Materials Research Proceedings **12** (2019) 110-116 https://doi.org/10.21741/9781644900215-16

Issues of Load Identification Using an Integrated Forces and Torques Sensor

Piotr Dudziński[a], Robert Czabanowski[b,*], Adam Konieczny[c], Andrzej Kosiara[d], Aleksander Skurjat[e] and Damian Stefanow[f]

Department of Off-Road Machine and Vehicle Engineering, Wrocław University of Science and Technology, Łukasiewicza 7/9, 50-371 Wrocław, Poland

[a]Piotr.Dudzinski@pwr.edu.pl, [b]Robert.Czabanowski@pwr.edu.pl, [c]Adam.Konieczny@pwr.edu.pl, [d]Andrzej.Kosiara@pwr.edu.pl, [e]Aleksander.Skurjat@pwr.edu.pl, [f]Damian.Sefanow@pwr.edu.pl

Keywords: Experimental Identification, Six-Axis Load Sensor, Calibration, Excavator, Finite Element Method

Abstract. The article presents a number of problems resulting from the need to identify complex loads acting on a working tool of a one-bucket excavator. The paper is focused on the presentation of conceptual design, calibration and protection of six-axis load sensor. A finite element model has been used to assess the applicability of measuring elements in a standard quick-coupler.

Introduction

Modern work machines (e.g. excavators, loaders) are used for various tasks, which require the use of various work tools. In order to optimally utilize the working time of the machine, quick-couplers are often used for excavators or loaders work tools, enabling quick and reliable tool changes, even without leaving the cabin by the operator. This tool change system is possible using hydromechanical quick-couplers controlled from the cabin. The use of various work tools is associated with wider requirements regarding the working system of the machine and its control system. It is worth mentioning here the need, for example, to limit the available force on the edge of the tool depending on the type and size of the tool. Implemented control systems make it possible to: monitor the loads acting on the tool and weigh the excavated material. It should be emphasized that permanent load control allows for: protection of the tool and work tools against overload or destruction, measurement of the excavated mass in bucket or scoop and performance evaluation, control of machine stability, evaluation of effort and forecasting tool durability. Therefore, as part of the European grant PROSYMA (in cooperation with the following partners: Cologne University of Applied Sciences, Lehnhoff Hartstahl GmbH & Co. KG, Gunderson & Løken AS and Sensors and Synergy SA), a system for identification of work tool loads was developed [1].

The concept of a sensor for measuring of force and torque

As part of the implemented project, the own concept of force and torque sensor was developed and implemented because the products available on the market could not, mainly due to the large dimensions, be installed in a standard quick coupler. The Lehnhoff Hartstahl quick-coupler was used after modification without affecting the functionality of the quick-coupler and machine performance (Fig. 1). The modification of the standard VL210 quick-coupler consisted in obtaining sufficient space for the assembly of the measuring segments system [1].

The six-axis load sensor was designed as a system of 4 measuring beams (Fig. 1-4) made of high-strength steel. Such material was used to obtain the highest possible sensitivity while

Materials Research Proceedings **12** (2019) 110-116 https://doi.org/10.21741/9781644900215-16

maintaining the ability to carry large loads (the VL210 quick coupler is dedicated to machines with a working weight of 20 t, which gives components of forces above 200 kN). In order to determine the potential of the measurement elements by determination of their strain and to verify the correctness of introduced structural changes to the original quick-coupler design, numerical simulations using finite element method were conducted (Fig. 2).

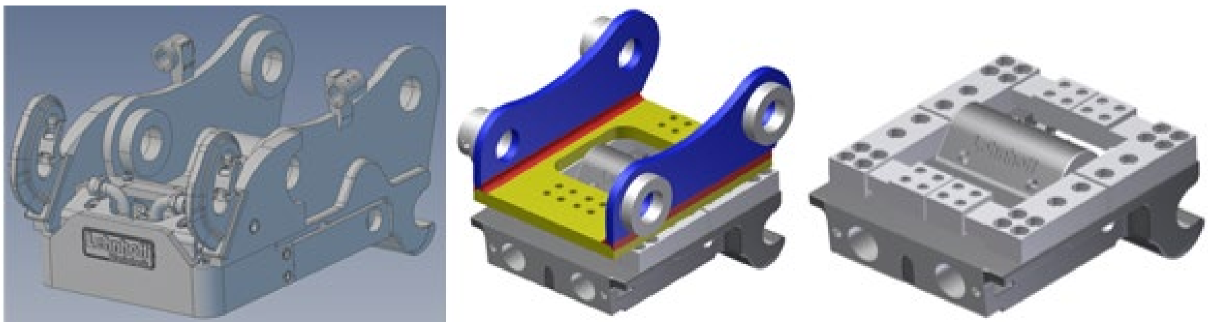

Fig. 1. Modification of the standard VL210 quick-coupler

The sensor of force and torque was designed as a system of 12 galvanic separated full strain gauge Wheastone bridges (Fig. 3, 4).

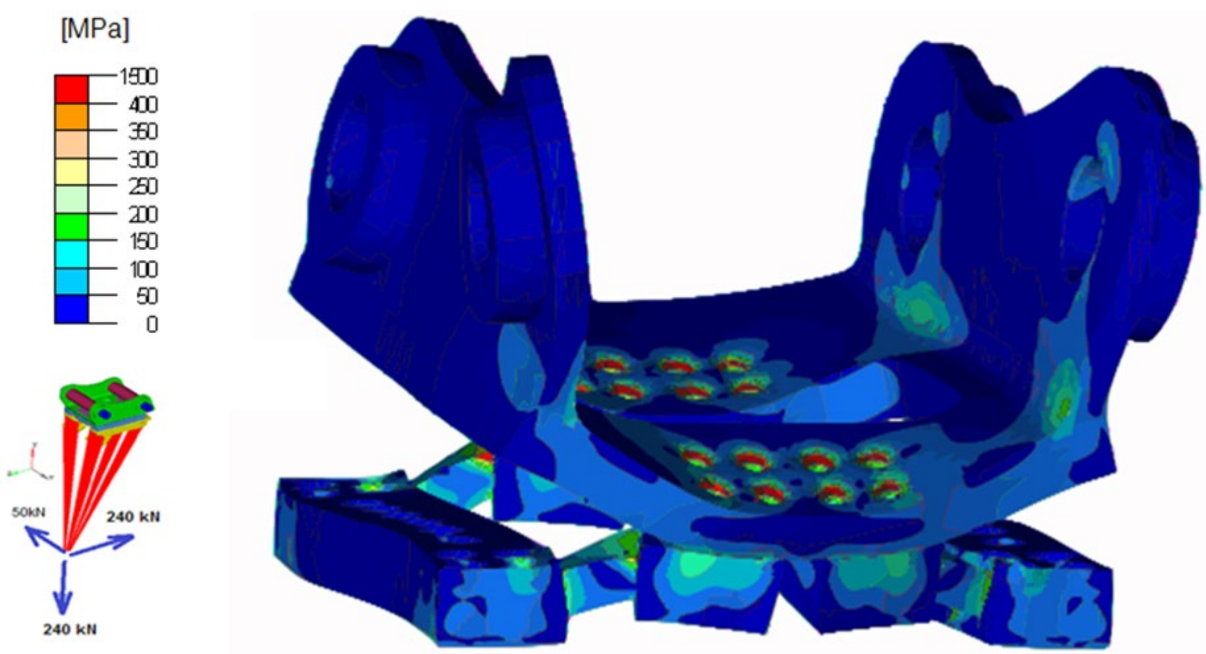

Fig. 2. Exemplary of results of numerical calculations of a measuring beams

Due to the fact that each of the measurement segments contained strain gauge systems dedicated to identification of individual load components, a sensor characteristic was developed to take into account the interaction between individual load components. Bearing in mind the previous experience in the construction and operation of multidimensional measuring sensors [1, 2], a matrix form of the characteristic was adopted (equations 1).

The matrix form of multi-axis sensor characteristic was adopted assuming that relations between force/moment and strain are linear, and that the relations between strain and voltage output are linear too [2, 3, 4].

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & a_{56} \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} \end{bmatrix} \begin{bmatrix} U_{F_x} \\ U_{F_y} \\ U_{F_z} \\ U_{M_x} \\ U_{M_y} \\ U_{M_x} \end{bmatrix} \quad \text{or} \quad [\overline{O}] = [\overline{C}][\overline{U}] \tag{1}$$

where:

$[F_x..M_z] = [\bar{O}]$ – load vector,
$[a_{11}..a_{66}] = [\bar{C}]$ – matrix of sensitivity factors,
$[U_{Fx}..U_{Mz}] = [\bar{U}]$ – measuring signals vector.

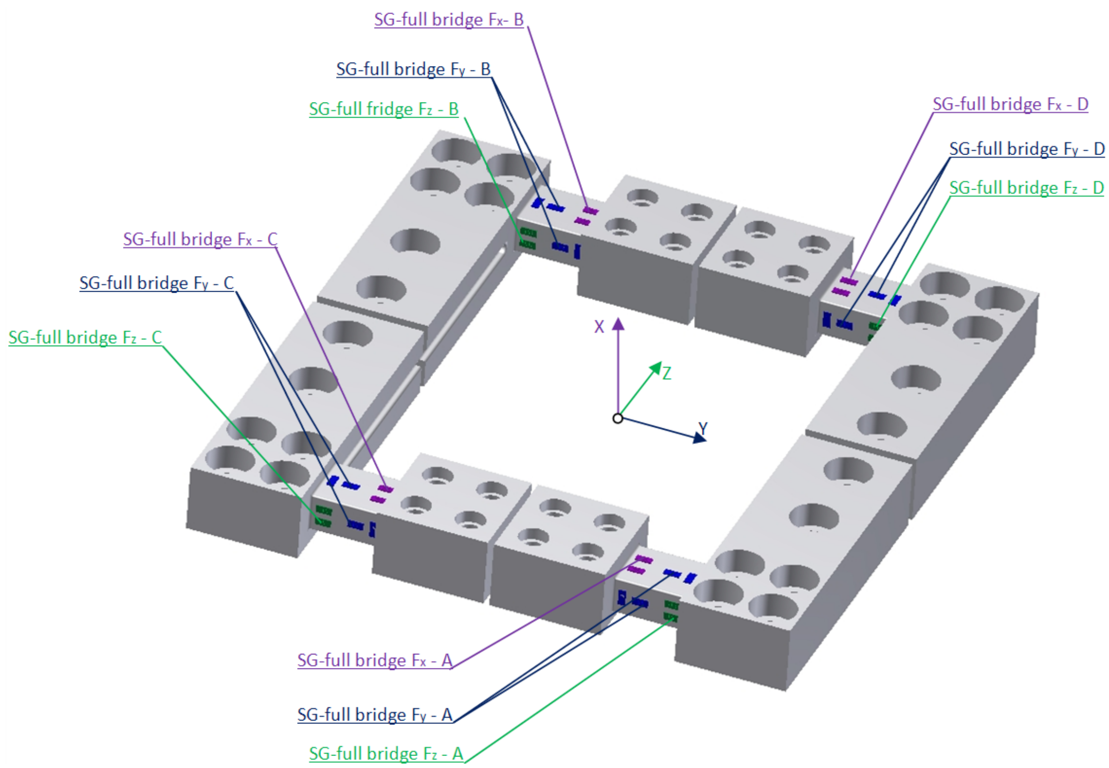

Fig. 3. Measurement beams system for identification of force-torque components

Calibration of six-axis load sensor

The complex form of the characteristic (equations 1) required proper conduct of experimental scaling of the measurement system. In order to obtain not peculiar matrix of coefficients, experimental testing was carried out by loading the system with six independent load cases. The Hottinger Baldwin Messtechnik QuantumX MX1615 amplifier, operating under control of CATMAN software was used for scaling. The testing was performed in two stages: in laboratory and in-situ tests.

To carry out laboratory pre-calibration laboratory strength testing machines were used. Due to the limited space, the tested system of measuring segments was mounted in specially designed housings enabling application of required load conditions using a testing machine. Figure 5 shows the arrangement of measuring segments at selected load states carried out during this stage of testing.

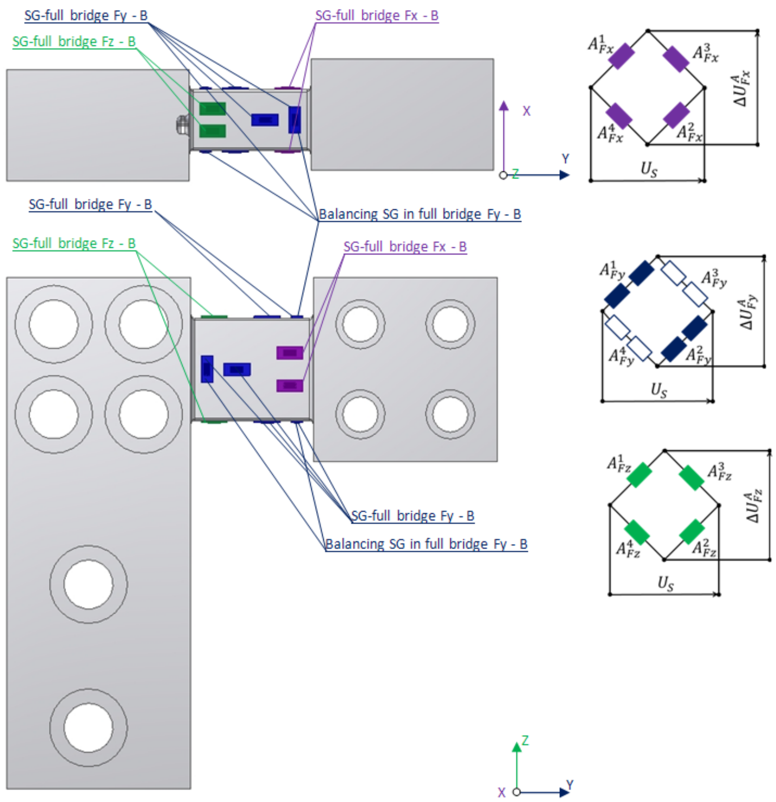

Fig. 4. Connections of strain gauge bridges at one of the measuring beams

The obtained results positively verified the concept of measuring force and torque, but due to the specificity of measuring segments assembly (location of measuring segments in a modified quick-coupler, required clamping forces), the obtained characteristic was treated as a preliminary, requiring verification on the work machine.

The final scaling of the force and torque sensor was carried out during in-situ tests. The system of measuring segments was mounted in the modified VL210 quick-coupler. The tests of the complete assembly were carried out on a Komatsu PC210 excavator with a mounted bucket (Fig. 6). Measuring scale was used to verify the real values of forces acting on the work tool.

Like in the laboratory, the tests were carried out in a manner enabling obtaining the required number of independent load states (two examples are shown in Figure 7). The obtained results of the measurements allowed, after statistical processing of a large set of results, to obtain the value of 36 coefficients of the sensitivity matrix (vide equation 1):

$$[\bar{C}] = \begin{bmatrix} 32{,}845 & -140{,}187 & -7{,}020 & 76{,}015 & 10{,}092 & 10{,}429 \\ 1{,}626 & 317{,}297 & 0{,}538 & 156{,}789 & -8{,}246 & -13{,}245 \\ -5{,}388 & 25{,}936 & -6{,}712 & -63{,}851 & 18{,}714 & -14{,}175 \\ 2{,}182 & -62{,}398 & 3{,}246 & -18{,}024 & -6{,}218 & 9{,}463 \\ 8{,}812 & 12{,}338 & -0{,}871 & 134{,}629 & 41{,}229 & -21{,}936 \\ -3{,}489 & 235{,}199 & 24{,}029 & -615{,}501 & 2{,}322 & 112{,}450 \end{bmatrix} \tag{2}$$

The values of the impact coefficients (a_{ij}, for $i \neq j$) are different for the order of magnitude, this is mainly due to the different stiffness of the measuring segments in the individual directions.

Fig. 5. Laboratory pre-scaling of force and torque sensor loaded with F_z and F_x

Fig. 6. Komatsu PC210 excavator equipped with modified VL210 quick-coupler with force and torque sensor and bucket during in-situ tests

Protection of strain gauge sensor

All measuring devices applied in a working machine operating in a wide range of environmental parameters must be properly secured. In the tested prototype it was not possible to use a closed housing. Due to the working conditions during the planned tests strain gauges and cable connections were secured with covering agent PU140 and covering putty AK22 and aluminum foil (products of Hottinger Baldwin Messtechnik).

During all tests (Fig. 8), the applied protective coatings ensured the required level of protection against external factors (temperature, pollution, humidity), but in the case of applications in more difficult conditions (impacts of rock fragments, presence of large amounts of water), it would be necessary to rebuild the quick-coupler so that the sensor can be better protected.

Materials Research Proceedings **12** (2019) 110-116 https://doi.org/10.21741/9781644900215-16

Fig. 7. Final calibration of the sensor prototype allowing the measurement of six load components using bucket and measuring scale

Fig. 8. Measuring beams with protective coatings mounted in the modified quick-coupler during digging

Tests of multi-axis load sensor during normal operation

The measurement results (Fig. 9) obtained during digging (Fig. 8) show the correct operation of the force and torque sensor and the possibility of its application in the quick-coupler. In the diagram shown (Fig. 9) fluctuations in load indications (here F_x, F_y and F_z components) are predictable when unloading the bucket, whereas the mass calculated on the basis of the characteristics of the force and torque sensor significantly changes its values because the values shown in the diagram do not include corrections calculated by the system based on the measured accelerations.

Summary

A new force and moment sensor as a part of modified quick-coupler has been designed, built, calibrated and tested. In this paper some problems with multi-axis load sensor have been described. The use of the finite element method allows the verification of the initial concept of the form of the deformable part of the force and torque transducer.

Preparation for work of a strain gauge multi-axis sensor requires a particularly accurate determination of the characteristic, and in the case of predicted use in difficult condition, adequate protection.

The experimentally tested modified quick-coupler with the multi-axis load sensor can be implemented in machines using various work tools due to the use of quick-couplers. The use of

Materials Research Forum LLC
https://doi.org/10.21741/9781644900215-16

this solution allows to protect the machine and tools from overloads, evaluate machine performance and help protect the machine against loss of stability.

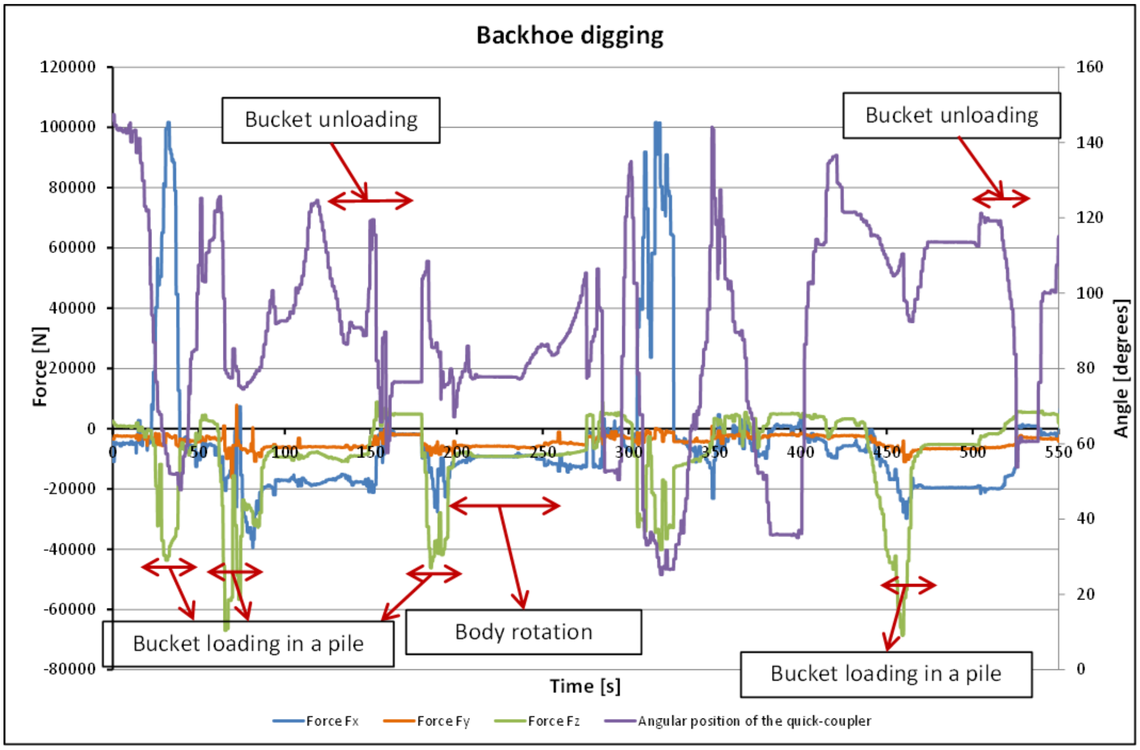

Fig. 9. Forces acting on the modified quick-coupler during digging process

Acknowledgement

The research was carried out as part of the PROSYMA project "Process-Optimized System Functionality of Mobile Work Machines", financed under the 7th Framework Program, (ID: 606227, FP7-SME-2013).

References

[1] M. Bürkel, B.E. Busterud, S. Sendrowicz, A. Ulrich, J. Lommatsch, M. Heuckeroth, M. Diefenbach, P. Dudziński, R. Czabanowski, A. Konieczny, A. Kosiara., A. Skurjat, D. Stefanow, Development of a modular information and assistance system for excavators, Fachtagung Baumaschinentechnik: Maschinen, Prozesse, Vernetzung: Tagungsband, Forschungsvereinigung Bau- und Baustoffmaschinen, Frankfurt, 2015, pp. 241-252.

[2] P. Dudziński, An unconventional transducer for measuring forces and moments in machine rotary pairs, 2nd Scientific Conference - Experimental Methods in Construction and Operation of Machines, Wrocław-Szklarska Poręba, 1995.

[3] G. Mastinu, M. Gobbi, G. Previati, A New Six-axis Load Cell. Part I: Design, Experimental Mechanics, Volume 51 (2011), p. 373-388. https://doi.org/10.1007/s11340-010-9355-1

[4] G. Mastinu, M. Gobbi, G. Previati, A New Six-axis Load Cell. Part II: Error Analysis, Construction and Experimental Assessment of Performances Experimental Mechanics, Volume 51 (2011), p. 389-399. https://doi.org/10.1007/s11340-010-9350-6