loads at the rollers.

As a measure of tip-over stability surplus in the system, the lowest distance of the ZMP (Zero Moment Point) to the tipping line was assumed. The ZMP method was previously developed in order to control the tip-over stability of humanoid robots (Kajita et al., 2014). Due to its versatility, it has been recently used for control of tip-over stability of such objects more often. ZMP coordinates can be determined based on the following expressions:

$$ZMP_x = \frac{\int_S x \cdot \rho(x,y) dS}{\int_S \rho(x,y) dS} \quad (1)$$

$$ZMP_y = \frac{\int_S y \cdot \rho(x,y) dS}{\int_S \rho(x,y) dS} \quad (2)$$

where:

S – track-ground contact area,

ρ – track pressure on ground,

x, y – coordinates of selected contact points.

It is assumed that track-ground contact points lie on the same plane – the one which is defined by axes X, Y of applied global coordinate system. However modelling the tracked vehicle as an object supported only in contact points of rollers with ground, the above equations become simplified:

$$ZMP_x = \frac{\sum_{i=1}^{i=n} F_i \cdot x_i}{\sum_{i=1}^{i=n} F_i} \quad (3)$$

$$ZMP_y = \frac{\sum_{i=1}^{i=n} F_i \cdot y_i}{\sum_{i=1}^{i=n} F_i} \quad (4)$$

where:

F_i – normal reaction at the i-th supporting roller,

x_i, y_i – coordinates of i-th roller contact point with ground.

Equations(3, 4) have been used in the system for estimation of location of the ZMP. In turn, calculation of the stability surplus (SI) value is done by means of equation (5):

$$SI = min\left[\frac{\frac{L}{2} - |ZMP_x|}{\frac{L}{2}}, \frac{\frac{B}{2} - |ZMP_y|}{\frac{B}{2}}\right] \cdot 100\% \quad (5)$$

where:

L – distance between the front and back tipping line,

B – distance between side tipping lines.

The beginning of the coordinate system that defines ZMP position is located in the center of the stability rectangle formed by the tipping lines. For such assumptions, 100% stability surplus (SI = 100%) corresponds with situation, when the ZMP is located in the center of the stability rectangle. Shifting of the

ZMP to the tipping line means loss of stability surplus and a state when the vehicle is at the limit of stability.

Based on presented above conception, a demonstrator of the developed system for monitoring of tip-over stability has been built. The values calculated by the system: stability surplus and ZMP coordinates are depicted on a screen using appropriate pictograms, as shown in Fig. 5.

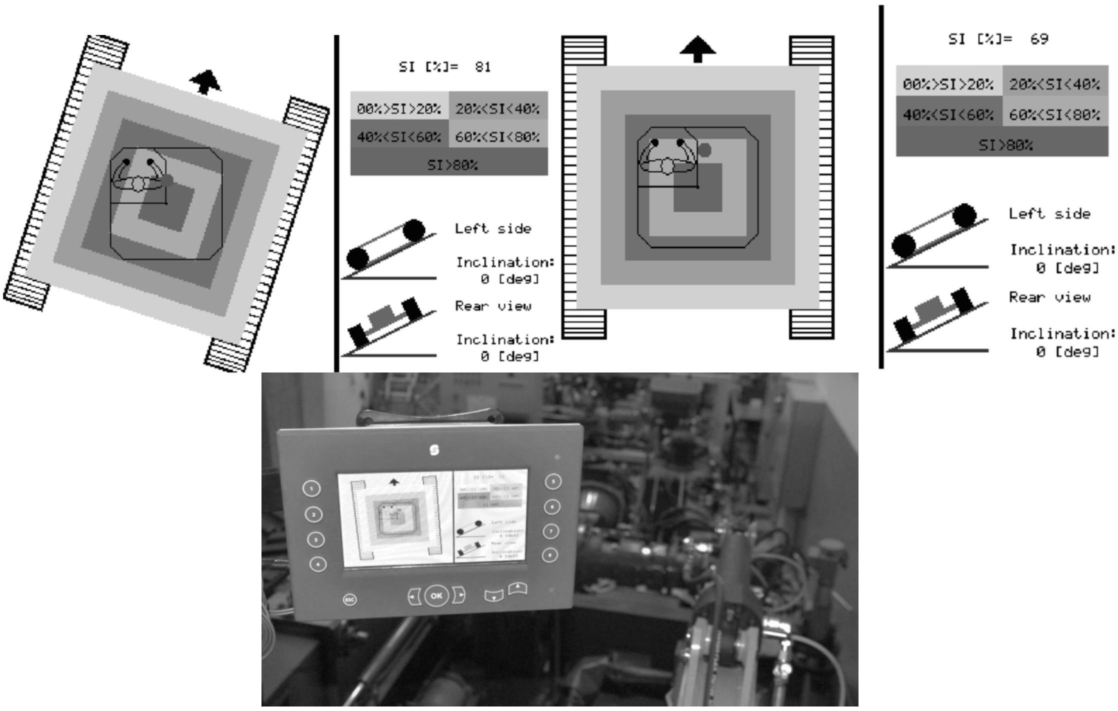

Fig. 5 Exemplary pictograms visible on the operator's screen of the new system

TEST AN DEVELOPMENT OF A NEW SYSTEM FOR MONITORING THE TIP OVERSTABILITY OF MOBILE MACHINES ON TRACKED UNDERCARRIAGE

The developed system is currently upgraded and tested. Tests are being conducted two in ways: using a simulation model and using special laboratory test stands. In order to conduct simulations, a numerical model of the excavator was made in MSC Adams software. The model was described in the paper (Kosiara and Tetlak, 2019). The virtual excavator during simulations is placed on different soft grounds. Then, different loads are placed in its bucket and the machine is being moved. During the operation of the virtual excavator, reactions at different supporting rollers are measured. These values are used by the system to determine the SI values. Such simulations allow to verify the system in different simulated states of the excavator. Exemplary results from the simulations are shown in Table 1. In particular, the table shows: sum of normal reactions determined for supporting rollers – F_i (indexing from the sprocket to the idler), coordinates of the ZMP estimated by the system – ZMP_x, stability surplus values estimated by the system – SI and mass of the load in the bucket – Q. Results presented in Table 1, were obtained during simulations of the system for a 22-ton single-bucket excavator.

Table 1 Exemplary results obtained in simulations (description in the text)

F_1 [N]	F_2 [N]	F_3 [N]	F_4 [N]	F_5 [N]	F_6 [N]	F_7 [N]	F_8 [N]	F_9 [N]	F_{10} [N]	F_{11} [N]	ZMP_x [m]	SI [%]	Q [t]
0	0	0	0	0	0	3925	32047	63526	67196	89899	1.307	28.6	4.6
0	0	0	0	0	0	0	0	16894	117609	148932	1.558	14.9	5.6

The bucket excavator was placed on sandy loam with the manipulator extended to its maximum reach. Deformation of the ground under the tracks was calculated based on a semi-empirical pressure-sink age model proposed by Bekker (Wong, J.po-0Y., 1993).The visualization of the excavator model is depicted in the Fig. 6.

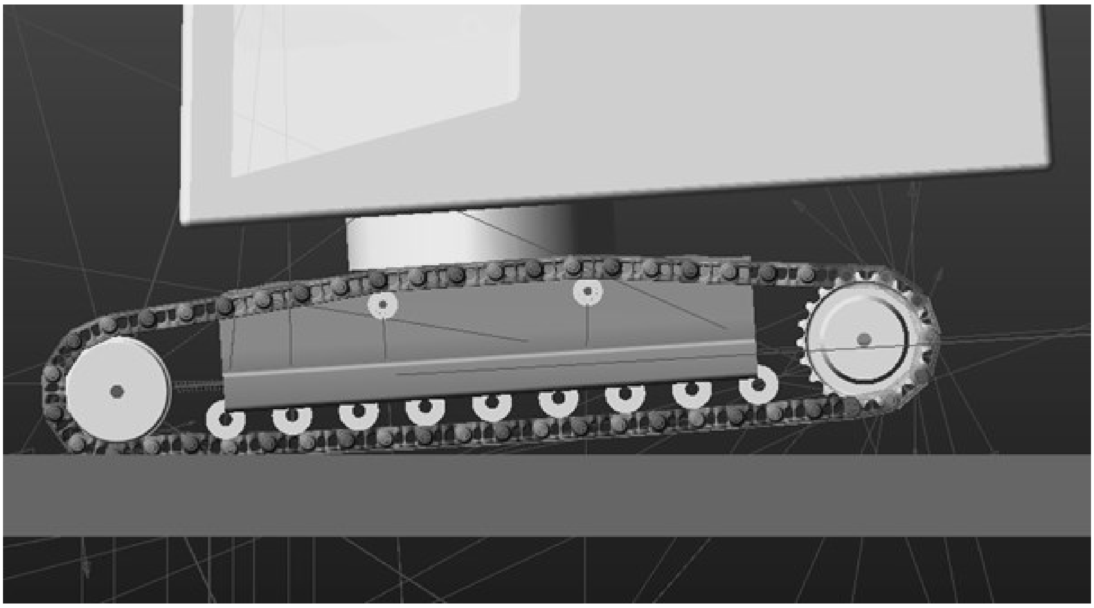

Fig. 6 Visualization of the virtual excavator modelled in simulations

One of the test stands used during the research is depicted in the Fig. 7 (Dudziński et al., 2018). It is a unique tracked vehicle, equipped with sensors that measure normal reactions under all supporting rollers. In the figure it is located on a special test platform which allow to set any ground inclination angle. The test vehicle allows verification of the developed system in close to real-life conditions.

Fig. 7 The vehicle used for tests of the developed system for monitoring of tip-over stability

CONCLUSIONS

Modern market-available systems for monitoring tip over stability of heavy machinery do not include all factors significant for stability prediction.

The proposed system has a great potential to become a reasonable alternative them. Preliminary simulations and laboratory tests, confirmed that after improvements it will be capable of determining so-called stability surplus, at higher precision than other known systems. Its particular feature is the possibility of predicting the loss of stability during failure of the slope on which the machine stands.

The developed system has been granted a patent PL 230153.

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Abstract.

The article points out that the operational safety of mobile excavating machines can be significantly improved by equipping them with on-board systems for tip over stability monitoring. Critical analysis has been conducted on tip over stability monitoring systems available on the market. Their capabilities and limitations have been analysed. The second part of the article presents an innovative concept of on-board systems for monitoring tip over stability in tracked excavating machines. This concept was developed to create a device that would allow the vehicle's tip over stability to be monitored with greater accuracy and reliability compared to current systems of this type. The article also presents a demonstrator and a simulation model of the developed device. The final part of the article presents exemplary results obtained in preliminary simulation tests of the developed system.

Keywords: tip over stability, operator assisting system, monitoring system, mobile excavating machines