ACTA IMEKO
ISSN: 2221-870X
December 2020, Volume 9, Number 5, 143 - 149

PRACTICAL INVESTIGATION FOR THE CONCEPT OF A SERIAL-TYPE BUILD-UP FORCE MEASUREMENT SYSTEM

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Abstract:
This paper introduces a proposed design for the first Serial-type Build-Up System (S-BUS). The work includes the design and implementation of two S-BUS prototypes, the metrological characteristics of the prototypes were evaluated. The evaluation results prove the validity of the system practically. The paper also discusses the key differences between the Parallel Build-Up System (P-BUS) and the S-BUS, and what makes it important to study the S-BUS concept.

Keywords: build-up system; meganewton; force traceability

1. INTRODUCTION

All force measuring instruments take their traceability from force standard machines. The Deadweight Force Standard Machines (D-FSM) are the most precise machines for force generation but these types of machines have limited capacities due to their high manufacturing cost furthermore their huge size at high capacity [1]. The force amplification machines replace the deadweight machines at higher force ranges, these machines still have problems such as manufacturing cost and complex technology requirements [2].

Currently, the comparator type force standard machines which use a BUS as a reference are considered the optimum solution for traceability issue at high force level (meganewton range). The calibration is carried out by comparing the response of the force measuring unit under calibration with the response of the standard one (BUS) [3]. There are many machines worldwide work based on this principle [4] [5] [6]. Furthermore, the BUS individually can work as a transfer standard [7] [8]. The P-BUS consists of three or more identical force transducers arranged mechanically in parallel. Based on three-transducer based P-BUS (Figure 1 and Figure 2), it is found that each force transducer carries one-third of the load acting on the system. The P-BUS has advantages such as small size relative to a force standard machine at the same range, capable of measuring high forces more economically, and the most important is that it is used to transfer the traceability from smaller force standard machines to larger force measuring systems.

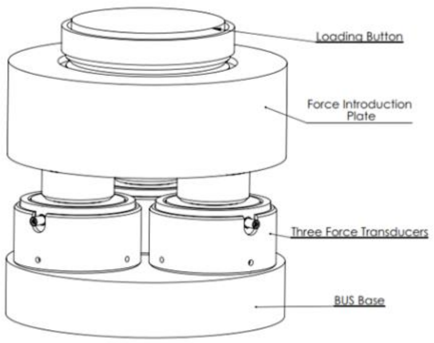

Figure 1: A schematic drawing of the P-BUS

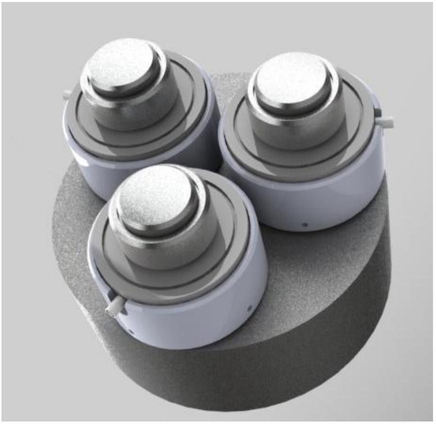

Figure 2: P-BUS-Top View (without upper plate)

To allow the transducers within a BUS to carry an equal share of force, the system shall include a force introduction plate with enough stiffness to distribute the load on the force transducers. This arrangement has some disadvantages as the size becomes huge at high rated forces also the mechanical stability and stiffness of the overall system become a big challenge. In 2013 the European Association of National Metrology Institutes (EURAMET) launched a project entitled

“Force traceability within the meganewton range” under designation EMRP SIB63 [9], the main objective of this project is to extend the traceability of force measurements up to 50 MN and to give users new procedures and technical guidelines on the use of high force measurement devices [10]. The work of the project was split into six work packages. The main objective of work package WP1 was to develop transfer standards (based on BUS) for forces up to 50 MN with the lowest possible uncertainty, also all expected influences on measurement uncertainties had been studied during this project [9]. Indeed, there were great works that had been done during this project, many designs for P-BUS were built. Most of the uncertainty sources were discussed. Some innovative adaptation parts were designed and tested to investigate their intended effect. Now there is enough knowledge about the P-BUS and how to use it.

2. S-BUS CONCEPT

Force transducers are available in many design configurations; tension rods, compression strut, bending beams, shear beams etc [11]. Bending-ring force transducers, also known as pancake design, are one of those widely known for their good metrological characteristics. If this type is modified to allow many units to stand above each other, this will help in the design of the target S-BUS as shown in Figure 3. Using the proposed design, it is expected that the total load will be distributed on the force measuring units equally. One benefit of this design is the measuring units have the same loading axis. Under this condition, the bending moments and cross forces will nearly vanish. There is no need for the upper force introduction plate as in the P-BUS. The geometry of the proposed system is simpler than the P-BUS. Two finite element models were developed to check the validity of the proposed design. The first model represents a single transducer loaded with a 10 kN axial compressive force while the second model represents three transducers above each other loaded with 30 kN axial compressive force (three times the load in the previous model). The related stress and strain results prove the validity of the design, where the stress and strain values are nearly the same (Figure 4 and Figure 5). This demonstrates that every unit in the second model is still subjected to just 10 kN compressive force, also this proves that the stiffness of the second model was increased to three times the stiffness of the first model. The trick of the design is the three units contact each other at the inner hub as shown in Figure 5, this allows them to deflect as a single unit and to work together to carry higher force since their stiffness increased by three due to this arrangement. For the first model, the maximum Von-Mises stress is 527 MPa - the maximum equivalent strain is 2.261×10^{-3} - and the maximum axial deflection is 0.13 mm. For the second model, the maximum Von-Mises stress is 549 MPa - the maximum equivalent strain is 2.377×10^{-3} - and the maximum axial deflection is 0.14 mm. This preliminary study shows that the S-BUS concept is valid theoretically from the point of load distribution. To test the concept practically a 20 kN and a 30 kN S-BUS prototypes were designed and implemented then tested on the PTB 20 kN and 100 kN (D-FSM).

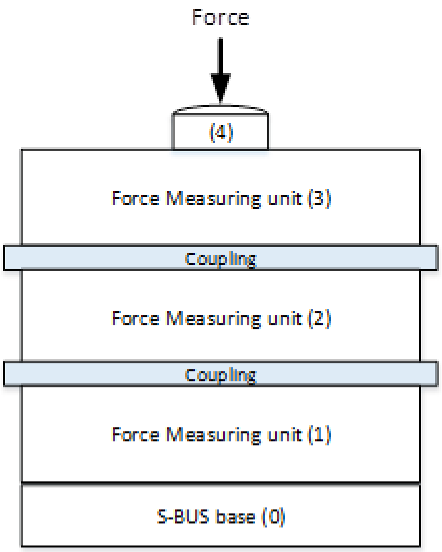

Figure 3: The schematic drawing of the proposed design of the S-BUS

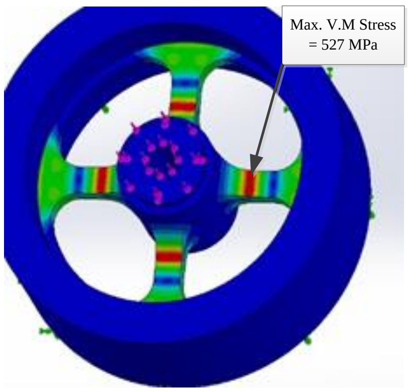

Figure 4: FE results for Single transducer Model (10 kN force)

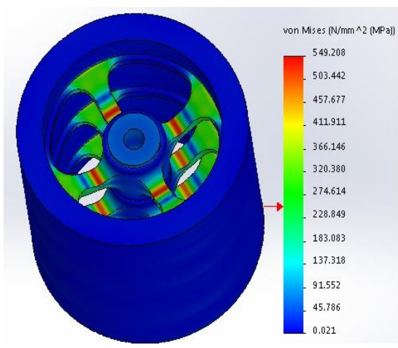

Figure 5: FE results for S-BUS model (30 kN force)

3. MAJOR DIFFERENCES BETWEEN P-BUS AND S-BUS

A comparison between P-BUS and S-BUS was prepared before building the S-BUS prototypes (Table *1*). The purpose of this survey is to determine the factors/parameters that were found to affect the P-BUS behaviour based on the knowledge previously gathered through the SIB63 project. It's expected that those factors/parameters will take more interest during the study of the S-BUS.

Table 1: Comparison between S-BUS and P-BUS

Parameter	P-BU System	S-BU System
BUS Structure: • Force introduction plate. • Base plate. • Loading button. • Overall size.	▪ It is found that the stiffness of the adaptation parts has a significant effect on the system behavior, the more stiff parts are the best behavior the system can give, but this criterion has a limitation where the weight is the opposite face for the stiffness. For the 50 MN P-BU system, the introduction plate weighs 900 kg [10]. At high rated capacities the overall dimensions of the system become relatively large.	▪ The S-BUS does not include force introduction plates or other adaptation parts are required. ▪ The overall size is very compact compared to a same capacity P-BUS.
Influences related to structure: • Bending moment. • Cross forces	▪ These influences are consequences of elastic deformation for the adaptation parts, especially the force introduction plate, to reduce these effects some work had been done during the SIB63 project such as: ▪ There is a patented design for a force introduction plate that has been created and studied to nearly eliminate these effects [12]. ▪ For 15 MN Ukrainian P-BUS, the force introduction plate had been optimized to keep the elastic deformation as low as possible to avoid cross forces and bending moments [7].	▪ It is expected a very small effect as similar to bending-ring transducers. ▪ The transducers can be enhanced using special load cups to improve their compensation for any structure related influences [12].
Type of force transducer used:	▪ Standard columns type or bending-ring type can be used. ▪ The bending-ring transducers show the best behavior in the range up to 1 MN [10]. ▪ There is strong evidence that the strain cylinders are more suitable than bending-ring transducers for use in the P-BUS at higher rated loads as they can usually be assembled in a more compact arrangement [12].	▪ Only a bending-ring type can be used. ▪ Future studies could be carried out to benefit from its design at a high level may be by building the transducer from ground plates.
No. of force transducers:	▪ For PTB 50 MN, maximum no. is 5 transducers. ▪ For GTM 5.4 MN, maximum no. is 9 transducers [13]	▪ Still under investigation.
BUS Capacity	▪ There is a 60 MN P-BU system available right now in FJIM, China [14].	▪ Still under investigation
Application of force on force transducers	▪ During the individual calibration – the load comes directly from a FSM into the transducer. ▪ During the BUS calibration – the load shifted through adaptation parts.	▪ Single- Directly from FSM. ▪ BUS- Same load axis (No load shift)
Metrological Characteristics: • Reproducibility. • Creep and creep recovery. • Hysteresis • Indication Deviation	▪ The influences of different structures on the uncertainty are more significant than expected [15]. ▪ The reproducibility of some P-BUS's is better than the reproducibility of a single transducer. ▪ It's found that the creep of the P-BUS is sensitive to the BUS structure while the creep recovery is not affected by the structure [16]. ▪ The number of contact surfaces between single adaptation parts increases the hysteresis effect [12]. ▪ The BU system deviation is affected by all system stiffness, the larger the system stiffness the lower the indication deviation is [12].	▪ The characteristics of the system are still under investigation, but it is expected to be good due to the similarity of the system to bending-ring force transducers.

4. S-BUS PROTOTYPE DESIGN

A 30 kN capacity was chosen to build the first S-BUS prototype which consists of three force measuring units. It is expected that each unit will carry one-third of the total applied load. Each force measuring unit is designed in the form of a bending ring elastic body with 8 strain gauges installed to it at pre-determined locations.

The elastic element design process began by proposing a preliminary design, then this design developed step by step to reach the point at which the proposed "model" design would meet the key design criterion. The main design criterion is achieved when a local average normal strain with a value of 1000 µm/m has resulted in the strain gauge pre-determined position, this criterion has to be achieved at a safe stress level relative to the material allowable stress limit. If it's possible to minimize the maximum stress corresponding to 1000 µm/m strain value, this will improve the linearity and hysteresis of the measuring units [17].

The material used- the material chosen to build the elastic element is the 30CrNiMo8 (Mat. No.1.6580) spring steel. This material is well known in the force transducers manufacturing field due to its good mechanical properties e.g. stiffness and yield strength.

Strain gauge selection- a linear strain gauge with a 3 mm length measuring grid and 350 Ω resistance was chosen to measure the strain. The grid carrier dimensions are 7.3×4.5 mm; this is the area where the mean strain is measured.

5. S-BUS SIGNAL GENERATION AND PROCESSING

The signal of the S-BUS is generated as illustrated in Figure 6. The S-BUS signal is displayed in the force unit (N). The S-BUS signal F_S is the sum of the three force transducers signals ($F_{IS,1}$, $F_{IS,2}$, $F_{IS,3}$), also these three signals are in force unit (N). In order to obtain a force transducer signal in a force unit, a polynomial equation should be obtained by calibrating the force transducer then fitting its calibration data. Using the polynomial equation, the force transducer response (mV/V) could be converted into a force unit (N). The three transducers were calibrated individually according to ISO 376:2011 [18], then three third-order polynomial equations were obtained. Finally, the signal of the S-BUS is compared to the force standard machine load step F_{LS} to determine the real-single indication deviation of the S-BUS d_L. The calibration and evaluation of the S-BUS are carried out according to the procedure mentioned in [10] and [15].

6. EXPERIMENTAL SETUP AND CALIBRATION

The PTB 20 kN and 100 kN D-FSMs were used to calibrate the three transducers and the whole S-BUS. Each machine has a relative expanded uncertainty of 2×10^{-5}. The transducers were calibrated individually one by one using the 20 kN D-FSM (Figure 7). Once the individual calibrations were finished, two transducers were assembled to build a 20 kN S-BUS, this system was calibrated on the 20 kN D-FSM then its calibration results were analysed according to procedures mentioned in [10] and [15]. Finally, the three transducers are assembled to build a 30 kN S-BUS, this system was calibrated as a single unit on the 100 kN D-FSM (Figure 8).

As an additional step, each transducer is dismounted and calibrated individually for the second time to determine the stability of the transducers and also to determine any negative influences coming from the loading of the three transducers above each other in the S-BUS assembly.

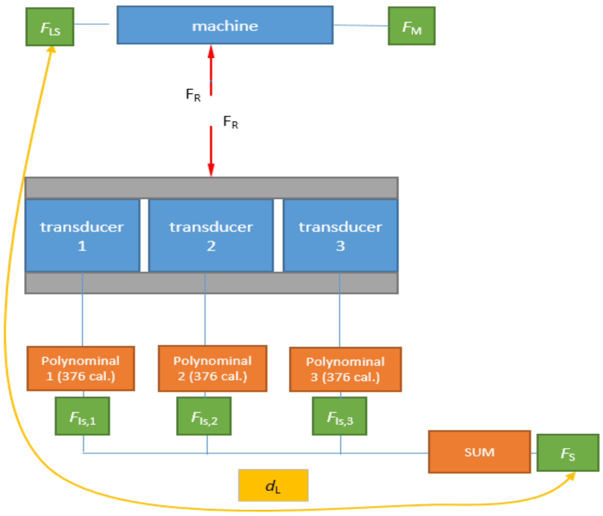

Figure 6: Signal generation from the real acting force to the measured sum force [10]

Figure 7: Calibration of a 10 kN transducer on the 20 kN PTB D-FSM

Figure 8: Calibration of the 30 kN S-BUS on the 100 kN PTB D-FSM

7. CALIBRATION RESULTS AND ANALYSIS

Each transducer consists of three parts, For example, transducer no 1 consists of the base no. 0, loading button no. 4, and the elastic element no. 1 (Figure 3). The calibration results for the three transducers are shown in Table 2. Each transducer is designed to a capacity of 10 kN, but the calibration was stepped up to 8 kN only for safety purposes. As shown in Table 2, the transducer no. 1 gives the best behaviour where its calibration results prove class 00 according to ISO 376 starting from 10 %, while the transducer no. 3 proves class 0.5 from 10 % and the transducer no. 2 proves class 0.5 from 20 %.

Once each transducer was calibrated individually, two of them (no. 1 and no. 2) are assembled to build a 20 kN S-BUS, this system was calibrated up to 16 kN only. The results are collected and analysed according to the procedure mentioned previously. The calibration results are presented in Table 3.

Figure 9 shows the behaviour of real-indication deviation d_L along the 20 kN S-BUS range. Indeed, these results are better than expected, the indication deviation values are better than 2.7×10^{-4} and the relative expanded uncertainty of the system doesn't exceed 3.2×10^{-4}.

Finally, the three transducers are assembled above each other, as in Figure 8, constituting a 30 kN S-BUS. The system was calibrated on the 100 kN PTB D-FSM up to 25 kN only, the calibration results are presented in Table 4. The behaviour of real-indication deviation resulted along the whole range is shown in Figure 10. It's highly appreciated for the first prototype to prove the validity of the concept and to achieve this level of precision. The maximum indication deviation was increased to 6.6×10^{-4}, this may be because of the excess deformation resulting from the increase in the applied force although this point should take a special interest in any future studies especially when adding more units. The transducers' signals are collected using The HBM DMP41 measuring amplifier which has a resolution of 0.000 001 mV/V and an excitation voltage of 5 V (Figure 8).

Table 2: The calibration results for the three transducers (individually calibrated)

Load Step F_{LS}	Transducer no. 1 Mean Response $\bar{X}_r$	Transducer no. 2 $\bar{X}_r$	Transducer no. 3 $\bar{X}_r$
kN	mV/V	mV/V	mV/V
1	0.314 184	0.307 153	0.307 189
2	0.628 532	0.614 343	0.614 557
3	0.942 957	0.921 610	0.922 052
4	1.257 456	1.228 957	1.229 683
5	1.572 027	1.536 387	1.537 440
6	1.886 651	1.843 877	1.845 308
7	2.201 320	2.151 426	2.153 274
8	2.515 998	2.459 013	2.461 315

Table 3: The calibration results of 20 kN S-BUS

Load Step	Indication deviation		Calibration result	
F_{LS}	d_L	$W(d_L)$	F_S	$W(F_S)$
kN	%	%	kN	%
2	-0.024	0.011	2.000	0.032
4	0.005	0.011	4.000	0.030
5	0.012	0.011	5.000	0.030
6	0.016	0.011	6.001	0.029
8	0.015	0.010	8.001	0.029
10	0.018	0.010	10.002	0.028
12	0.019	0.010	12.002	0.028
14	0.022	0.010	14.003	0.028
15	0.025	0.010	15.004	0.028
16	0.027	0.010	16.004	0.028

where $W(F_S)$ is the relative expanded uncertainty of the sum force,
d_L is the real indication deviation
$W(d_L)$ is the relative expanded uncertainty associated with d_L.

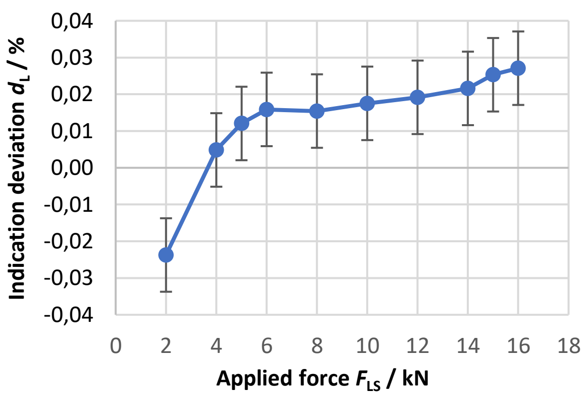

Figure 9: The 20 kN S-BUS indication deviation

Table 4: The calibration results of 30 kN S-BUS.

Load Step	Indication deviation		Calibration result	
F_{LS}	d_L	$W(d_L)$	F_S	$W(F_S)$
kN	%	%	kN	%
2	0.000	0.010	2.000	0.027
4	0.029	0.009	4.001	0.025
6	0.040	0.009	6.002	0.024
8	0.044	0.009	8.003	0.024
10	0.049	0.009	10.005	0.024
12	0.053	0.009	12.006	0.023
14	0.056	0.009	14.008	0.023
16	0.061	0.009	16.010	0.023
18	0.063	0.009	18.011	0.023
20	0.065	0.009	20.013	0.023
25	0.066	0.009	25.017	0.023

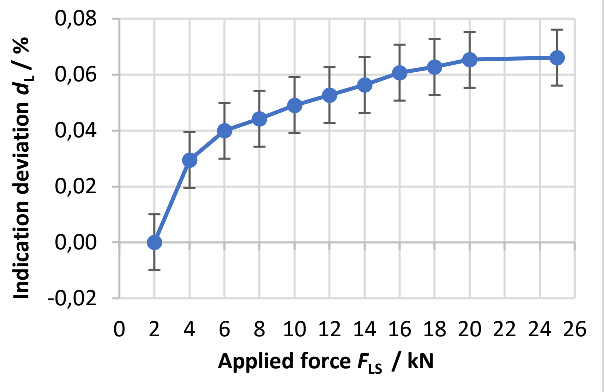

Figure 10: The 30 kN S-BUS indication deviation

8. SUMMARY

The work involved in this study introduces a new term to the community of force metrology. Achieving the concept of serial type build-up system is the aim of this study. The work involves numerical then experimental validation for the proposed S-BUS design. Two S-BUS's prototypes were implemented during this study, the first based on two force transducers with a 20 kN capacity and the second based on three force transducers with a 30 kN capacity. The evaluation results were better than expected. The deviation of the 20 kN S-BUS is below 0.027 % while for the 30 kN S-BUS the deviation did not exceed 0.066 %.

9. ACKNOWLEDGMENT

The research team would like to acknowledge that without the help of PTB staff, particularly Mr A. Schmidt and Mr F. Ries, this work could not be completed within the scheduled time plan.

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