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DYNAMIC WEIGHING SYSTEM USED IN EXCAVATOR

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Abstract

In many industrial applications is taken to consider change of payload potential energy while lifting it. It allows obtained directly benefits. For example, the cost of material loaded on a dump truck in a composition of coal is generally priced by its weight. In this case, the truck has to pass a stationary scale twice to identify its payload, before and after loading. Measuring weight of the material instantly while loading the truck, increases the efficiency of the process and makes a stationary scale unnecessary. In addition, it is possible to prevent overloading of means of transport, which use public roads, and can be weighed by the road service. The typical solutions of the static and dynamic weighing system from market were compared. The theoretical model is presented basing on geometrical and mass parameters of excavator CAT 301.5. The weighing system used in off-road machines is usually based on the measurement of the working fluid pressure in the piston chambers of the hydraulic cylinders, which lift the machine work equipment together with a payload. In this article is shown a solution with load pin, which allows the determination of the load mass independently of the several factors affecting the classic weighing system. The possibility of payload mass measuring on the excavator was estimated during tests on prepared research stand. There were obtained a good agreement of experimental research results with the mathematical model.

Keywords: *weighing, excavator, load pin, pressure, pay load*

1. Introduction

The energy efficiency and energy saving have become important practical research topics in off-road mobile machinery [2]. In addition, attention is paid to systems that support of operator work of the machines and connected infrastructure [7]. The weighing systems installed on hydraulic machines allow quickly and accurately determining the weight of the payload [3]. When the linkages of excavator are in calibration configuration, the load mass is proportional to the drive system parameter measured, usually the operating pressure of oil. Systems offered on the market are mainly intended for wheel loaders or cranes, but attempts are made to implement similar solutions also in excavators. Due to the greater complexity of the work equipment structure, it is not an easy task. For example, in the wheel loader during weighing the load, the bucket cylinder is extended to the upper end stroke position what always set up the same configuration of mechanism and is easy to repeat for the operator of the machine. The position of the centre of gravity of the load is approximately constant and is above the pin join, which connects the bucket to the boom, and thus does not introduce an additional load torque. The excavator is additionally equipped with an arm mechanism. That forces an increase in the number of used sensors and the expansion of mathematical formulas.

An alternative solution is to mount strain gauges to the machine construction and load measurement by using them. For example, smart forks can be implemented in forklifts. Unfortunately, this solution is limited constraints by correct pallet placement or proper mast tilt angle. Another approach is to propose the use of four force sensors at the points connecting the machine frame to the wheel axles. This circuit allows to determine the potential loss of wheel loader stability while driving, but also to calculate the current load in the bucket [1].

Additionally, the scales mounted on mobile machines can limit problem of overloaded road vehicles already during loading process. Alternative tools designed to measure the weight and individual axle loads of vehicles are the systems weighing vehicles in motion [5].

2. Off-road machine scales

The market solutions of weighing systems implemented for mobile off-road machines, including excavators, can be divided into static and dynamic (market terminology).

The typical static weighing system has a simple construction, a limited number of sensors and an easy calibration procedure. The purchase and installation cost of around € 2,000 returns in a few weeks of normal use of a wheel loader. However, this system has some disadvantages. The biggest problem is the oscillation of the hydraulic oil pressure in the piston chamber of the boom cylinder after the work equipment has stopped in the calibration position. This is mainly due to the compressibility of the working medium and the inertia of elements and payload. To achieve a high accuracy, the centre of gravity of the payload must be in a previously defined position. It depends on the experience and the focus level of the machine operator. Next assumption applies to a bucket that is completely filled with bulk material of a constant density such as sand. Other kind of materials like rocks can have influence on gravity centre position. The catalogue accuracy of this system is equal about ±1%, but it is very optimistic value especially in off-road conditions.

In machines with an implemented dynamic weighing system, the problem of oscillation of the measured pressure is avoided by the smooth realization of the boom lift movement through the narrow measuring zone without stopping (6). Throughout the measurement process, the machine must not bounce or oscillate and only constant movements are allowed (8). The accuracy of the payload measurement is acceptable as long as the measurement is taken at a previous specified loader attachment position during a defined boom up movement.

The dynamic weighing system is based on an on-board computer installed close to the operator, which collects and processes data from sensors mounted on the work equipment of the machine giving precise information about payload. The dynamic weighing process itself takes place most often when an inductive sensor mounted on the boom gives signal during lifting of working mechanism. At the moment of appear first signal, the mass is measured until the second inductive sensor passes the signal to terminate calculation. In this way, the scales of the machine have a certain area in which it can measure and, as a result, presents the average value of the weighing process. This kind of scales used in off-road machines obtains accuracy about ±3%.

The demand of weighing system users has forced the modifications of described dynamic weighing systems to enable the calculation of mass loads in the broadest angular range of the machine boom positions, and in the case of the excavator also in different configuration of the arm mechanism.

3. Model of fully dynamic weighing system used in excavator

The mathematical model of dynamic weighing system requires taking into account many of the mass and geometric parameters of the excavator's working equipment, especially of the moving parts. Centre of gravity position and inertia moment of particular linkages of mechanisms have to be known. This kind of information is available only in technical centre of company which producing analysed machines. An alternative way to determine these parameters requires drawing 3D solids based on documentation each element and estimating the value of these parameters in Cad software. Due to the complexity of the excavator mechanism, several assumptions were made:

- mass of the cylinders, hydraulic pipes, pins are not take to account,
- working fluid is incompressible,
- value of angular acceleration of boom is almost equal zero,
- excavator operates on a flat surface.

The object of simulation was an excavator Caterpillar 301.5. The working mechanism of this machine was analysed in the Working Model 2D software. The view of model is presented in Fig. 1. For calculations, the force F_N in the boom cylinder and the gravity forces Q_W, Q_R and Q_L of the main components of the working mechanism are taken into account.

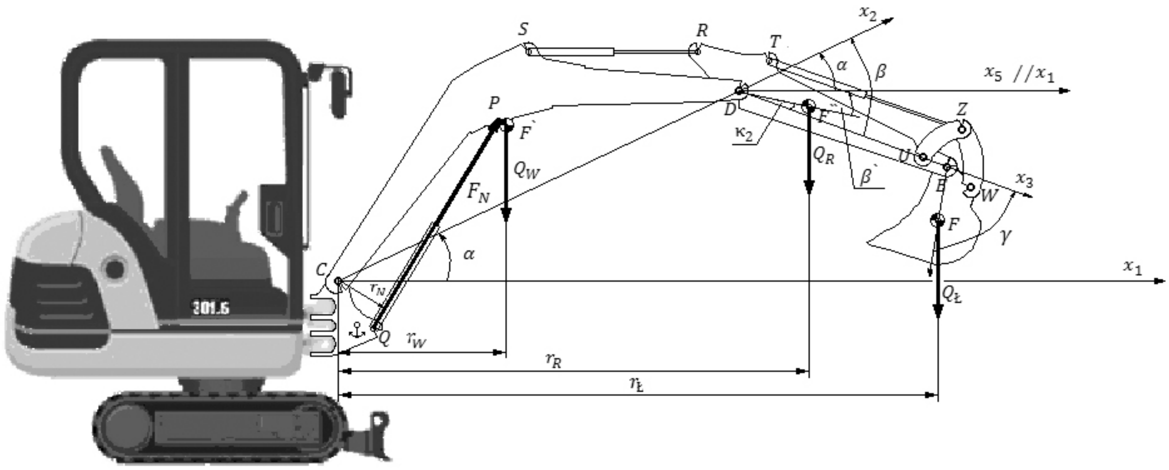

Fig. 1. Examples of excavator's geometric parameters used to determination mass of payload

The calculation based on the motion equation (1) which is written in the following form:

$$J_r \cdot \frac{\mathrm{d}\omega}{\mathrm{d}t} = \Sigma M_{Oi}, \tag{1}$$

where:
J_r – moment of inertia reduced to point of boom rotation,
ω – boom angular velocity,
ΣM_{Oi} – sum of moment of forces.

Considering the assumptions mass of payload could be determined from equation (2) written as a sum of static moment:

$$m_L = \frac{\frac{F_N \cdot r_N}{g}}{r_L} - m_W \cdot r_W - m_R \cdot r_R, \tag{2}$$

where:
m_L – mass of payload,
m_W – boom mass,
m_R – arm mass,
F_N – force of boom cylinder,
r_N – radius of boom cylinder force,
r_W – radius of arm force of gravity,
r_L – radius of payload force of gravity,
g – g-force acceleration.

The radiuses of forces are determined according to geometrical relations, as a function of dimensions and angles of particular elements of excavator (Fig. 1 and Fig. 2).

Difficulties that occur during build of the mathematical model are:
– a large number of equations, which must be implemented to controller of scales on the real machine,
– accurate technical drawing to determine the centre of gravity of each element,
– necessity of taking into account each mass element,
– influence of higher velocity of cylinder movement on accuracy of weighing.

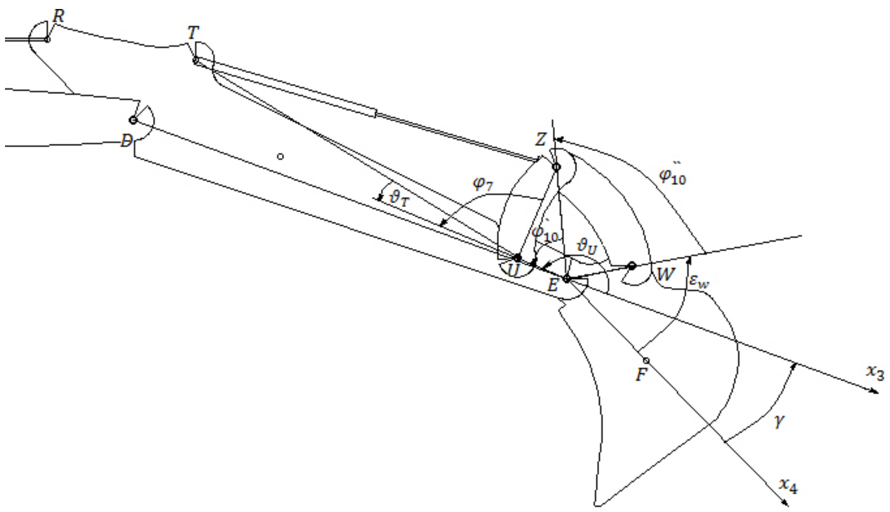

Fig. 2. Geometric parameters of arm and bucket mechanism

Tab. 1. Formulas describing the kinematic properties of excavator working elements

Boom cylinder $r_N = \dfrac{l_{AC}\cdot l_{AB}\cdot\sin(\alpha+\varepsilon_P+\delta_Q)}{S_{PQ}}$
Boom $r_W = l_{CF'}\cdot\cos(\kappa_1+\alpha)$ $\alpha = \arccos\dfrac{l_{CQ}^2+l_{CP}^2-l_{PQ}^2}{2\cdot l_{CQ}\cdot l_{CP}}+\delta_Q-\varepsilon_P$
Arm $r_R = l_{CD}\cdot\cos\alpha + l_{DF''}\cdot\cos\beta''$ $\beta = \vartheta_R-\varepsilon_S+\arccos\dfrac{l_{DS}^2+l_{DR}^2-l_{SR}^2}{2\cdot l_{DS}\cdot l_{DR}}$
Bucket $r_L = l_{CD}\cdot\cos\alpha + l_{DF''}\cdot\cos\beta''-l_{EF}\cdot\cos\gamma'$ $\varphi_{10}' = \arccos\dfrac{l_{EU}^2+l_{EZ}^2-l_{UZ}^2}{2\cdot l_{EU}\cdot l_{EZ}}$ $\varphi_{10}'' = \arccos\dfrac{l_{UZ}^2+l_{EU}^2-2\cdot l_{UZ}\cdot l_{EU}\cdot\cos(\pi+\varphi_7)+l_{EW}^2-l_{WZ}^2}{2\cdot l_{EW}\cdot\sqrt{l_{UZ}^2+l_{EU}^2-2\cdot l_{UZ}\cdot l_{EU}\cdot\cos(\pi-\varphi_7)}}$ $\gamma = \vartheta_U-\varepsilon_W-\varphi_{10}'-\varphi_{10}''$

The static force R of boom cylinder was calculated for three different equipment positions and for two values of bucket load (26 [kg] and 52 [kg]):

– bucket and arm cylinders in position l_{min} with empty bucket (notation – A0B0),
– bucket and arm cylinders in position l_{min} with 26 kg bucket load (notation – A0B026),
– bucket and arm cylinders in position l_{min} with 52 kg bucket load (notation – A0B052),
– bucket and arm cylinders in half stroke l_{mid} (notation – A1/2B1/2),
– bucket and arm cylinders in maximum stroke l_{max} (notation – A1B1).

This force in function of boom cylinder length is shown in Fig. 3.

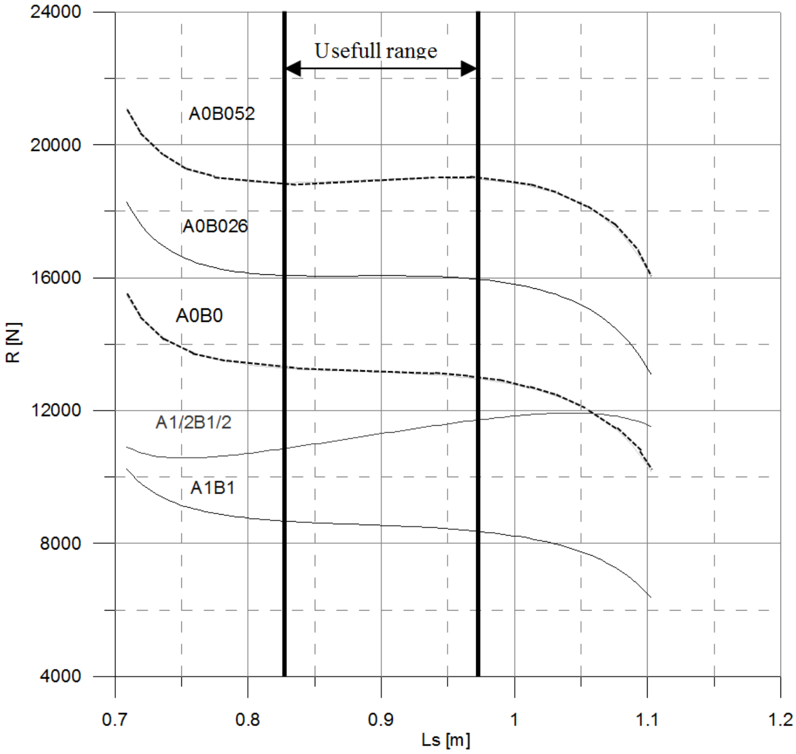

Fig. 3. Force R in function of boom cylinder length

The results presented in the plot show that, for middle positions of the excavator's work equipment, the cylinder force value has character quasi-linear and additionally, the force characteristics have a similar shape. This area is indicated in the Fig. 3. as a "useful range". In this movement, range of main cylinder the carried load can be defined continuously during the lifting process with high accuracy.

Tests of scales model were made for different configurations of excavator's working equipment, different value of payload and during simultaneous movement of boom and arm cylinders. Example results of measuring accuracy of scales system realized for boom cylinder velocity equal 50 mm/s and arm cylinder velocity equal 20 [mm/s] are presented in Tab. 2.

Tab. 2. Test results with combined movement of excavator work equipment components

Arm cylinder velocity 20 [mm/s]		
Payload [kg]	Average absolute error [kg]	Average relative error [%]
82	0.74	0.73
122	0.83	0.68
162	1.01	0.63

The average relative error calculated from "useful range" is below 1%. However, the simplified assumptions for the weighing system model should be kept in mind.

Excavator Cat 301.5 can operates with maximal velocity of boom cylinder about 90 [mm/s]. It has not significant influence on calculated accuracy during weighing process. For bigger machines should be defined factor to correct final results.

4. Research tests of weighing system

The weighing system presented in Fig. 4 has been mounted in the tested excavator CAT 301.5. The scales are based on the measurement of pressures (4) in both sides of the boom cylinder. The current position of the main working parts of the machine is determined by means of magnetic sensors of angular (3) and the encoder (5). Measured signals are collected by PLC controller (7) which is directly connected with HMI panel (1). This system can operate as: weighing the payload in the bucket, overload protection, control of operating parameters, information about the calibration position achieved by the joystick vibration (6).

Fig. 4. Dynamic weighing system mounted on CAT 301.5

This scales measured mass of payload only in calibration position of excavator's working elements such as boom, arm and bucket. This position is determined by encoder. Oscillations of pressure are limited by smooth movement without stopping of boom cylinder directly in measurement range.

The operating parameters of the actuator and therefore the achieved accuracy of the weighing system are influenced by the change in the hydraulic oil temperature. These changes require the use of a thermal factor when scales defining the payload. In order to skip this phenomenon in the test excavator the original pin that connects the cylinder with the boom was replaced by the load pin. The mounted pin had the same external dimensions as a factory element and measuring range +/– 40 [kN]. Taking into consideration influence of variable angle of the force generated by the boom cylinder the dual axis load cell has been selected. Load pin was connected to PLC too.

In weighing mode, results of mass from the measuring load pin and pressure transducers are displayed on the screen as is shown in Fig. 5. In addition, there are two indicators, which confirm the correct position during the weighing process for the boom and bucket: the minimum length of the arm cylinder and the bucket closure. If any of the conditions are not fulfilled, the weighing procedure will not start. There is also a field showing the current actual value of the alpha 1 angle and the "Return" button, transferring to the main monitor screen of the monitoring and warning system.

The research tests of excavator's scales were made for different value of payload mass. Example results for boom cylinder velocity equal 50 [mm/s] are presented in Tab. 3.

The accuracy of the measured weight was better for larger loads. It was due to the limitation of occurring the vibration of the excavator components and also the pressure oscillation of compressed hydraulic oil under the piston of the main cylinder.

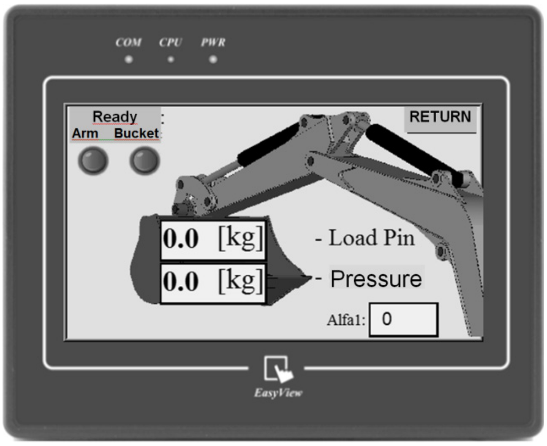

Fig. 5. HMI screen with function of weighing system

Tab. 3. Test results of quasi-dynamic weighing system on Cat 301.5

No. [–]	Load Pin [kg]	δ [%]	Pressure sensor [kg]	δ [%]
Payload – 20 [kg]				
1	20.0	0.0	18.9	5.5
2	20.8	4.0	18.9	5.5
3	19.6	2.0	18.9	5.5
4	19.6	2.0	18.9	5.5
5	19.3	3.5	18.9	5.5
Payload – 80 [kg]				
1	80.8	1.0	82.4	3.0
2	81.4	1.8	83.7	4.6
3	81.3	1.6	83.0	3.8
4	80.2	0.3	82.4	3.0
5	80.4	0.5	83.0	3.8

5. Summary

The fully dynamic weighing system is mathematically modelled. By knowing the kinematics and parameters as well as cylinder pressures or cylinder force the lifted payload can be defined continuously during the working process. However, due to the large number of data difficult to collect as well as complicated equations this system seems to be not suitable for common use.

Quasi-dynamic systems determine the mass of the load stored in the bucket only in one configuration of the work equipment. This is a significant limitation consider a typical duty cycle of this kind of machine.

The use of a load pin as a sensor in weighing systems eliminates the mass determination error, which for scales system with pressure transducers can be result from friction in the boom cylinder and variable value the drop pressure in parts of hydraulic circuit accompanying a change in the oil temperature.

Analysing the functionality of weighing systems revealed that there is a need for an integrated and flexible technical solution for dynamic and continuous weighing of the payload during the operator's work process. The payload measurement must be independent of the position as well as movements of the machine. The calibration process of the scales must be easy to perform and adaptable to structure changes

The devices and sensors of weighing systems mounted in off-road machines may be the basis for other operator support systems such as warning overload or warning of loss stability during driving.

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