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Enlargement of a force sensor measurement range based on a build-up principle

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Abstract

This paper introduces a full study to extend the capacity of a force sensor to three times its original capacity based on the build-up principle. The force sensors that have good metrological characteristics are costly devices. Such devices could fail as soon as the load exceeds its designed capacity. For covering a wide force measurement range, several force sensors shall be available. The systems that are designed to work over a wide force measurement range such as the system under study are a good replacement for many force sensors. It is expected that using a build-up system based on a single-active force sensor will be an advantage from the cost point of view. The metrological validation of the system was proved through analyzing experimental results, which are obtained during the test of a single-active sensor build-up system. The system achieves class 1 according to ISO376:2011. ***Further, as an excess step for the validation of the system under study, the new system based on a single-active force signal was used as a reference to calibrate a 2500 N force measurement sensor***. It is found that the maximum measurement error is about 0.23 %.

Keywords:

Force sensor, load cell, strain gauge, multi-capacity, multi-range force transducer.

1. Introduction

The force sensors are crucial measurement members in many fields including the energy industry, construction, automation, testing and inspection, medical industry, food industry...…etc. ***The majority of force sensors are composed of two main parts; the first is the elastic element, which is designed to carry the rated capacity. The second part is the sensing element, which is used to detect the deformation of the elastic element under the applied load***. The most famous sensing element used with the elastic element to build a force sensor is the strain gauges. These sensing elements are used to convert the deformation of the elastic element into a measurable quantity. The force sensors/load cells have many designs; column type, bending beams, flange type…etc [1]. Each design takes a different configuration for a certain purpose, perhaps to be suitable for tension measurement, compression measurement, or bending. Any of these designs might fail if the applied load exceeded its rated capacity, therefore it is recommended not to go beyond the designed capacity. The force sensors' major failure cause ever recorded up to now is the overloading [2]. Building a force measurement system capable of working over a wide force measurement range is an interesting topic, many researchers tried to do their best to invent such systems.

Many designs are available in the literature concerning force measurement systems that are capable of working over a wide force measurement range. These designs could be divided into two groups. The first group includes the designs which were built based on a single-active force signal; such as the devices developed by ***Yalof et al*** [3], ***Osman et al*** [4], and ***M.Abdulhakim et al*** [5]. The second group includes all the devices which were built based on more than one active force signal, this includes the systems developed by ***Interface*** [6] and ***Lorenz*** [7]. The systems that were built based on a single-active signal are more economical than others because the full active sensor is the most expensive component over the whole system.

This study introduces a proposed design for extending the capacity of a force sensor based on a build-up principle. Using this principle, the user could extend the capacity of a force sensor to three times its capacity or maybe more based on the number of dummy elements being used side by side with the active force sensor. ***The building of a build-up system based on a single active force sensor is an economical solution for force measurement, where the cost of two active force sensors will be saved. In the new system, two active force sensors are replaced by dummy elements. The manufacturing cost of dummy elements does not exceed 10 % of the active ones.***

2. Build-up principle

The build-up force measurement system (BUS) is a combination of force sensors arranged mechanically in parallel either in series arrangement [8], or parallel-radial arrangement [9] (Figure 1). The BUS could consist of three or more active force sensors. The main target of using such systems is to transfer the traceability of force measurement from a smaller capacity force standard machines into a high capacity force measurement system [10]. Each force sensor or force measuring system shall be calibrated periodically to ensure its accuracy and precision, to do so there shall be a reference force machine, but these types of machines have limited capacities due to their huge manufacturing cost. Above the limit of these machines, the BUSs are usually used to calibrate the systems that have larger capacities.

A. Serial arrangement BUS

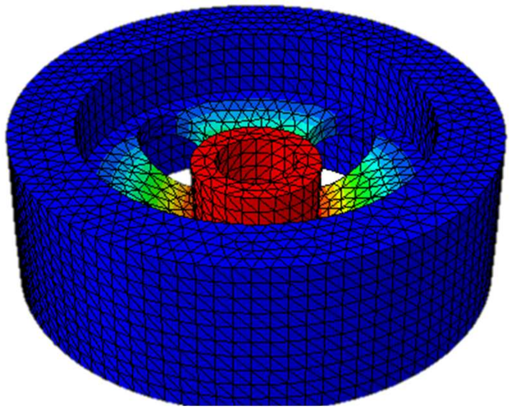
B. Parallel-radial arrangement BUS

Figure 1 The two types of the BUS

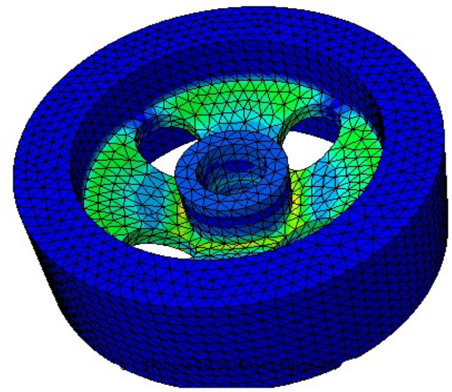
The capacity of a BUS based on three-active force sensors is equal to three times the capacity of a single force sensor. If each force sensor could have a capacity equal to the capacity of the maximum available reference machine, hence, the capacity of the BUS could be equal to three times the capacity of the reference machine used to calibrate its sensors. As an example; if the maximum available reference force standard machine has a capacity of 1000 kN, then a BUS with three active force sensors each has a capacity of 1000 kN could calibrate measurement systems up to 3000 kN.

3. Proposed design based on a single-active force sensor BUS

The proposed design is a parallel-radial BUS, which has only a single-active force sensor. The other two force sensors were replaced by dummy elements, these dummy elements do not have any sensing elements (strain gauges). The dummy element could be considered as a mechanical member used only to carry the load and to keep the system balanced. The dummy elements were designed to have the force-deflection behavior as same as the active force sensor in order to keep the equilibrium of the system over the whole measurement process. According to the datasheet of the active force sensor, the maximum displacement proportional to the rated capacity (1000 N) is 0.05 mm [11], so each dummy element was designed to have the same deflection limit at 1000 N as shown in Figure 2. The material of the dummy elements is stainless steel AISI 316 which has 200 GPa modulus of elasticity, and 205 MPa yield strength. The factor of safety is around 2.3. ***The outer diameter is 76 mm while the total height is 68 mm(same dimensions as the active transducer)***. The upper and lower plates of the BUS were designed to be rigid enough to minimize the total axial deflection as possible***, both has 12 mm thickness*** (Figure 3). The high rigidity of the system will enhance the ability of the plates to transfer the applied load to the elastic elements without any bending moments or parasitic loads which it is found negatively affect the behavior of such systems [12]. The capacity of the active-force sensor is 1000 N, hence the target capacity of the system under this study is 3000 N. Probably other systems could use single-active force sensor with four dummy elements to reach higher capacities similar to the BUS which was built based on five-active force sensors at PTB, Germany [13].

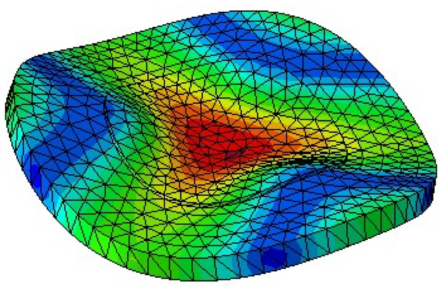


A. Maximum deflection ≈ 0.05 mm

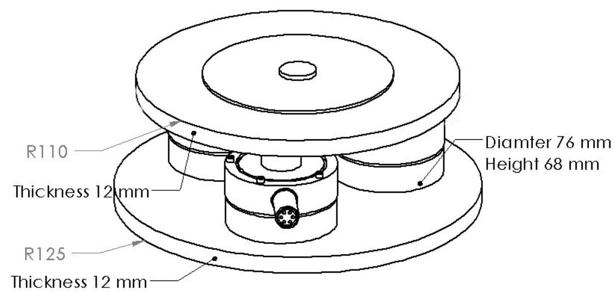


B. Maximum Von-mises stress ≈ 90 Mpa

Figure 2 Stress and displacement analysis of the elastic element under the rated load



A. Upper plate max. def. ≈ 0.003 mm



B. Overall system dimensions

Figure 3 The displacement of the upper plate under 3000 N applied load

4. Experimental setup

The proposed design was validated according to the following steps; **first**, the active-force sensor was calibrated up to 1000 N to determine its metrological characteristics according to ISO 376:2011 [14]. **Second**, the whole system was assembled as shown in Figure 5. The active-force sensor was arranged radially in parallel with the two dummy elements, then the new system was calibrated up to 3000 N.

Third; the BUS system is used as a reference to calibrate a load cell has a capacity of 2500 N. Once the calibration process was done, the measurement errors were calculated over the whole measurement range. The acceptance criterion is; the measurement errors shall be below 1% to allow this system to work as a reference to check the performance of other force measurement systems as universal testing machines. The signals of the force sensors were collected using the LT-Digitizer data acquisition system which has a resolution of 0.00001 mV/V.

4.1 Summary of the calibration and evaluation procedures;

The calibration scheme is graphically illustrated in Figure 4, this scheme could be demonstrated as follows:

I. Start the calibration by applying three preloads to the maximum load, the duration for each preload shall be between 60 s and 90 s as possible.

II. Apply two-series of increasing forces to the sensor without rotating the device (series 1 and 2).

III. Apply at least two-series of increasing/decreasing force values (series 3/4 and 5/6). Between each of the further force series, rotate the sensor around its axis to locations equally distributed over 360° (i.e. 0°,120°, 240°). After each rotation, make further preload to the maximum load.

IV. The response corresponding to zero-force shall be documented after waiting 30 s from removing of the applied load.

V. Wait nearly 3 minutes between every two series.

5. Results and discussions

The calibration results of the 1000 N force sensor are shown in Table 1, the results prove that the force sensor achieves class 0.5 according to ISO376:2011. This class is the second-best class according to the standard classification. This sensor is used as the single-active signal for the BUS as previously stated in the above sections. After assembly of the whole system as shown in Figure 5, the system was calibrated up to 3000 N, its calibration results are stated in Table 2.

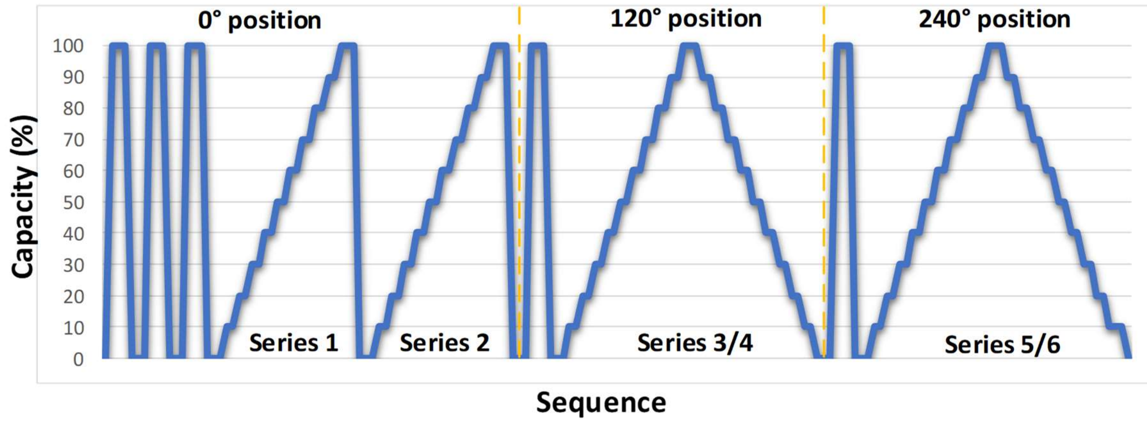


Figure 4 Calibration scheme according to ISO 376:2011

Table 1 Calibration results for the 1000 N force sensor.

Applied force	Force sensor response (mV/V)							Relative expanded uncertainty
	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6	Mean	
N	0° position		120° position		240° position		1,2,3	%
100	0.20222	0.20221	0.20220	0.20225	0.20224	0.20226	0.202220	0.018
200	0.40439	0.40442	0.40440	0.40452	0.40445	0.40453	0.404413	0.019
300	0.60658	0.60660	0.60662	0.60672	0.60671	0.60681	0.606637	0.018
400	0.80878	0.80883	0.80883	0.80895	0.80896	0.80899	0.808857	0.017
500	1.01097	1.01099	1.01106	1.01115	1.01111	1.01122	1.011047	0.012
600	1.21309	1.21312	1.21320	1.21332	1.21331	1.21338	1.213200	0.014
700	1.41522	1.41528	1.41528	1.41544	1.41540	1.41552	1.415300	0.011
800	1.61733	1.61736	1.61739	1.61754	1.61753	1.61765	1.617417	0.010
900	1.81935	1.81950	1.81950	1.81946	1.81965	1.81967	1.819500	0.013
1000	2.02142	2.02145	2.02156	--	2.02179	--	2.021590	0.013

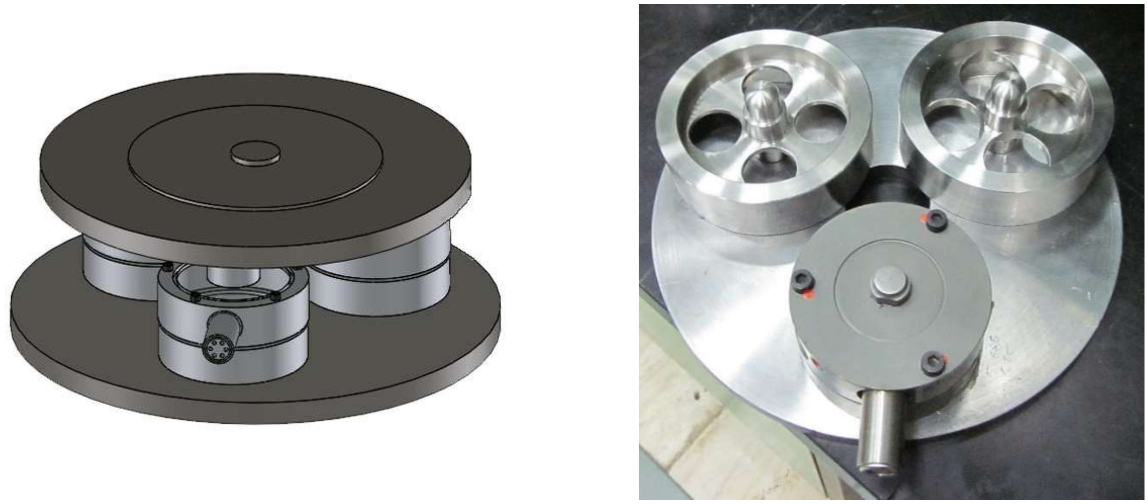


Figure 5 Single-active -force sensor BUS

The calibration results achieve class 1 according to the same standard. The maximum relative expanded uncertainty is 0.055 %. According to ISO 7500-1, the specification of the reference which could be used to calibrate or check the performance of the uniaxial testing machines shall be class 1 or better [15]. The results prove that the BUS based on a single-active force signal is still capable to calibrate such testing machines. The calibration data were fitted to obtain a 2^{nd}-degree polynomial equation (Equation 1) which is used later to convert the output of the BUS from mV/V to N.

$$F = X * R + Y * R^2 + Z * R^3 \qquad \textit{Equation 1}$$

Y = 0.494846

X = 1487.746052

Z = 0.0526455

Where:- F is the actual applied force in N
R is the mean reading of BUS active signal in mV/V
X, Y, and Z are the calibration coefficients

Further, the new system is used to calibrate a load cell up to 2500 N. This load cell was previously calibrated using a deadweight force standard machine, so it is easy to calibrate this load cell again, but this time the calibration will be carried out in force against force (the two signals are in force units; N). This will aid in the determination of the measurement error which could not be calculated in case the load cell is calibrated in mV/V output. The signals of both sensors were collected with the aid of VN-digitizer software – channel 1 is the load cell signal (under calibration) while channel 2 is the BUS signal (reference) as shown in Figure 6. Using this software, the signals could be converted directly to the force unit based on the calibration equations of each sensor that were obtained from the previous calibrations. The calibration results for the 2500 N load cell are displayed in Table 3. The maximum measurement error is within 0.23 %, this value is far below the acceptance criterion, which is 1%. Hence, the new system could be used to calibrate force measurement systems up to a capacity equal to three times the capacity of the active force sensor being used in the system.

Equation 1
Y = 0.494846

Table 2 Calibration results for the 3000 N multi-capacity sensor.

Applied force	BUS mean Response (mV/V)	Relative expanded uncertainty
N	1,2,3	%
300	0.201634	0.055
600	0.403238	0.030
900	0.604812	0.027
1200	0.806354	0.020

1500	1.007862	0.016
1800	1.209335	0.013
2100	1.41077	0.013
2400	1.612166	0.013
2700	1.813521	0.012
3000	2.014833	0.002

Table 3 Calibration results for 2500 N load cell

Applied force	Load cell response	Indication error
N	N	%
250	250.587	0.23
500	499.616	-0.08
750	748.731	-0.17
1000	997.942	-0.21
1250	1247.324	-0.21
1500	1496.889	-0.21
1750	1746.563	-0.20
2000	1996.395	-0.18
2250	2246.356	-0.16
2500	2496.630	-0.13

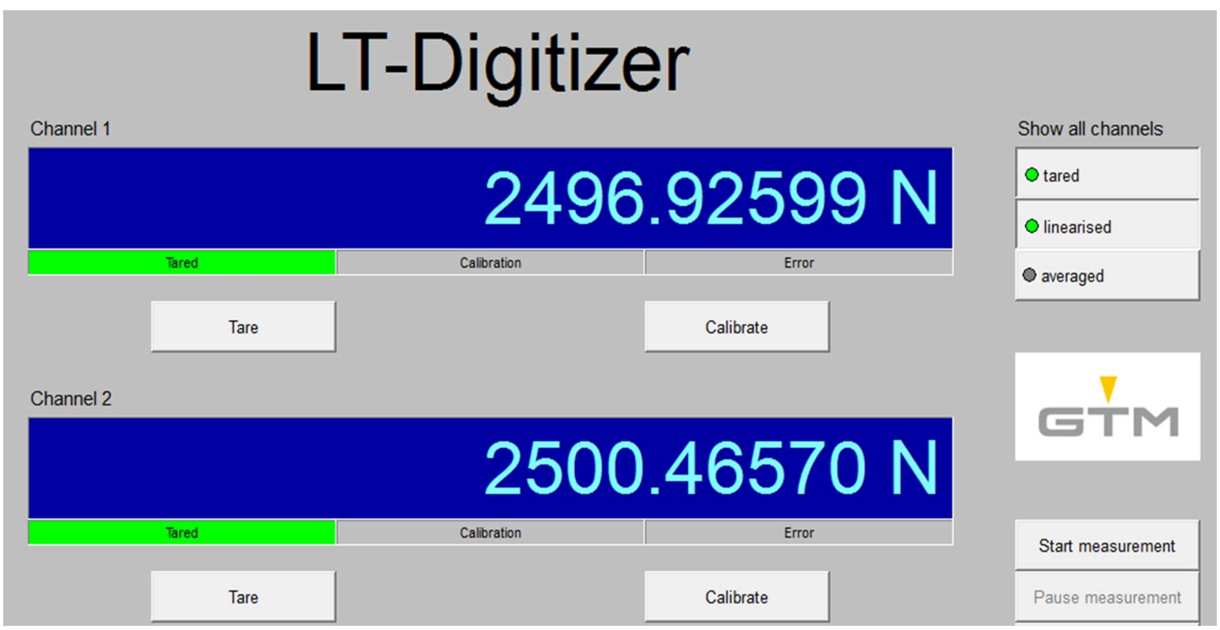


Figure 6 VN-digitizer software

Figure 7 shows the behavior of the 2500 N load cell over the whole measurement range, while Figure 8 shows the behavior of the measurement error obtained from the calibration using a single-active force sensor BUS as a reference. Considered all these results, the BUS using just one active force sensor could be used as a reference to calibrate or periodically check the validity of the uniaxial testing machines as required by ISO 17025 [16].

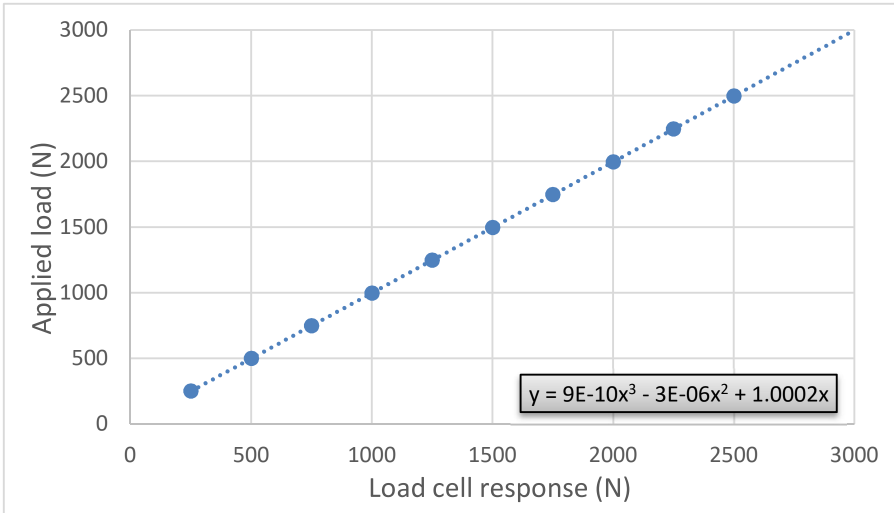


Figure 7 The behavior of the 2500 n load cell over the whole measurement range.

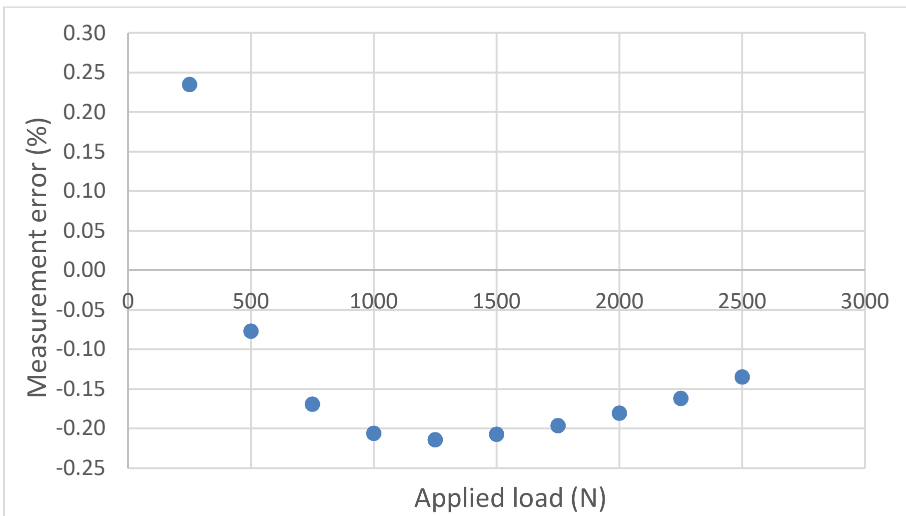


Figure 8 The measurement error obtained from the calibration of 2500 n load cell using a single-active force sensor BUS as a reference

6. Conclusions

The idea of extending a capacity of a force sensor based on a build-up principle is interesting where it introduces an economical solution for force measurement needs over a wide range. Building a dummy element is more economical and simpler than purchasing or manufacturing a full active force sensor. The experimental results prove the validity of the design where the calibration results indicate that the new system achieves class 1 according to ISO 376:2011. The new system is used as a reference to calibrate 2500 N load cell, the measurement errors are within the acceptable limit, which is 1%. The single-active signal BUS introduces a good solution to periodically check the validity of the uniaxial testing machines, which are found in many mechanical testing labs.

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