VERIFICATION OF FORCE TRANSDUCER FOR DIRECT AND INDIRECT MEASUREMENTS

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Paper deals with verification of high load force sensor using the small weight weights. Test band was built for this purpose. Verification of test band were executed using the etalon reference sensor. Small forces were executed via using the direct method through the applying of weights. High forces were executed using the indirect method through the lever amplification of load derived from small weights. Uncertainties of measurement were evaluated.

KEYWORDS

Force sensor, measurement, calibration, reference standard, verification, uncertainty, measurement error

1 INTRODUCTION

This article deals with force transducers (Fig. 1), referred to as load cells, which are composed of a strain gauge with a strain gauge. The whole system is in a metal case with connection to a suitable electronic unit, which contains an amplifier, a filter and possibly also a converter to a suitable digital signal. Electronic signal processing electronic is as a stand-alone module or is already built into the load cell. Load cell is used to measure the weight or force applied to an object. The transducer converts the measured weight or force into an electrical signal (electric current, voltage or digital signal). Load cell is characterized by good robustness, high accuracy and reliability and is therefore used mainly in industrial applications [Muller 2010].

Force sensors are frequently used for measurement of technological process parameters, but these sensors are also used in other application like automotive application, medical equipment, etc. [Bergs 2019, Daniyan 2019, Krenicky 2010 and 2011].

Figure 1. Force transducers – load cells.

To ensure trouble-free and accurate operation of the transducer, it is necessary to periodically calibrate this measuring transducer. In [Giesberts 2018] a test frame was used for load cell testing, but this only allowed compressive loading. The work [Milosavljevic 2018] deals with bendig load cell calibration using the direct measurement using the weights. The load cell [Mencattelli 2014] was statically calibrated by applying known weights between 0 N and 2 N equally spaced of 0.05 N. The authors [Fastier-Wooller 2016] used a universal test machine for tensile and compressive deformation tests for verification and calibration of a load cell. Tension sensor [Nagamune 2015] was calibrated with stress testing machine. Authors of work [Slais 2016] used piezoelectric sensor for calibration of measurement chain for impact force measurement. The study [Faber 2012] describes a novel calibration method for six-degrees-of-freedom force/torque sensors. The paper [Zarutckii 2016] deals with a calibration method that allows performing automated force-torque sensor calibration (with a number of components from one to six) both with selected components of the main vector of forces and moments and with complex loading. Work [Vanwalleghem 2015] assumed calibration of force sensor using the cantilever beam configuration. Calibration masses have been used for sensor calibration. The paper [Nasir 2016] discusses the calibration of two-axis force sensors which were embedded into the fingertip of a three-fingered robot hand. Reference weights have been used for calibration. Reference force sensor has been used for calibration of tested weight sensor attached to mechanical frame with weights loading system [Walendziuk 2020]. A custom calibration procedure was developed, using a drop hammer and force platform to replicate the experimentally observed forces and loading rates [Oudshoorn 2016]. The static calibration hardware system based on large-tonnage hydraulic loading principle and the static calibration software system including data acquisition, processing, calibration and performance analysis are developed [Zhongpan 2011].

There are several works focused to dynamic calibration of force sensor [Fujii 2004 and 2009]. There are three types currently used as impact force, oscillating force, step force applied to calibrated sensor. Most of authors used inertial force of a mass used as known dynamic force as reference force for calibration force. Similar devices focused to didactical purposes have been developed also in works [Hargas 2014, Pavlasek 2018].

2 FORCE CALIBRATION DEVICE

Force calibration device has been developed for calibration of load cells. It consists of frame and lever mechanism for tensile and compressive loading of load cell. Measurement range of calibrated load cells is up to 1 kN. The load cell can be calibrated by direct measurement by applying a weight to the calibrated load cell. In the case of a measuring range of 1 kN, this would mean using a weight with a weight of 100 kg, which is already a relatively large weight for handling.

The aim of this work is to prepare a compact measuring device for load cell calibration with a range of 1 kN when using weights with low weight (Figs. 2 and 3).

The proposed device allows to load the load cell with tensile force by direct measurement (up to 10 kg) and indirect measurement (up to 100 kg) (Fig. 2). The device can load the load cell with compressive force, both by direct measurement (up to 10 kg) but also by indirect measurement (up to 100 kg) (Fig. 3). In indirect measurement, the same weight is used, but it is applied by means of a lever transmission so that the applied force from the weight is multiplied. Thanks to the use of lever transmission, it is possible to use weights only up to 10 kg to create a load of up to 100 kg. Handling this small weight is much easier and much safer. The device with this methodology is compact and easily portable. The construction costs of this device are relatively low and the device can be easily built and possibly adjusted to its parameters as needed. The stated properties of the device are unique and in this article the aim is to determine the metrological characteristics of this device.

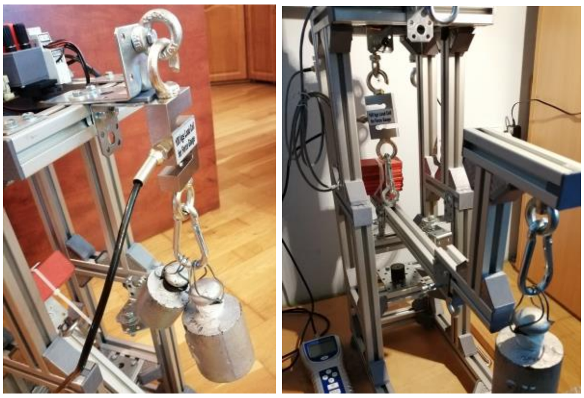

Figure 2. Force calibration device – load cells loaded by tensile force by direct (upper) and indirect (lower) measurement.

To create a force load, the weights used were modified so that they could be suspended by means of a carabiner on the load cell suspension eye or a load device for indirect measurement by means of a lever. These adjusted weights were calibrated using a reference scale. The weights of fasteners (carabiners, hooks and reducers) were also taken into account in the evaluation of measurements.

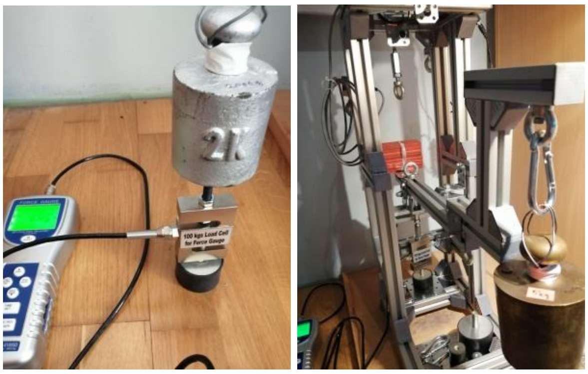

Figure 3. Force calibration device – load cells loaded by compressive force by direct (upper) and indirect (lower) measurement.

3 VERIFICATION OF FORCE CALIBRATION DEVICE

The reference standard instrument FG-6100SD was selected to verify the functionality of the force calibration device. This reference standard instrument was used mainly to determine the transformation ratio of the lever used for the indirect load of the load cell. Before using the reference, the standard instrument was tested with reference weights (Fig. 4 and Fig. 5). Each displayed measured point is the arithmetic mean of the ten measurements. All measurement errors are less than maximum permissible errors defined by producer.

The relative measurement error (Fig. 5 and Fig. 6) for the reference instrument FG6100SD obtained from the verification process with reference weights is less than 4% of the measured value for tensile stress and for compressive stress, which is sufficient for normal measurements.

The force calibration device has a lever transmission, to increase the loading force when using the same reference weights. This is an indirect measurement, as the loading force must be multiplied by a lever magnification. This lever magnification can be determined from the dimensions of the lever with respect to the joint and the place of attachment of the loaded load cell.

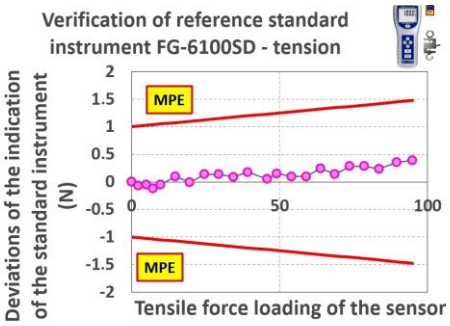

Figure 4. Verification of reference standard instrument FG6100SD with tensile force loading.

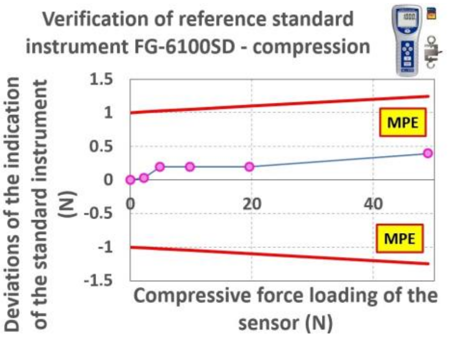

Figure 5. Verification of reference standard instrument FG6100SD with compression force loading.

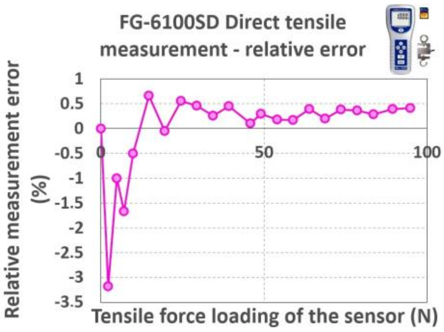

Figure 6. Relative error from verification of reference standard instrument FG6100SD with tensile force loading.

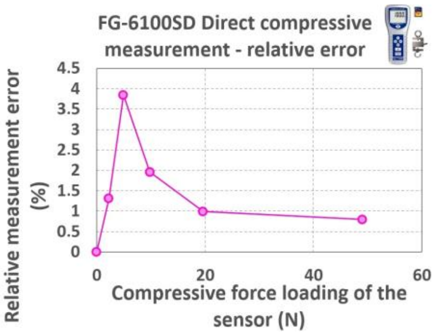

Figure 7. Relative error from verification of reference standard instrument FG6100SD with compression force loading.

However, these dimensions are difficult to determine, and length measurements would be inaccurate using commonly available measuring devices. The reference standard instrument FG6100SD was used to determine this leverage magnification by placing it at the location designated for load cell verification, and it was possible to determine this leverage magnification using reference weights.

This force calibration device allows lever loading for tensile force loading but also for compressive force loading. Transformation characteristics were determined for both cases (Fig. 8 and Fig. 9). Using linear regression, mathematical models of these characteristics were determined, where the first coefficient in the equation is the magnification lever coefficient just sought (Fig. 8 and Fig. 9). For tensile force lever loading, this magnification lever factor has a value of 14.91 and for compressive force lever loads, this magnification lever factor has a value of 14.25. These coefficients will be used to recalculate the load applied by the lever, which is referred to as the indirect measurement, because the load values need to be calculated.

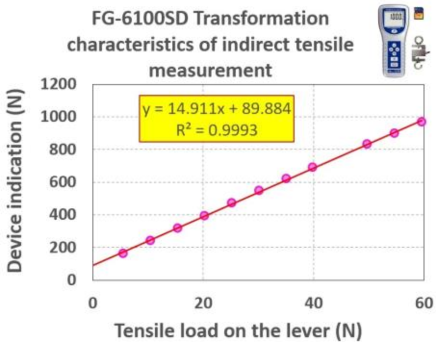

Figure 8. Transformation characteristic of indirect tensile measurement using the reference standard instrument FG6100SD.

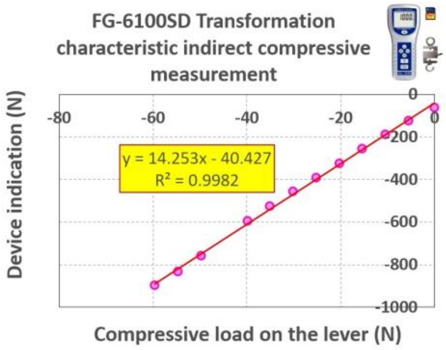

Figure 9. Transformation characteristic of indirect compressive measurement using the reference standard instrument FG6100SD.

From the calibration of the reference weights and by processing the measurement uncertainties, it is possible to determine the total uncertainty of the reference weight combinations used (Fig. 10).

The load using the reference weights (Fig. 10) can be converted to the values of the reference loading forces (Fig. 11) and it is also possible to determine the values of the combined uncertainty of the determination of the reference loading forces. In the calculation, the considered value of the gravitational acceleration was determined for the measuring point g = (9.80857±0.000005) ms^{-2}.

The magnification lever coefficient was determined from experimental data and so its value will be associated with the uncertainty of determining this coefficient using the general linear regression model ($y = a \cdot x + b$). A general relationship can be used to determine this uncertainty:

$$u^2{}_{(a)} = \frac{n}{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2} \cdot \sigma^2 \tag{1}$$

where n - is the number of evaluated pairs of experimental data (x_i, y_i); x_i - force generated by the reference weight applied to the lever; y_i - loading force on increased by means of a lever acting on the calibrated load cell; σ is a mean square error MSE and indicates how the experimental points are dispersed around the regression model and can be determined using the relation:

$$\sigma_{MSE}^2 = \frac{1}{n-k}\sum_{i=1}^{n}[w_i - (a \cdot x_i + b)]^2 \tag{2}$$

where k - is the number of estimated parameters of the regression function, which in our case of the linear model is equal to two; w_i - is the value of the output quantity.

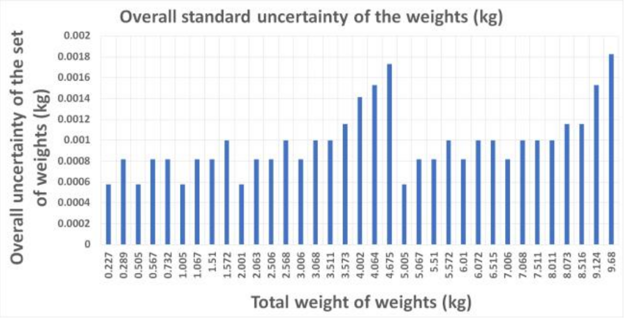

Figure 10. Overall standard uncertainty of used combination of reference weights.

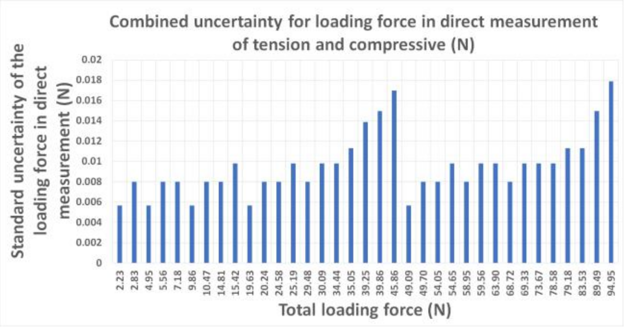

Figure 11. Combined uncertainty for loading force.

It is then possible to write the result of the experimental determination of the magnification lever coefficient for the tensile force $k_{TENSILE}$ = (14.91 ± 0.12) and for the compressive force $k_{COMPRESSIVE}$ = (14.25 ± 0.19). For these results, the standard uncertainties are determined by considering the covariance according to the general relation:

$$u_{a,b} = \operatorname{cov}(a,b) = \frac{-\sum_{i=1}^{n} x_i}{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2} \cdot \sigma^2 \tag{3}$$

These uncertainties in determining the leverage coefficients are less than 1.3% of the nominal value of this coefficient. The uncertainties of these leverage coefficients are very important for the resulting uncertainty in determining the uncertainty of the force acting on the calibrated load cell.

The load in indirect measurement applied by lever can be determined by multiplying by the magnification lever coefficient, but since the uncertainty of determining these coefficients for tensile and compressive force is determined, then it is possible to determine the uncertainty of force load indicated by lever transmission (Fig. 12 and Fig. 13).

Knowledge of the value of the magnification lever coefficient and the uncertainty of its determination is necessary for the calibration of other load cells, which can be verified and calibrated on this proposed force calibration device. In the next part of this work, the results of load cell calibration with an amplifier with analogue output (voltage) are presented.

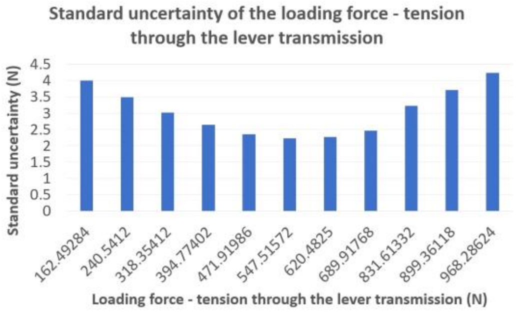

Figure 12. Standard uncertainty of the loading force for tensile force through the lever transmission.

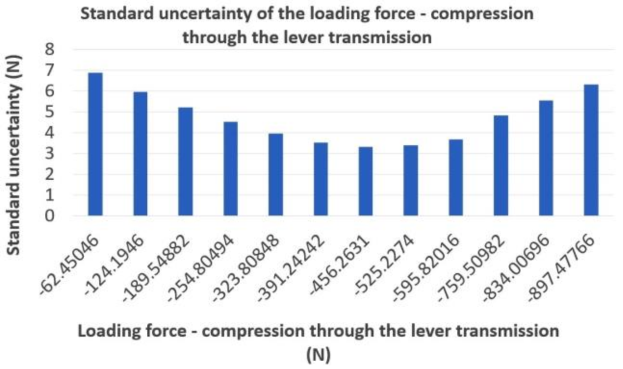

Figure 13. Standard uncertainty of the loading force for compressive force through the lever transmission.

4 CALIBRATION OF LOAD CELL USING DIRECT MEASUREMENT

The calibrated load cell has a measuring range of 1 kN and the output from the sensor is connected to the Load Cells Signal Conditioner, which contains an amplifier, an active filter and a converter with output to voltage and current. The load cell has threaded ends at both ends and can be used for tensile or compressive force measurements. For tensile measurement, it is necessary to fasten the suspension bolts, and for compressive force measurement, a silent block must be used to compensate for inaccurate mounting and vibration to prevent damage to the load cell (Fig. 14).

Direct measurement with tensile load was performed and a transformation characteristic was created from this measurement, while each point on the graph (Fig. 15) is determined as an arithmetic average of ten measurements performed under the same measurement conditions. For the purposes of calculating the applied force from the measured value of the electrical voltage, it is also necessary to create a calibration characteristic (Fig. 16), which is created by swapping the axis of the transformation characteristic graph. The calibration characteristic (Fig. 16) can be approximated by a calibration equation, which can be implemented in a suitable calculation system for the conversion of the measured electrical voltage to determine the applied loading force in a particular application.

Figure 14. Calibrated load cell for measuring tensile force (left) and compressive force (right).

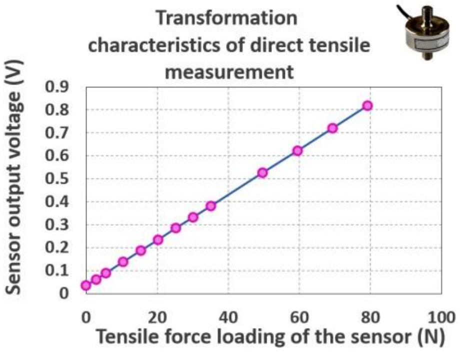

Figure 15. Transformation characteristic of direct measurement with load force under the tensile force loading.

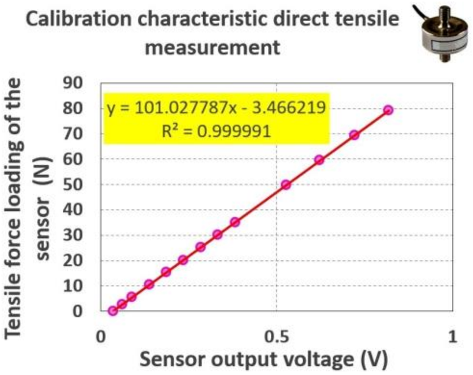

Figure 16. Calibration characteristic of direct measurement with load force under the tensile force loading.

The electrical voltage at the output of the load cell signal conditioner was measured with a digital multimeter, for which the manufacturer specified the maximum permissible error. Individual measurements were performed several times under the same conditions and so from this information it was possible to determine the combined uncertainty of measuring the output voltage from the sensor with the signal conditioner (Fig. 17). The combined uncertainty was determined according to the standard [EA-4/02M 2013].

The graph of the combined uncertainty of measuring the output voltage from the sensor with the signal conditioner (Fig.

17) has an increasing tendency and the magnitude of this uncertainty does not exceed the value of 3 mV.

For the loading compressive force, a series of measurements were performed for six different values of the loading compressive forces, with ten measurements being made for each value, from which an arithmetic average was formed. The values of the measured electrical voltages at the output of the calibrated load cell at these values of compressive forces were recorded in the graph (Fig. 18) in the form of a transformation characteristic and for practical use in the form of a calibration characteristic (Fig. 19).

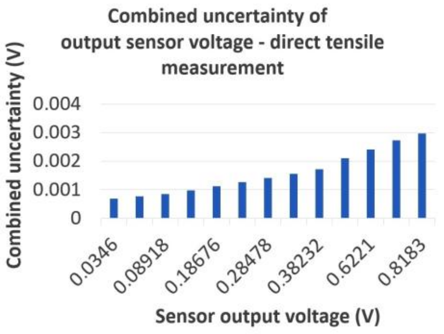

Figure 17. Combined uncertainty of measuring the output voltage from the sensor with the signal conditioner for direct measurement of tensile force loading.

The calibration characteristic for direct measurement under compressive force loading was also approximated by a linear model (Fig. 19). Also in this case, the combined uncertainties of the voltage measurement at the load cell with signal conditioner output were determined (Fig. 20).

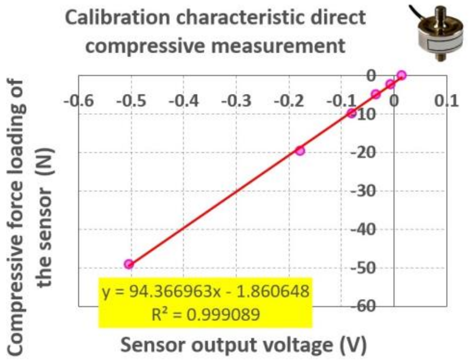

Figure 18. Transformation characteristic of direct measurement with load force under the compressive force loading.

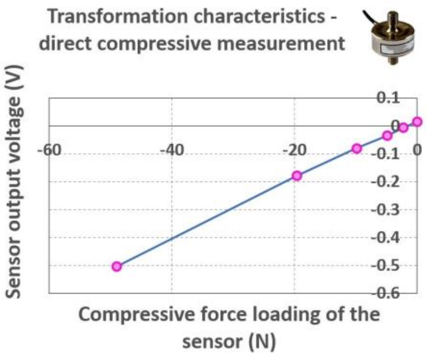

Figure 19. Calibration characteristic of direct measurement with load force under the compressive force loading.

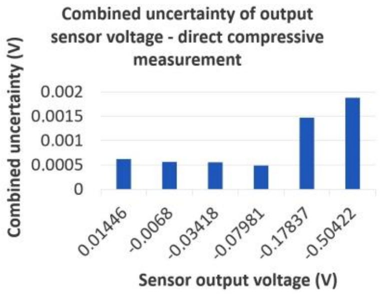

Figure 20. Combined uncertainty of measuring the output voltage from the sensor with the signal conditioner for direct measurement of compressive force loading.

5 CALIBRATION OF LOAD CELL USING INDIRECT MEASUREMENT

For large force loads (above 100 N) load cell calibrations were performed using indirect measurement, which was performed using a lever. The load that was applied to the load cell therefore had to be multiplied by the lever magnification. The transformation characteristic of this indirect measurement for tensile force loading is shown in Fig. 21 and the calibration characteristic shown in Fig. 22.

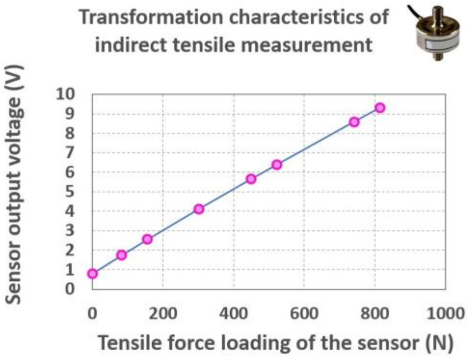

Figure 21. Transformation characteristic of indirect measurement with load force under the tensile force loading.

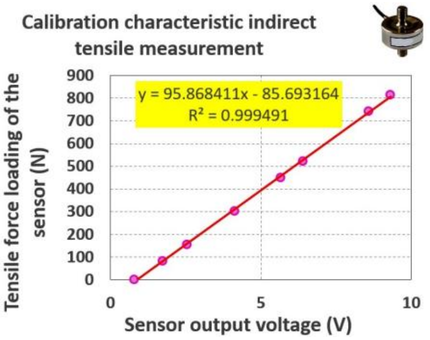

Figure 22. Calibration characteristic of indirect measurement with load force under the tensile force loading.

Measurements (Fig. 21 and Fig. 22) were performed at each displayed point ten times under the same unchanged measurement conditions. For these measurements, the measurement uncertainties were determined using method A and also using method B. From these measurement uncertainties, the resulting combined measurement uncertainty (Fig. 23) was determined for the measured voltage output from the load cell with the signal conditioner for tensile force loading.

Similarly, load cell calibration was performed using indirect compressive measurement and the result is a transformation characteristic (Fig. 24) and a calibration characteristic (Fig. 25).

Also for this indirect measurement, the lever magnification coefficient for the compressive force loading determined using the reference standard instrument was used. The combined measurement uncertainties for the load cell output voltage were similarly determined for these measurements (Fig. 26).

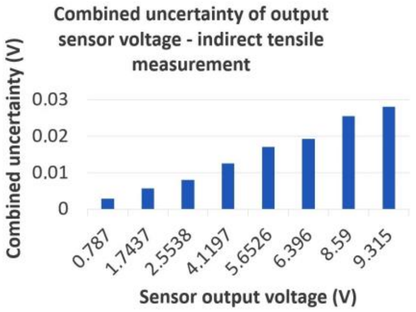

Figure 23. Combined uncertainty of measuring the output voltage from the sensor with the signal conditioner for indirect measurement of tensile force loading.

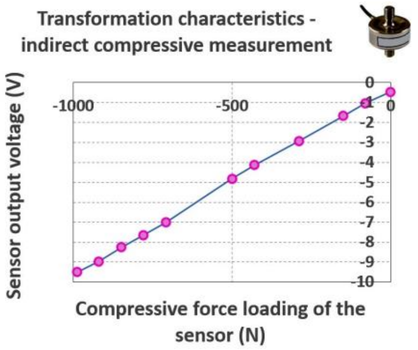

Figure 24. Transformation characteristic of indirect measurement with load force under the compressive force loading.

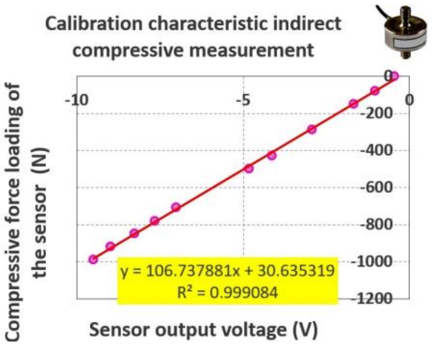

Figure 25. Calibration characteristic of indirect measurement with load force under the compressive force loading.

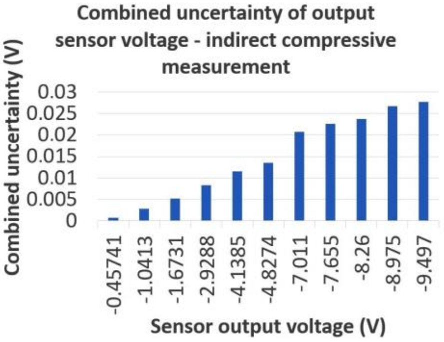

Figure 26. Combined uncertainty of measuring the output voltage from the sensor with the signal conditioner for indirect measurement of compressive force loading.

6 CONCLUSIONS

In this work, a prototype test band was created for the calibration of load cells with a measuring range of up to 1 kN, using only weights with low weights. Small weights of weights were used in direct measurements to create a load of up to 100 N, and in indirect measurements using a lever, it was possible to perform measurements up to 1 kN using the same weights. Since only light weights are used during the calibration process, this method of calibration is safer for the user. In addition, the device is easy to build and can be easily modified to adjust its properties if necessary. The test band was verified using a reference standard instrument. Using this reference standard instrument, the lever magnification coefficient for the tensile load force and also for the compressive load force was experimentally identified. These leverage magnification factors were then used to determine the applied force to the load cell in indirect lever measurements. The uncertainties of determining these coefficients and the uncertainty of the loading force were also determined by the analysis. The selected load cell with signal conditioner was calibrated on this test band. The result of this process are calibration characteristics for the entire range of load cell measurements (1kN) for both tensile force and compressive force.

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REFERENCES

[Bergs 2019] Bergs, T., Schraknepper, D., Goetz, S. Estimation of Engagement Conditions Using an Ann Pattern Recognition System on The Base of a Sensory Tool Holder. MM Science Journal, 2019, Vol. 12, pp. 3310-3315.

[Daniyan 2019] Daniyan, I.A., et al. Modelling and Optimization of the Cutting Forces During TI6Al4V Milling Process Using the Response Surface Methodology and Dynamometer. MM Science Journal 2019, Vol. 12, pp. 3353-3363.

[EA-4/02M 2013] EA-4/02 M: 2013. Evaluation of the Uncertainty of Measurement in Calibration. Publication Reference. European Accreditation. 2013, rev 01, 75 p.

[Faber 2012] Faber, G.S., et al. A force plate based method for the calibration of force/torque sensors. Journal of Biomechanics, 2012, Vol. 45, pp. 1332–1338.

[Fastier-Wooller 2016] Fastier-Wooller, J. et al. Novel Low-Cost Sensor for Human Bite Force Measurement. Sensors, 2016, Vol. 16, p. 1244.

[Fujii 2004] Fujii, Y. Dynamic Force Calibration Methods for Force Transducers. IMTC 2004 - Instrumentation and Measurement Technology Conference, Corno, Italy, 18-20 May 2004, pp. 352-357.

[Fujii 2009] Fujii, Y. Toward Establishing Dynamic Calibration Method for Force Transducers. IEEE Transactions On Instrumentation and Measurement, 2009, Vol. 58, No. 7, pp. 2358-2364. ISSN 0018-9456.

[Giesberts 2018] Giesberts, R.B., Sluiter, V.I., Verkerke, G.J. Design and Test of a New Inductive Force Sensor. Sensors, 2018, Vol. 18, p. 2079. https://doi.org/10.3390/s18072079.

[Hargas 2014] Hargas, L., Koniar, D., Simonova, A., Hrianka, M., Loncova, Z. Novel Machine Vision Tools Applied in Biomechatronic Tasks. Procedia Engineering, 2014, Vol. 96, pp. 148-156.

[Krenicky 2010] Krenicky, T. The Monitoring of Technical Systems Operation Using Virtual Instrumentation. Strojarstvo extra, 2010, No. 5, pp. 25/1-25/2. ISSN 1335-2938. (in Slovak)

[Krenicky 2011] Krenicky, T. Implementation of Virtual Instrumentation for Machinery Monitoring. In: Scientific Papers: Operation and Diagnostics of Machines and Production Systems Operational States: Vol. 4, RAM-Verlag, Lüdenscheid, 2011, pp. 5-8. ISBN 978-3-942303-10-1.

[Mencattelli 2014] Mencattelli, M., Donati, E., Cultrone, M., Stefanini, C. Customized Load Cell for Three-Dimensional Force-Moment Measurements in Orthodontics. 2010. In: 2014 5th IEEE RAS & EMBS Int. Conf. on Biomedical Robotics and Biomechatronics (BioRob) August 12-15, 2014. São Paulo, Brazil, pp. 238-243. ISBN 978-1-4799-3128-6.

[Milosavljevic 2018] Milosavljevic, S., Milovanovic, A., Koprivica, B. Virtual Instrumentation for Load Cell – Calibration and Measurements. In: 7th Int. Sci. Conf. Technics and Informatics in Education Faculty of Technical Sciences, Cacak, Serbia, 25-27th May 2018. Session 3: Engineering Education and Practice, pp. 347-350.

[Muller 2010] Muller, I, Machado de Brito, R., Pereira, C.E., Brusamarello, V. Load Cells in Force Sensing Analysis – Theory and a Novel Application. IEEE Instrumentation & Measurement Magazine, 2010, pp. 15-19. ISSN 1094-6969.

[Nagamune 2015] Nagamune, K, Kawaguchi, S. A Development of Tension and Length Measurement System for Knee Bending Motion in Medial Patello-Femoral Ligament Reconstruction. In: 2015 Int. Conf. on Informatics, Electronics & Vision (ICIEV). 15-18 June 2015, Fukuoka, Japan, pp. 1-4. DOI: 10.1109/ICIEV.2015.7334012.

[Nasir 2016] Nasir, K., Shauri, R. L. A., Jaafar, J. Calibration of Embedded Force Sensor for Robotic Hand Manipulation. In: 2016 IEEE 12th Int. Colloquium on Signal Processing & its Applications (CSPA2016), 4 - 6 March 2016, Melaka, Malaysia, pp. 351-355. ISBN 978-1-4673-8780-4.

[Oudshoorn 2016] Oudshoorn, B.Y., Driscoll, H.F., Dunn, M., James, D. Pressure sensor calibration for measuring stud-player impacts. Procedia Engineering, 2016, Vol. 147, pp. 688–693. doi: 10.1016/j.proeng.2016.06.273.

[Pavlasek 2018] Pavlasek, P., et al. Flexible Education Environment: Learning Style Insights to Increase Engineering Students Key Competences. In: EDULEARN Proceedings, 10th Int. Conf. on Education and New Learning Technologies. Palma, Spain. Chova, L.G.; Martinez, A.L.; Torres, I.C. (Eds.), pp. 10156-10165.

[Slais 2016] Slais, M., F Slais, M., Dohnal, I. Verification of Measurement of Dynamic Loading During the Taylor Anvil Test. MM Science Journal, 2016, Vol. 9, Issue: November, pp. 1343-1345. ISSN 1803-1269. DOI: 10.17973/MMSJ.2016_11_2016117

[Vanwalleghem 2015] Vanwalleghem, J., De Baere, I., Loccufier, M., Van Paepegem, W. Dynamic calibration of a strain gauge based handlebar force sensor for cycling purposes. Procedia Engineering, 2015, Vol. 112, pp. 219 – 224.

[Walendziuk 2020] Walendziuk, W., Walendziuk, L., Idzkowski, A. Development of a Wireless Weighing Transducer and its Calibration. In: Int. Conf. on Mechatronic Systems and Materials (MSM). 1-3 July 2020, Bialystok, Poland. IEEE, 2020, pp. 1-6. ISBN 978-1-7281-6956-9.

[Zarutckii 2016] Zarutckii, N., Bulkin, R. Accuracy Specifications of Calibration Device for Force-Torque Sensors. In: IEEE Int. Conf. on Multisensor Fusion and Integration for Intelligent Systems (MFI) 2016. Baden-Baden, Germany, Sep. 19-21, 2016, pp. 78-83. ISBN 978-1-4673-9708-7.

[Zhongpan 2011] Zhongpan, S., Yanzhi, Z., Lihuan, L., Changtao, D., Tieshi, Z. Development and calibration of large range flexible joints six-component force platform. In: 10thj Int. Conf. on Electronic Measurement & Instruments ICEMI 2011. IEEE, pp. 278-281. ISBN 978-1-4244-8161-3.

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