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LINEAR LOADING MEASUREMENT LINE FOR STATIC TORQUE AND ITS PERFORMANCE

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Preliminary notes

The focus of this work is aimed on enhancing the present design solution of the measurement line that would provide more accurate results and increase the speed and reliability of the recalibrating process of torque tools. Tools considered here are operated by hand, thus subjected to the performance (skill, physical strength and knowledge) of the operator. Since the pulling speed and the force are difficult to maintain or repeat by manual handling results are scattered and differ from expected values. In order to improve this process as well as fulfil compliance with international norms electrically controlled actuating device is considered. Among several analyzed solutions one with gearbox and trapezoidal spindle is chosen to be manufactured and implemented. Device testing has shown enhanced repeatability of the measurement, ease of operation and suitability for implementing automation features.

Key words: *torque, measurement, automation*

Izvedba i karakteristike linije za mjerenje statičkog okretnog momenta linearnim opterećenjem

Prethodno priopćenje

Težište ovog rada je usmjereno na modernizaciju postojeće mjerne linije statičkog okretnog momenta u cilju ostvarivanja točnijih rezultata uz povećanje brzine postupka umjeravanja naprava za unos ili indikaciju okretnog momenta. Predmetnim se napravama manipulira ručno pa su rezultati direktno ovisni o vještini, fizičkoj snazi i umijeću rukovatelja. Tijekom ovakvog načina rukovanja nemoguće je brzinu i silu povlačenja održati konstantnima niti ponoviti mjerenje s istim parametrima. Iz navedenih su razloga podaci mjerenja više ili manje raštrkani oko očekivanih vrijednosti. U cilju unaprjeđivanja postupka te usklađivanja s međunarodnim normama u području mjerenja statičkog okretnog momenta razmatrana je mogućnost ugradnje upravljivog uređaja za opterećivanje s električnim pogonom. Između nekoliko mogućih rješenja za realizaciju je odabrana izvedba s moto-reduktorom i trapeznim vretenom. Uz jednostavniju uporabu rezultati ispitivanja uređaja pokazuju povećanu ponovljivost mjerenja, a konstrukcijsko rješenje ostavlja prostor za dodatno poboljšanje upravljanja do razine polu automatskog sustava.

Ključne riječi: *okretni moment, mjerenje, automatizacija*

1 Introduction
Uvod

Although almost invisible to the eyes of layman torque tools are unavoidable in everyday life. They are used by machinists, auto mechanics, steel construction workers, dentists, etc. Their working principles and load ranges differ as well as design, size and accuracy. They are briefly divided into two groups: indicating and setting torque tools [1]. While indicating tool is intended to indicate torque exerted by the tool at the output drive, the purpose of setting torque tool is to exert the prescribed value of the torque followed by appropriate signal. General use of the setting tool is to set the desired amount of axial force into a screw or bolt joint. The connection between the introduced torque and the achieved force is complex though often reduced to only a few parameters on account of simplicity of calculation [2]. However, the basic assumption that must be met to even approximately achieve the desired force is that the torque tool exerts the prescribed value of torque within the limits of acceptable tolerance as described in [1]. In order to provide such performance, torque tools must be recalibrated periodically. The issue of this work is the recalibration procedure of the setting torque tool that should be conducted by a certified calibration laboratory and the appropriate equipment that should be used according to [1] and [3].

2 Existing measurement line
Postojeća mjerna linija

The existing measurement line [4] (Fig. 1) is based on comparison between the value adjusted on the torque tool against the one that is achieved due to loading of the system. It consists of few basic parts. Tool driving square adapter (part number 2) is mounted on the top flange of the measurement shaft (part number 1). Four strain gages (part number 3) forming full bridge connection are attached to the outside diameter in the middle of the shaft and wired to the digital measurement acquisition system (part number 4). The last item in the line is a PC equipped with software compatible to the acquisition system (part number 5). Replaceable driving square adapter complies with international norm [5] and measuring shaft with international norm [3].

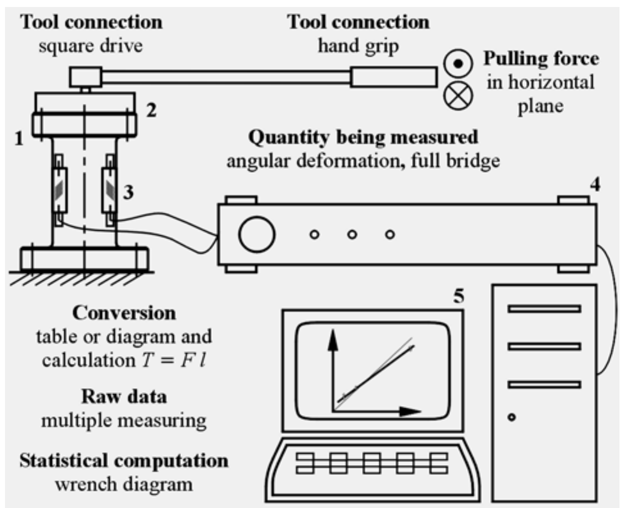

Figure 1 *Existing measurement line schematic*
Slika 1 *Shematski prikaz postojeće mjerne linije*

2.1 Measurement procedure
Postupak mjerenja

The measurement procedure as described in [1] and [6] is conducted by hand pulling of the torque tool previously

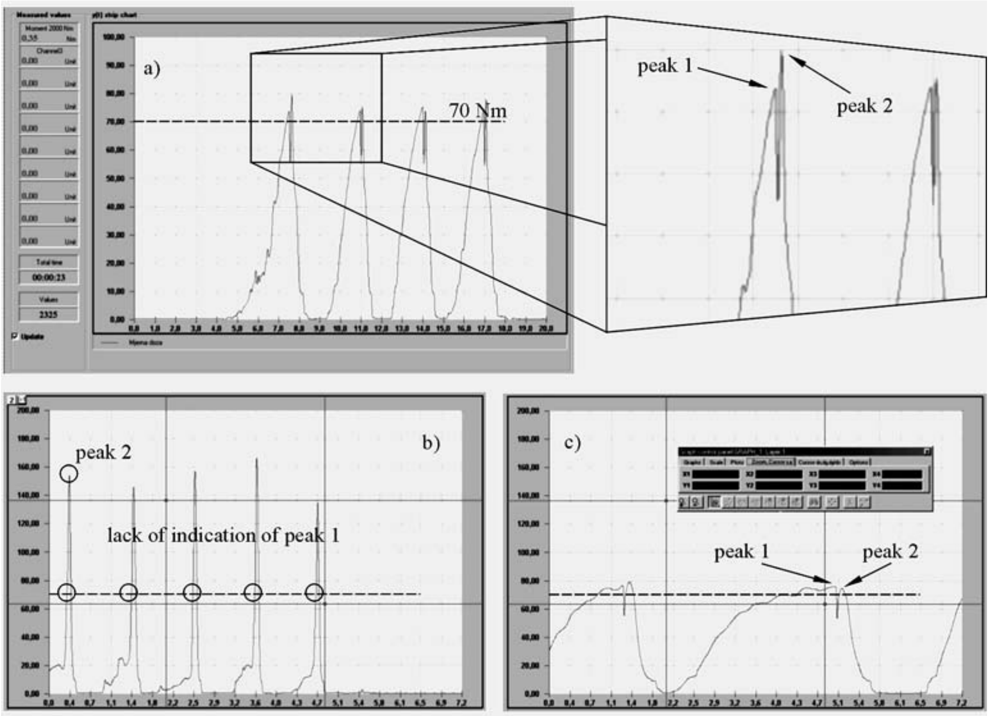

Figure 2 *Data recorded on hand pulling torque wrench set to* 70 N·m*: a) normally, b) aggressively, c) smoothly*
Slika 2 *Podaci zabilježeni tijekom ručnog povlačenja moment ključa podešenog na* 70 N·m*: a) normalno povlačenje, b) odlučno, c) pažljivo*

adjusted to desired value and mounted on a driving square attached to the top of the measurement shaft (Fig. 1). Due to angular deformation of the shaft electrical resistance of strain gages is changed and picked up by the acquisition system in the form of electrical potential change. Those changes are recorded continuously by PC software as an array of discrete points (Fig. 2a, 2b and 2c).

Diagrams in Fig. 2 are showing several cases of results of a measurement procedure. Fig. 2a (with characteristic part enlarged) shows the diagram obtained by usual operation, while 2c is achieved by very smooth pulling with fine force increment. Fig. 2b is the most important because of the lack of indication of tool triggering due to careless and aggressive pulling. What should be specially depicted is another peak that occurs when the tool mechanism hits the wrench casing allowing overload and potential tool damage. Since the curves are not smooth and in cases 2b and 2c neither are they characteristic, they are not suitable for automated software processing.

It should be pointed out that the operating torque was adjusted at 70 N·m which should be considered as a small value, thus easy to handle. Wrenches designed for higher amounts of torque are usually robust, equipped with appropriate grip extension in order to provide less force on a larger distance for the operator to have better control over the force and the speed. However, the extension requires more space for manipulation forcing the operator to maintain control over a longer path leading back to measurement inaccuracy.

3 Design guidelines
Smjernice

Basically, every torque tool has to exhibit some rotational movement to produce torsion. Torque tools considered here operate while rotating around the axis of joint being fastened. To simulate same kinematics, few basic design solutions of measurement lines are possible: either torque tool rotates while measurement shaft is fixed or vice versa. Both of them could be actuated by linear or circular actuating device. Considering the nature of the joint fastening process, one can speculate that the most suitable design would be with circular actuation of torque tool against fixed measurement shaft. However, other design solutions, perhaps because of their simplicity, are very common.

Operating performance has significant influence on the measurement accuracy as well as on the measurement repetition. In order to provide both, instead of proved traditional measurement method by torque balance a new transmission device is considered, preferably electrically controlled with fine gradient adjustment. Instead of hand pulling, the wrench would be driven by an actuator while the measurement shaft would stay still. The equipment should be able for operation in both directions to meet various tools capabilities (clockwise and counter clockwise turns). Additionally, since the measurement shafts are preferably optimally designed for particular torque range [3], several shafts should be produced to cover at least the most usual ranges of torque tools [4]. The procedure should be kept simple without the need of changing measurement shafts, thus saving the time in preparation of measurement. Finally, because of the well controlled input, smooth output diagrams could be created, suitable for automated processing. With all prerequisites fulfilled the system described above should be suitable for implementing a software procedure for automatic peak detection and recording. On that basis, the coupling between software and the actuator could be created allowing semi-automatic operation within one measurement procedure. This way should provide less operator's influence on measurement accuracy which would be benefit expected.

4 Design solution
Konstrukcijsko rješenje

Based on the requested properties a prototype of new measurement line is produced (Fig. 3). Among the analysed design solutions the one with gearbox and trapezoidal spindle was chosen. The actuator and the transmission are chosen as compact product capable of both electrical and hand operation. Additional equipment provides capability

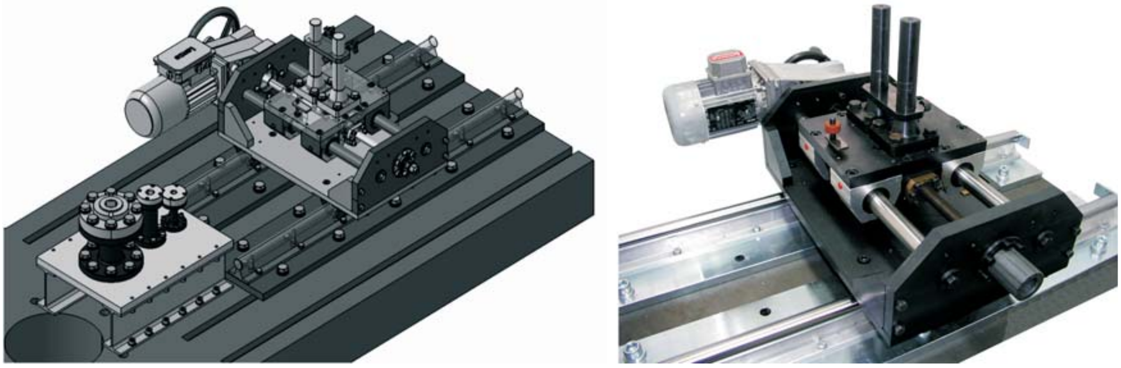

***Figure 3** Mechanical part of the measurement line model (left) and the loading part of the prototype (right)*
***Slika 3** Model mehaničkog dijela mjerne linije (lijevo) i proizveden dio kojim se regulira opterećenje (desno)*

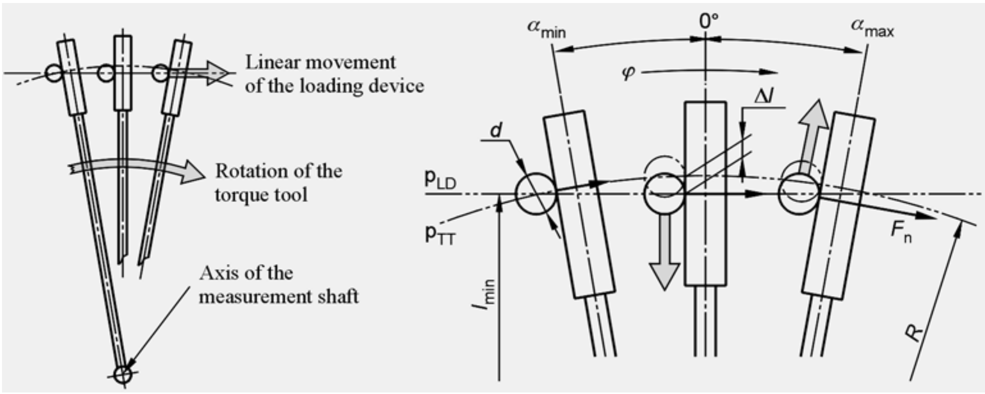

***Figure 4** Analysis of kinematics of the loading device and torque tool*
***Slika 4** Analiza kinematike uređaja za opterećivanje i ručice moment ključa*

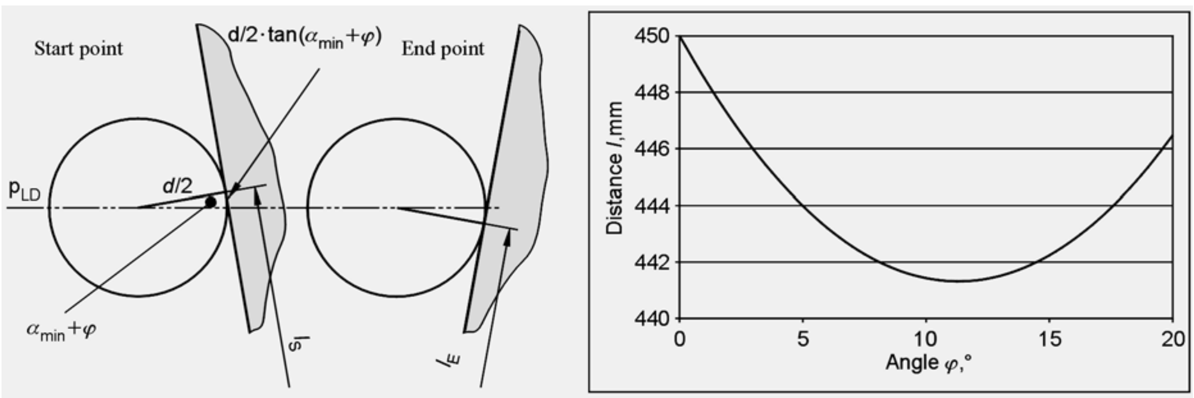

***Figure 5** Example of change of the distance between acting force and measurement shaft for initial distance of* 450 mm*,*
diameter of supporting cylinder 20 mm *and angle ranging from* −10 *to* +10
***Slika 5** Primjer promjene udaljenosti hvatišta sile i osi vrtnje mjernog vratila uz početni krak od* 450 mm*,*
promjer oslonca 20 mm *i raspon kuta zakreta alata od* −10 *to* +10

to control turning speed to meet the requirements of measurement procedure described in [1]. The force is provided by transversal movement while adjustment in the longitudinal direction gives capability for testing various sizes of torque tools. The limiting load and the operating dimensions correspond to the tool with maximum torque value of 3000 N·m.

4.1 Analysis of the design solution
Analiza rješenja

Measurement line considered in this work could be classified as a linear type corresponding to the movement of loading device. Compared to the process of fastening, this type has some drawbacks regarding kinematics and friction. This occurs because of different movements between torque tool and measurement shaft (Fig. 4). As it may be seen, the supporting part of loading device (represented by circle in Fig. 4) that drives the grip of the torque tool performs linear movement (path p_{LD}) while the torque tool rotates around the measurement shaft's axis (path p_{TT}).

Because of this incompatibility in movement, distance between acting force and the measurement shaft's axis changes continuously. Besides obvious difference there is small additional contribution due to diameter of cylindrical part of the loading device (left in Fig. 5). This value continuously decreases this distance (ranging from l_S at the start point to l_E at the end point) thus the resulting distance is not symmetric regarding zero angle (right in Fig. 5).

The normal force (F_n in Fig. 4) between supporting cylinder and the grip of the torque tool is conditioned by the angular position of the tool and dependant of its characteristic which is linear or approximately linear for valid torque tools. Hence torque changes with angular position following the same rule as the distance does. Since this change is not a rapid one (in example described with Fig. 5 and force of 1500 N at angle zero equals 1,6 %) its influence on measurement procedure could be neglected.

It is important to notice that torque tool grip and supporting cylinder are exhibiting rolling and sliding movement simultaneously which is not usual effect for normal use of torque tool. Rolling part is taking place over the small arc of the supporting cylinder following involute curve while the sliding is present on whole path. Up to approximately angle zero supporting cylinder slides towards axis of the measurement shaft and after that away from it (see greyed arrows in Fig. 4). Because of this traction force is changing direction thus inducing change in amount and direction of bending moment regarding measurement shaft (in example described with Fig. 5, with measurement shaft's bending height of 100 mm and range of friction coefficient from 0,1 to 0,4 bending moment could change from 0,5 up to 7,7 percent). Amount of the traction force is dependent on amount of the normal force and friction coefficient between supporting cylinder made from steel and the torque tool grip. One can conclude that influence of the traction force will be stronger for non-metallic grips and higher amounts of normal force. Since the strain gages attached to the measurement shaft are combined in a way to compensate bending moment this influence is probably avoided. However, comparative study should be conducted to prove such action.

5 Testing results
Rezultati ispitivanja

As mentioned before, expected benefit of using machine loading is to reduce operator's influence in measurement procedure, particularly in repetitive loading phase, and thus in accuracy of results. In order to quantify this benefit testing was performed on one torque tool with three different amounts of torque and three different loading scenarios: machine loading, careful trained operator's loading and aggressive loading. Important is that once the tool is adjusted and mounted on the top of the measurement shaft all loading scenarios are carried out without dismounting or any other change or adjustment of any piece of the equipment for one particular value of torque.

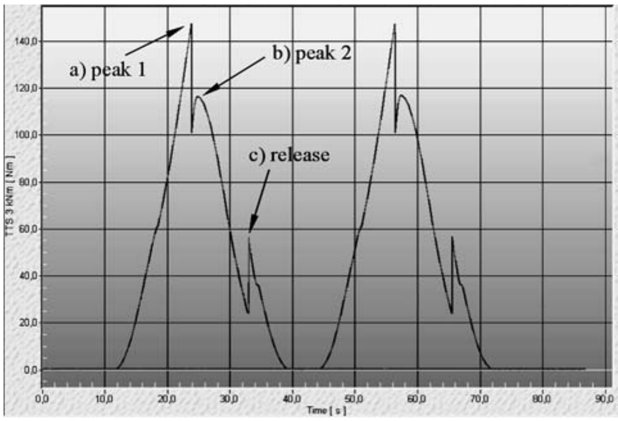

Figure 6 *Common look of loading diagrams for machine supported measurement procedure*
Slika 6 *Uobičajeni izgled dijagrama opterećenja kod mjerenja sa strojnim opterećivanjem*

Testing of the prototype line was conducted for one setting torque tool with scale graduation of 5 Nm at torque values of 50, 140 and 230 N·m according to [1]. Fig. 6 shows common diagrams plotted out on the basis of discrete points. On this enlargement scale one could conclude that there is no difference between two consecutive measurements. The diagrams are practically identical and most important, independent of the operator's physical and skill performance. Three significant moments could be clearly seen in each measurement cycle: a) torque peak, b) secondary load due to mechanism impact with tool casing and c) releasing of the mechanism allowing another operating cycle.

Data for each measurement scenario was recorded and processed. Adjusted and recorded values as well as exceptions presented in form of absolute number and relative difference are shown in Tables 1a to 3a for corresponding scenarios. Calculation results for expanded relative uncertainty of measurement according to [3] are shown in Tables 1b to 3b for corresponding scenarios.

Table 1a *Scenario 1 - Measurement results for machine loading*
Tablica 1a *Rezultati mjerenja za slučaj strojnog opterećivanja*

Steps, N·m	Indication in N·m				
Steps, %	Exception from adjusted value, %				
50	52,32	52,20	52,02	51,90	51,90
20,0	4,6	4,4	4,0	3,8	3,8
140	145,94	145,94	145,82	145,70	145,70
60,0	4,2	4,2	4,2	4,1	4,1
230	240,93	240,92	240,32	240,26	240,14
100,0	4,8	4,7	4,5	4,5	4,4

Table 1b *Scenario 1 - Relative uncertainty for machine loading*
Tablica 1b *Relativna mjerna nesigurnost za slučaj strojnog opterećivanja*

Steps, N·m	Relative uncertainty contribution of repeatability, %	Uncertainty contribution of resolution, %	Relative uncertainty contribution of the torque calibration machine, %	Expanded relative uncertainty of measurement, % (k=2; P=95 %)
	wb'	wr	wtcm	w
50	0,57	2,89	0,01	8,24
140	0,12	1,03	0,01	2,93
230	0,23	0,63	0,01	1,84

***Table 2a** Scenario 2 - Measurement results for operator's manual loading*
***Tablica 2a** Rezultati za slučaj pažljivog ručnog opterećivanja od strane laboranta*

Steps, N·m	Indication in N·m				
Steps, %	Exception from adjusted value, %				
50	52,38	51,96	52,26	51,84	51,78
20,0	4,8	3,9	4,5	3,7	3,6
140	146,22	146,04	145,86	145,74	145,32
60,0	4,4	4,3	4,2	4,1	3,8
230	241,92	241,74	241,38	241,20	240,66
100,0	5,2	5,1	4,9	4,9	4,6

***Table 2b** Scenario 2 –Relative uncertainty for operator's manual loading*
***Tablica 2b** Relativna mjerna nesigurnost za slučaj pažljivog ručnog opterećivanja od strane laboranta*

Steps, N·m	Relative uncertainty contribution of repeatability, %	Uncertainty contribution of resolution, %	Relative uncertainty contribution of the torque calibration machine, %	Expanded relative uncertainty of measurement, % (k=2; P=95 %)
	wb'	wr	wtcm	w
50	0,82	2,89	0,01	8,33
140	0,44	1,03	0,01	3,04
230	0,37	0,63	0,01	1,92

***Table 3a** Scenario 3 - Measurement results for aggressive manual loading*
***Tablica 3a** Rezultati za slučaj agresivnog ručnog opterećivanja*

Steps, N·m	Indication in N·m				
Steps, %	Exception from adjusted value, %				
50	52,39	52,32	52,27	51,09	50,90
20,0	4,8	4,6	4,5	2,2	1,8
140	146,43	145,40	146,28	146,17	145,57
60,0	4,6	3,9	4,5	4,4	4,0
230	240,99	241,89	241,52	240,65	239,70
100,0	4,8	5,2	5,0	4,6	4,2

***Table 3b** Scenario 3 - Measurement results for machine loading*
***Tablica 3b** Rezultati za slučaj agresivnog ručnog opterećivanja*

Steps, N·m	Relative uncertainty contribution of repeatability, %	Uncertainty contribution of resolution, %	Relative uncertainty contribution of the torque calibration machine, %	Expanded relative uncertainty of measurement, % (k=2; P=95 %)
	wb'	wr	wtcm	w
50	2,03	2,89	0,01	9,12
140	0,50	1,03	0,01	3,08
230	0,64	0,63	0,01	2,19

***Table 4** Relative uncertainty contribution of repeatability for three investigated scenarios*
***Tablica 4** Doprinos relativnoj mjernoj nesigurnosti uslijed ponovljivosti za tri ispitivana slučaja*

Steps, N·m	Scenario 1, %	Scenario 2, %	Scenario 3, %
50	0,57	0,82	2,03
140	0,12	0,44	0,50
230	0,23	0,37	0,64

Comparative results for relative uncertainty contribution of repeatability for investigated scenarios are shown in Tab. 5. What can clearly be seen is significant difference between the first and the second cases ranging from 1,4 up to 3,7 times and even more between the first and the third ranging from 2,8 up to 4,2 times.

6 Conclusion
Zaključak

Analysis of data recorded for measurement procedure operated manually (Fig. 2) as well as comparative results shown in Tab. 4 outlines the following:

- Accuracy of the measurement conducted for manual loading depends on the operator's physical performance and skill.
- For each manual loading scenario output data do not form smooth curves, and thus are not suitable for automated peak detection. On the contrary, in case of machine loading curves are well defined with recognizable characteristic points.
- Relative uncertainty contribution of repeatability is smallest for machine loading compared to other loading cases.
- There are possible issues with linear loading which should be analysed additionally and preferably practically confirmed.

As mentioned before in design guidelines, next step in development of the measurement line could be taken in the part of the system control. At the present time operator controls loading device by wire thus his attention is needed during the whole period of loading cycle. Since the data obtained for machine loading is suitable for automatic peak detection loop back control between actuator and acquisition system could be created. In that case software would control the loading following these steps:

- Increase load until peak point 1 is reached.
- Record data.
- Stop and reverse movement until measured quantity reaches zero.
- Repeat action until measurement cycle is completed and standby.

The measurement cycle could be repeated as many times as needed, number of which could be determined by the data stored about a specific torque tool. If so, the operator's concern would be to mount the tool, set the torque to be tested and introduce the tool type to the software. The rest of the work would be done by the measurement system.

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7 References
Reference

[1] ISO 6789:2003, Assembly tools for screws and nuts - Hand torque tools - Requirements and test methods for design conformance testing, quality conformance testing and recalibration procedure, ISO, 2003.

[2] Decker, K.-H. Machinenelemente: Gestaltung und Berechnung, 16. Auflage, C. Hanser Verlag, ISBN 3-446-19194-1, München, 2007.

[3] EURAMET/cg-14/v.01, Guidelines on the Calibration of Static Torque Measuring Devices (Previously EA-10/14), European Association of National Metrology Institutes, 2007.

[4] Opalić, M.; Vereš, M.; Žeželj, D. Measurement line design, Proceedings of 45th International Conference of Machine Design Departments, Mazal, P. (Ed.), pp. 78-83, ISBN 80-214-2702-7, Blansko, Czech Republic, September 2004, Brno University of Technology, Brno, 2004.

[5] ISO 1174-1:1996, Assembly tools for screws and nuts - Driving squares - Part 1: Driving squares for hand socket tools, ISO, 1996.

[6] Schicker, R.; Wegener, G. Measuring torque correctly, Hottinger Baldwin Messtechnik, ISBN 3000089454, Bielefeld, 2002.

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