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# Multi-capacity load cell prototype

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ABSTRACT
This article illustrates an advanced approach in force measurement standards. It gives a spot on the design, manufacturing and evaluation for a prototype force transducer with multi-capacity. This prototype has three adjustable capacities (5 kN, 10 kN and 15 kN) and works in compression mode. The introduced design offers a comparative load cell looking forward to replaceing three force transducers with the same capacities (5 kN, 10 kN and 15 kN) which are commercially available. Experimental results reveal satisfactory agreements with that calculated with an analytical method and simulation results using finite element techniques. The detailed metrological characteristics of this multi-capacity load cell will be published later.

**Section:** RESEARCH PAPER

**Keywords:** force measurements; transducer; conceptual design; proposed design

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## 1. INTRODUCTION

A force measurement system is made up of a transducer and associated instruments. The most common commercial force transducer is based on an electrical principle (the load cell). Different force transducers are usually used by national and accredited laboratories to calibrate force generated systems. The main part in the load cell is the elastic element on which a Wheatstone bridge circuit is formed [1]. The stiffness of the elastic element is a governing factor in determining the load cell capacity.

The concept of a force transducer with different capacities (multi-capacities, changeable-capacities) was recently introduced by NIS and PTB to overcome the additional costs of requiring several force transducers.

## 2. CONCEPTUAL DESIGN

Building a multi-capacity load cell requires different values of stiffness. The multi-capacity load cell was introduced based on increasing the stiffness ($k$) for each range [2]. Proposing a multi-capacity load cell with three different capacities requires a concept to offer three values of stiffness, one for each capacity [3]. The three different values could be offered through using three different elastic elements, one for each range, or combining elastic elements together to form three different stiffness values.

The combined stiffness resulting from adding elastic elements to each other in parallel is the sum of the individual stiffnesses. Equation (1) shows the combined stiffness ($k_p$) resulting from coupling three elastic elements in parallel [4].

$$k_p = k_1 + k_2 + k_3 \tag{1}$$

where $k_p$ is the resulted stiffness from coupling elastic elements in parallel, $k_1$, $k_2$, $k_3$ are the stiffness values of three elastic elements combined together in parallel.

In the current research work, for the first capacity an elastic element nominated for the first working range is used (see Figure 1). For the second capacity a new element is introduced instantaneously with the first element to withstand the applied load together (see Figure 1), and for the third capacity another new element is used instantaneously with the first and the second elements to withstand the load together (see Figure 1).

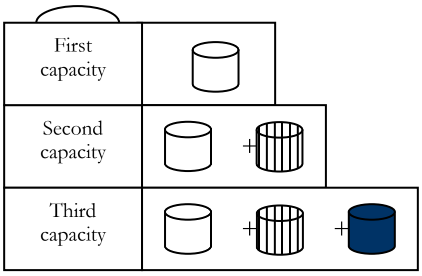


Figure 1. Schematic of the concept of adding elastic elements to form a three-range multi-capacity load cell.

## 3. PROPOSED DESIGN

The concept of the proposed design is adding elastic elements in parallel before applying the loads. Figure 2 shows the parts forming the proposed design. Mainly, the proposed design is based on using a base which has a protruded cylinder, a main rod, protruded cylinder, rotating cap and a set of strain gauges.

The set of strain gauges are bound on the main element forming a Wheatstone bridge circuit. The main element and the concentric cylinder are assembled on the base which has a protruded built-in cylinder. The cylinders have protrusions (see Figure 2).

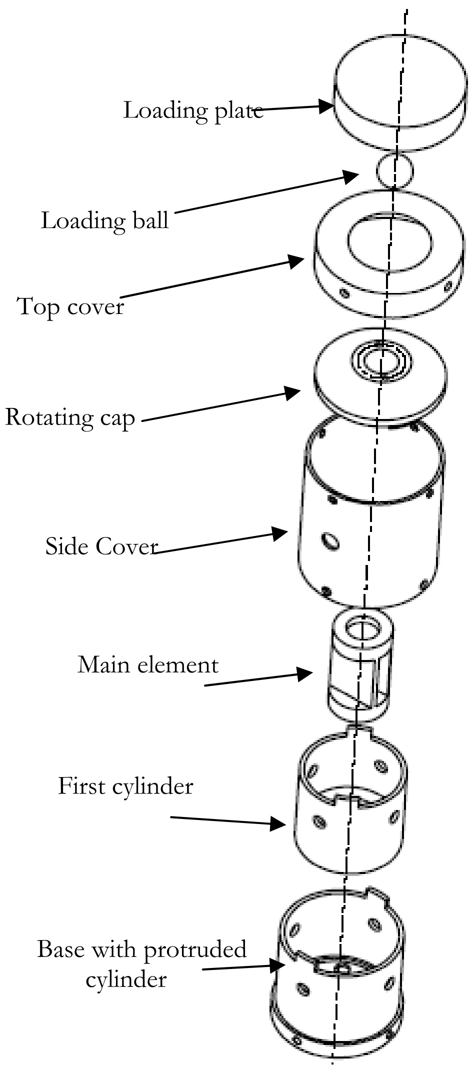


Figure 2. Proposed prototype.

The load is applied using a universal rotating cap enclosed to the load cell which is designed to rotate relatively to the load cell body. The universal cap has three pre-determined marks (see Figure 3). Each mark is nominated for a range. There are also three other marks on the load cell top cover. Each is nominated also for a specific range. These marks indicate three positions: Position 1: for applying the load on the main element; Position 2: for applying the load on the main element and the cylinder; Position 3: for applying the load on the main element, cylinder and base with the protruded cylinder. The load cell capacity is determined by rotating the cap until the required capacity mark is in line with the counterpart mark which is on the load cell top cover, which means that the right protrusions of both the cylinders and the cap face each other.

## 4. PROTOTYPES

Different prototypes were manufactured and evaluated at NIS and PTB. The preliminary checks carried out on the manufactured prototypes show that the conceptual design was applicable, the range selection mechanism was satisfactory and works successfully but the results reveal some criticism which was taken into consideration during developing the design of this prototype at PTB in order to manufacture an accurate and precise multi-capacity load cell.

## 5. FINAL PROTOTYPE

The final prototype was proposed after developing various tests. It is characterized by some new features related to the design and reflected on the load cell dimensions and weight to manufacture a comparative load cell (see Figure 4). Based on PTB past experience [5], the four main parts (main element,

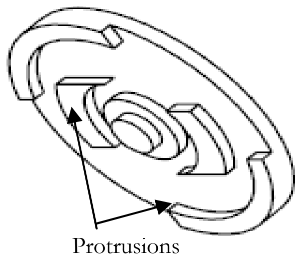


Figure 3. Universal rotating cap lower side.

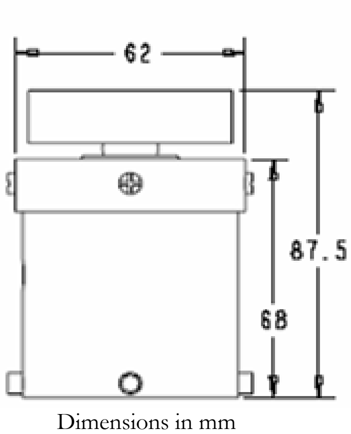


Figure 4. Load cell overall dimensions.

cylinder, the base with the protruded cylinder and the rotating cap) were manufactured from DIN 1.6580 (30CrNiMo8, бy≈1000 MPa). DIN 1.4301 (X5CrNi18-10, бy≈190 MPa) was used to manufacture the rest of the load cell as it has good corrosion resistance.

During the design phase; a comprehensive stress analysis using a Finite Element Analysis Program (Abaqus FE program version 6.5-1) was carried out to develop, optimize and check the efficiency of adding elements.

A compressive test load of 15 kN was used to verify the effect of adding elements in parallel. Three models were evaluated and each model simulates one capacity of the three capacities. First model: composed of the main element only; Second model: composed of the main element and the cylinder with protrusions; Third model: composed of the main element, the cylinder with protrusions and the base with the protruded cylinder. The 15 kN compressive load was applied on the three models.

Results show that the stress on the main element (first capacity) decreases by adding the new element (first cylinder-second capacity) from the hypothetical value 164 MPa to 115.5 MPa (i.e. 30 % decrease) and after adding the last element (the base with the protruded cylinder-third capacity) decreases more to be 100 MPa (i.e. 40 % decrease) with a difference equal to 64 MPa from the first range. Figures 5 to 7 show the results of the finite element analysis.

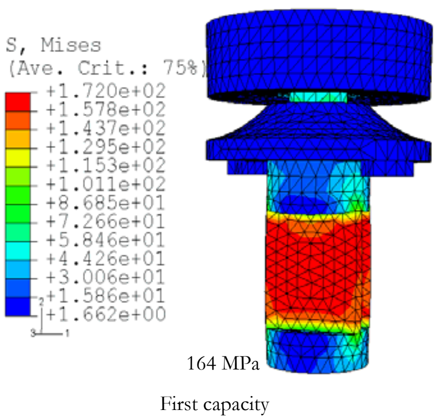


Figure 5. Results of FE stress due to 15 kN load on 1st range.

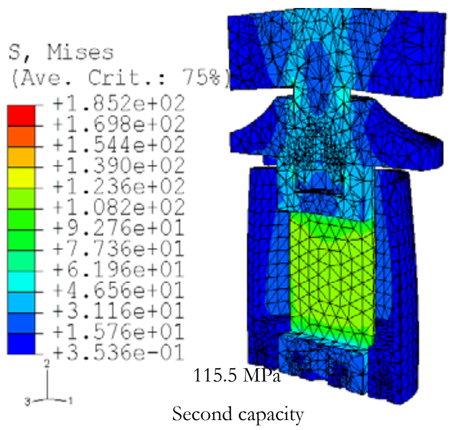


Figure 6. Results of FE stress due to 15 kN load on 2nd range.

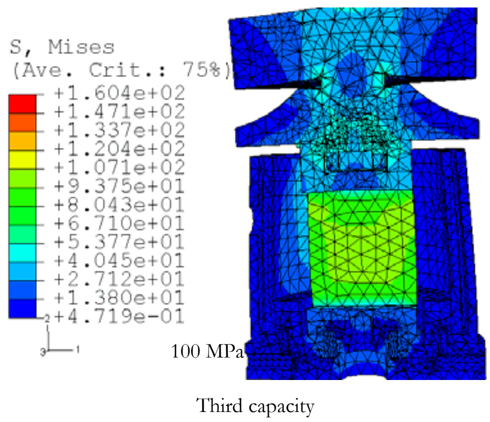


Figure 7. Results of FE stress due to 15 kN load on 3rd range.

## 6. MANUFACTURING

The machining process was carried out in PTB`s Scientific Instrumentation Department which is equipped with high accurate machines. After manufacturing the parts, the main element, the cylinder and the base with protruded cylinder were assembled together in what is known as main parts assembly (see Figure 8).

Low tolerances (approximately 10 µm flatness) were required at the top of the main parts assembly (see Figure 8). This is to ensure that the main element and the protrusions are on the same plan. This machining tolerance was achieved by a grinding process. Grinding is the final machining process that was applied to the top surface of the main parts assembly after the strain gauges were adhered to the main element and protected.

Two bi-axial strain gauges 1-XG11-3/350 manufactured by HBM with a 3 mm gauge length and a 350 ohm gauge resistance were adhered on the main element (one on each side) to form the Wheatstone circuit [6].

## 7. MEASUREMENTS

Two series of measurements were carried out to evaluate the manufactured prototype using the PTB 20 kN deadweight machine.

First, test measurements were carried out on the manufactured load cell to practically study the effect of adding elements. Two loads (3 kN and 5 kN) were applied on the three ranges. Table 1 shows the response of the manufactured

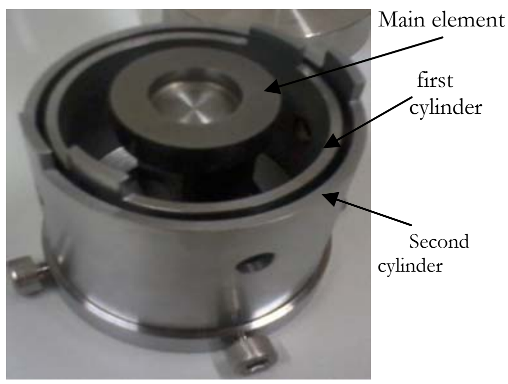


Figure 8. Main parts assembly.

Table 1. Response under loads.

| Load | Response (mV/V) | | |
|---|---|---|---|
| kN | First range | Second range | Third range |
| 3 | 0.221479 | 0.135401 | 0.103403 |
| 5 | 0.363655 | 0.232232 | 0.185130 |

transducer under the loads. Results prove the efficiency of adding elements to increase the stiffness.

In the next step the outputs of the three capacities were measured under loads up to the maximum capacity of each range to evaluate the efficiency of adding elements. These measurements were repeated during three different days. Eeach day the load cell was removed from the machine and placed again with different orientation with respect to the loading axis in order to randomize the measuring conditions.

Table 2 and Figure 9 represent the average response of the three ranges for the first prototype under loads up to the maximum capacity for each range. It was not possible to apply 15 kN load on the third capacity due to the loading schemes of the PTB 20 kN deadweight machine which increases loads by steps of 2 kN beginning from a 10 kN load.

Figure 9 shows that the values of the response decrease by adding a new elastic element which indicates that the range selection mechanism is satisfactory and works.

## 8. COMPARISON BETWEEN F.E.A. AND S.G. RESULTS

A comprehensive stress analysis using a Finite Element Analysis Program (Abaqus FE program version 6.5-1) was carried out during the design stage. Table 3 compares values of

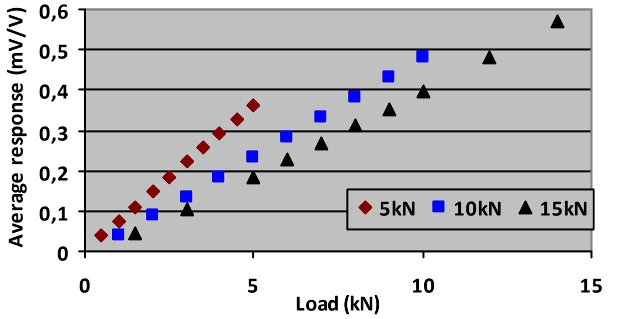


Figure 9. Representative graph for the average response for the three capacities at maximum load.

calculated stresses and deflections at maximum capacities (5, 10 and 15 kN) based on actual measured responses (Table 2) and the deduced responses using finite element analysis (Section 5).

The first and the second rows of Table 3 show the stress and the deflection of the main sensing element, concluded from the finite element analysis. The indicated values are for the maximum capacities. The third row of the table shows the actual response of the main sensing element presented in mV/V. The fourth and the fifth rows of the table show the calculated deflection and stress based on the actual response (third row). They were calculated by applying equations (2), (3) and (4) [7] which relate the Wheatstone bridge output to the induced deflections taking into consideration that in the manufactured prototype a full Wheatstone bridge circuit (four strain gauges) was used. Assuming an ideal case for strain distribution ($\varepsilon_1 = \varepsilon_3$, $\varepsilon_2 = \varepsilon_4$ and $\varepsilon_1 = -0.3\ \varepsilon_2$) and taking into consideration that the gauge factor ($k$) equals 2 and the gauge length ($L$) equals 30 mm.

$$\frac{V_A}{V_E} = \frac{k}{4}(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4) \tag{2}$$

$$\frac{V_A}{V_E} = 0.65k\varepsilon_1 \tag{3}$$

$$\Delta L = L\varepsilon_1 \tag{4}$$

where $V_A$ is the Wheatstone bridge output voltage, $V_E$ Wheatstone bridge input voltage, $\varepsilon_1$, $\varepsilon_2$, $\varepsilon_3$, $\varepsilon_4$, the strain induced in the strain gauges under load, $k$ is the gauge factor of the strain gauge and $\Delta L$ is the deflection.

Figures (10) and (11) illustrate the calculated values and the deduced ones for deflections and stresses, respectively.

The difference between the stress and calculated deflections based on the measured response and that concluded from finite element analysis stated in Table 3. It is worth mentioning that, in the ideal case, the stresses, strains and deflections of the main sensing element remain the same for each capacity and their values are equal to that of the first capacity.

Table 2. Response of the three capacities up to maximum capacity.

| **Load** | **Response(mV/V)** | | |
|---|---|---|---|
| **kN** | **First range** | **Second range** | **Third range** |
| **0.5** | 0.037586 | ---- | ---- |
| **1** | 0.074674 | 0.039140 | ---- |
| **1.5** | 0.111562 | ---- | 0.043274 |
| **2** | 0.148373 | 0.087196 | ---- |
| **2.5** | 0.185084 | ---- | ---- |
| **3** | 0.221479 | 0.135401 | 0.103403 |
| **3.5** | 0.257326 | ---- | ---- |
| **4** | 0.292858 | 0.183655 | ---- |
| **4.5** | 0.328269 | ---- | ---- |
| **5** | 0.363655 | 0.232232 | 0.185130 |
| **6** | ---- | 0.281025 | 0.226545 |
| **7** | ---- | 0.330136 | 0.268401 |
| **8** | ---- | 0.379518 | 0.310590 |
| **9** | ---- | 0.429235 | 0.353143 |
| **10** | ---- | 0.478793 | 0.395926 |
| **12** | ---- | ---- | 0.482352 |
| **14** | ---- | ---- | 0.569091 |

Table 3. Strain, stress and deflection deduced from F.E.A. and S.G. results.

| | | | First range ( 5 kN) | Second range (10 kN) | Third range (15 kN) |
|---|---|---|---|---|---|
| 1 | Deduced using F.E.A | Deflection (mm) | 0.0074 | 0.0098 | 0.0112 |
| 2 | | Stress (MPa) | 54.98 | 77.23 | 100.42 |
| 3 | Measured | Response (mV/V) | 0.363655 | 0.478793 | 0.60974 |
| 4 | Calculated | Deflection (mm) | 0.0083 | 0.011 | 0.014 |
| 5 | | Stress (MPa) | 58.56 | 77.73 | 98.93 |

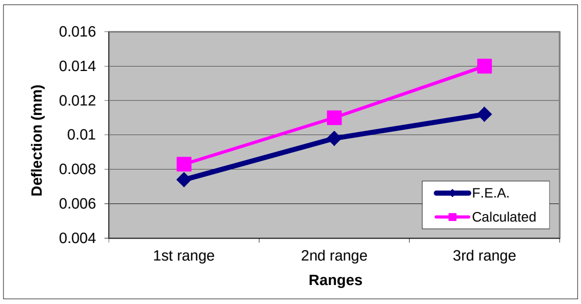


Figure 10. Illustration for calculated and F.E.A. deflections.

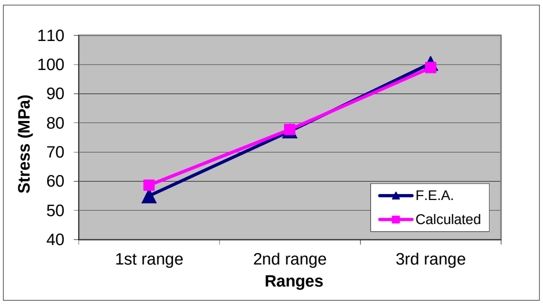


Figure 11. Illustration for calculated and F.E.A. stress.

## 9. OPINIONS AND INTERPRETATIONS

### 9.1. Wheatstone bridge circuit

The used Wheatstone bridge circuit was composed of four active strain gauges. Gauging was carried out through this work by the simplest method while in expert companies strain gauges bonding (curing, adhesive, uniform adhesive layer, gauging presser, etc) are carried out in more professional methods. In addition, more resistors and strain gauges could be introduced to the simple Wheatstone bridge circuit resulting in an improved, complicated and more reliable Wheatstone bridge circuit. The complementary strain gauges will work on adjusting the zero signals, compensate temperature effect and improve the load cell linearity.

### 9.2. Elastic element

The manufactured prototype was designed based on a simple column loading principle. The main reason to design and manufacture the main element as a column with rectangular cross section was to facilitate the machining process. A rectangular cross section was used as this offers a larger surface area on which the strain gauges could be easily fixed, but it makes the elastic element not symmetric and this may cause high effect induced by the rotation with respect to the loading axis.

### 9.3. Load distribution

In the manufactured prototype and according to the conceptual design, the load is distributed through the rotating cap to the required elastic elements. Force interaction between contacts of the rotating cap and those of the main element, the first cylinder and the second cylinder has a big influence on the multi-capacity load cell. More investigations are required for better contact profile in order to improve the efficiency of the load transmission which will be reflected on the metrological characteristics.

### 9.4. Uncertainty

A new source of uncertainty resulting from the effect of cap rotation will be introduced. It needs more research to be defined and estimated correctly as it may be affected by the manufacturer (depending on precise machining), by the user (depending on the user experience) or a combination of both.

## 10. CONCLUSION

In this article a prototype of multi-capacity load cell was designed, manufactured and evaluated as a facility in the force measurement field. The manufactured prototype works in compression mode with three-changeable capacities 5 kN, 10 kN and 15 kN (see Figures 12 and 13). It can replace three ordinary - one capacity - load cells which are commercially available. The pillar of the design concept increases the stiffness of the sensing element as the capacity is being changed. The required capacity can be chosen by rotating a special designed rotating cap. This cap allows loads to be distributed among several elastic elements; one of these elastic elements is the main sensing element on which the strain gauges are bonded to form a Wheatstone bridge circuit. Performance evaluation results showed that – in case of accurate machining and finishing – the design concept is effective.


Figure 12 . Manufactured multi-capacity load cell with loading plate.

Figure 13. Manufactured multi-capacity load cell without loading plate.

## 11. FUTURE WORK

The manufactured multi-capacity load cell will be calibrated according to the international standard ISO 376-11 to investigate its metrological characteristics [8]. The main idea of the multi-capacity approach by incorporating elastic elements with only one sensing element could be generalized and investigated in other areas in the field of force measurements. Also it would be more valuable to apply this concept in manufacturing a multi-capacity load cell with a range difference increase by a power of ten, for instance 5 kN, 50 kN and 500 kN.

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