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DEVELOPMENT OF A 15 MN BUILD-UP SYSTEM FOR CALIBRATIONS IN UKRAINE´S HEAVY INDUSTRY

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1 ***Abstract*** – This paper describes the constructional details of an FEM-supported construction of adaptation parts for a Build Up system up to 15 MN. After a short introduction about “Ukrmetrteststandard”, the NMI in Ukraine, several constructional details will be discussed which result in a very low measurement uncertainty. In addition, some experiences about the use of BU systems obtained during the evaluation will be presented.

Keywords: Ukrmetrteststandard, build-up system, mega-netwon range

1. INTRODUCTION

The measurement of force is an important tool for manufacturing high quality and precision products in heavy industries. Several competitive companies in the steel-industry are located in Ukraine, which was already a centre of the steel industry in the Soviet Union. Future developments and growth in this market can only be spurred on with research in material technology. Research in this technology can only go ahead with material testing. To enable the calibration of testing facilities of the highest capacity and the lowest measurement uncertainties in Ukraine and on the European market, "Ukrmetrteststandard" decided to realize a calibration possibility up to 15 MN.

"Ukrmetrteststandard" is the leading national metrology institute (NMI) in Ukraine. The institute has many national standards of units, one of them is the national force standard which realizes the unit of force in the range from 100 N to 200 kN. The force in the range from 100 N up to 2000 N was realized by deadweight machines with 100 N and 200 N steps. The relative, expanded standard uncertainty is lower than 0.003%. The 20 kN calibration facility is a lever-type force standard machine with an amplification ratio of 1:100. The measurement range extends from 500 N to 20 kN. The smallest force step is 500 N all over the range. The 200 kN is also a lever-type force standard machine with an amplification factor of 1:400. The measurement range extends from 5 kN to 200 kN with a smallest force step of 5 kN. The machine´s manufacturer is ASANO SEIKI Co. Ltd. Company, Japan. The relative, expanded standard uncertainty of both 20 kN and 200 kN machines is lower 0.01%.

2. TRACEABILITY OF FORCE UP TO 15 MN IN UKRAINE

Today there is a need for the improvement and extension of the traceable range of force in connection with the requirements of industry in Ukraine.

To enable the economic calibration of force measurement devices to support industry, it was the aim of Ukrmetrteststandard to cover a widespread range from over 1 MN (as the institute owns several 1 MN transducers) up to 15 MN. In the first step, a single 5 MN transducer will enable the calibration of testing facilities in this range. For that reason, an Anyload 106BH transducer has been selected. As an advantage, this transducer has a hermetic sealing. Reaching ‘class 05’ according ISO 376 was aimed at. It was calibrated several times at PTB´s 5 MN FSM in recent years. But there is a need for the calibration of facilities for even higher forces. From the beginning, it was the aim to realize one day a Build-Up system (BU system) with a rated load of up to 15 MN. For that reason, three identical Anyload transducers of that type were bought. It is the plan of the Ukrainian NMI, to develop and build the adaptation parts for the BU system later, on its own.

The reason for this was at least to realize a calibration possibility up to 15 MN for Ukraine’s 30 MN facility. This machine was built for the former Soviet Union´s leading weighing manufacturer “Tochmash” in Odessa. The company has built up a complete force and mass laboratory of impressive size. It was modernized in the early 90s with extensive equipment from Dartec, including a hydraulic 2 MN and 10 MN facility. But today the company has stopped working,

The 30 MN facility, shown in Fig. 1, is almost a twin to NPL´s 30 MN FSM, especially since it was built by the same company. Today, the machine in Odessa is still in good condition and should be used again for calibrations in future. Maybe it will be possible to move the machine to the laboratory in Kiev one day, which would be a reasonable decision, as the demand for calibrations in the MN range is rapidly growing. To enable a calibration possibility at least to half the rated load of the machine, the 15 MN BU system should be built.

In the first step, the adaptation parts for the 15 MN BU system were to be realized. At the same time, some preliminary investigations for a new EURAMET funded research project were undertaken. Within a thesis, the possible use of numerical and physical investigations about BU systems has been examined, the first results have proven the excellence of a finite element analysis to obtain knowledge about possible parasitic force components and to optimize the design of BU systems by eliminating them via an optimized constructional outline.

Fig. 1. 30 MN calibration facility with mounted 15 MN BU system during preload test in Odessa

2. DESIGN OF UKRMETRTESTSTANDARD`S 15 MN BU SYSTEM

Due to the considerable contacts between Ukrmetrtest-standard and PTB, a research collaboration has been formed with the aim of jointly developing an optimized set of adaptation parts to finish the BU system. The mechanical parts were produced by “Stankin Ltd” in Kiev. Their main activity is tooling, machining, the overhaul of machines and CNC manufactured products, etc. This company also produces parts for air- and oil-bearings for the international market.

The design of the BU system has been set up to have high safety regarding the mechanical failure of the entire system or its components. All in all, the equivalent stresses occurring according to van Mises theorem within the Hertzian pressure area have been kept at a half level as usual at BU systems, compared to data from relevant manufacturers. Many theories say that the intensive use of material lowers the uncertainty. With an optimized design for the construction, however, the outline can be changed in a way to enable the lowest uncertainties and to lower the weight for easy handling. The individual parts will be described in the following.

The design of the base plate keeps the distance of the transducers to each other to less than 5 mm in order to reduce the outer dimensions of the plate as well keeping as the lever length from the force introduction point of the system to the force application point into the transducer to a minimum. To save material, the plate is designed in the form of a triangle which is rounded at the corners and correlated to the outer radii of the transducer. Figure 2 shows a numerical simulation of the plate. The following figures show numerical simulations concerning the 3-axial stresses according to van Mises.

Since elastic deformations, which are basically caused by the stress distribution, are primarily responsible for the generation of parasitic forces as well as the increase of measurement uncertainties, it is necessary to keep these stresses as low as possible. That means that the material needs to be formed in a way that mechanical stresses drop to very low levels towards the edges. Another advantage is that the material quality of this large component can be balanced with its costs. Thus, the steel used for this body is of the type of DIN/EN 1.6511 or GOST 40KHN2MA with a tensile strength of 1080 MPa.

Accordingly, the maximum stress in the range up to 220 MPa is much lower than the strength of the steel.

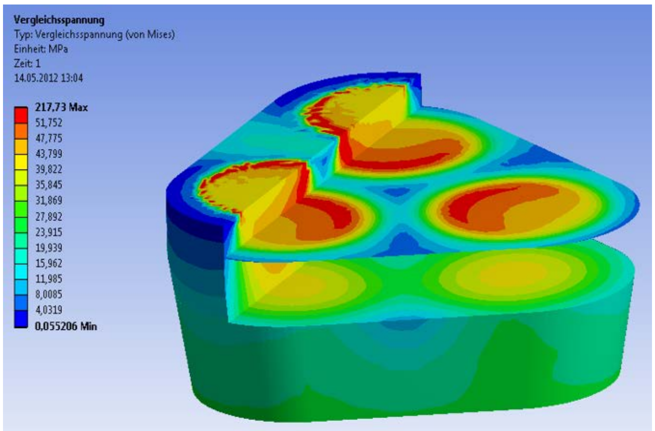

Fig. 2. FEM simulation of the stress in the optimized ground plate at a nominal load of 15 MN

Figure 3 shows the design of the load cup of a single 5 MN transducer. An essential aspect of this design is the concave shape of the contact surface. This serves to reduce the Hertzian pressure at the contact surface towards the load buttons of the transducer. The conical shape is formed in order to enlarge the compression surface toreduce the surface pressure. Inside the material, the stress in compression direction can unscrupulously go up to 1100 MPa. Certain manufacturers even gon up to more than twice the yield strength of the material within a Hertzian pressure area. That is possible, since there is only a discrete area of pressure stresses within the material, where displacements in microstructure are strongly limited and no crack initiation or crack growth can be triggered. The original load cups delivered by Anyload show almost critical stresses of up to 2600 MPa. In the case of the BU system, the decision has been made to keep stress as low as possible because the system might be loaded in a machine with compression plates which are not exactly orientated. The load distribution on each single transducer may vary within a range of up to 15% of 5 MN for each transducer.

Figure 3 shows the results of the numerical simulation of the stress distribution in the described load cup. Here again, all dimensions were fitted until a minimum of stresses had been achieved. The dimensions are chosen together with the upper plate in such a way, that the sideways forces and bending moments are as low as possible.

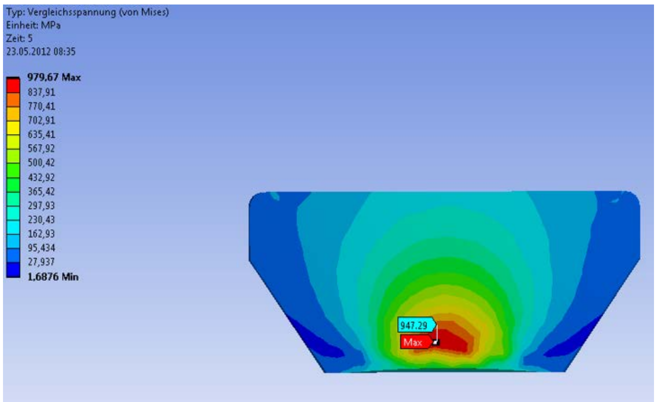

Fig. 3. FEM simulation of the stress in the optimized load cup at a nominal load of 5 MN per single transducer

The upper force introduction plate that is formed quite similarly to the ground plate, has also been optimized in a way to keep elastic deformation as low as possible to avoid cross forces and bending moments. The final paper will give more information about this.

The last detail is the upper load cup. It provides a spherical contact area to compensate for the introduction of moments into the system. As mentioned, it is the aim to keep the stresses inside the material low and to enhance safety against mechanical failure. In order to meet this objective, the radius of the load cup needs to be as large as possible. In the case of a misalignment of the machines compression plates, the middle point of the contact area will move sideways more than if the radius were very small. To keep stresses and the displacement of the contact point of the force vector as low as possible, both parts have a spherical surface, the force introduction plate on the top of the transducers has a radius of 1000 mm, the load cup on the contact area has a radius of 800 mm. Figure 4 shows a photograph of both parts standing on each other. Figure 5 shows a numerical simulation of the stress deviation inside the upper cup. Figure 6 shows a visualization of the contact area. A piece of paper was centred in the middle of the upper connection plate to check the exact production of the parts as this is perfectly round and aligned in the middle.

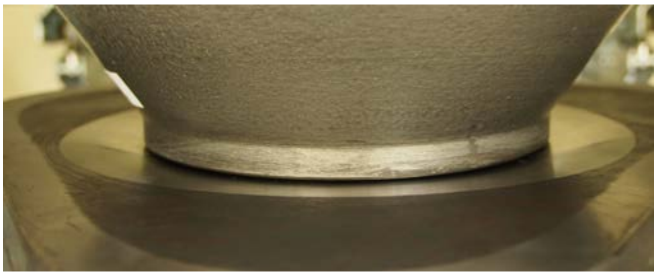

Fig. 4. Photo of the upper load cup standing on the upper connection plate for the force introduction into the transducers, the upper part of the BU system in Fig. 5

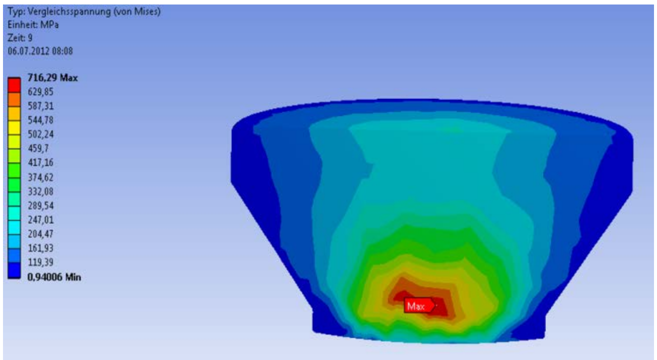

Fig. 5. FEM simulation of the stress in the upper load cup on the top of the system at a nominal load of 15 MN

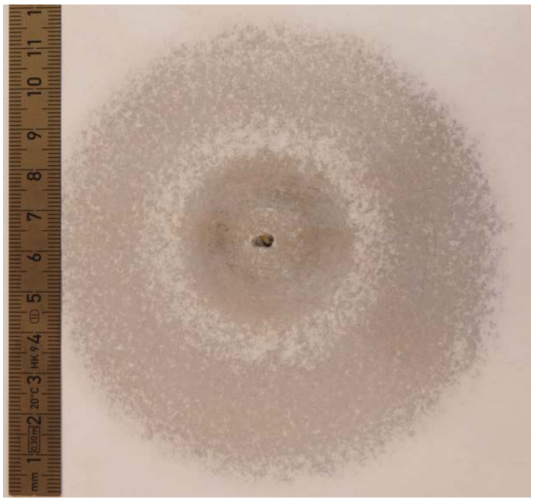

Fig. 6. Photo of the impressions on a piece of paper between upper load cup and the upper connection plate after 7.5 MN. The little hole in the centre was used to adjust it on the plate

Finally the BU system assembled in PTB´s 16.5 MN FSM is shown in figure 7.

3. MEASUREMENT RESULTS GAINED IN THE EVALUATION OF THE SYSTEM

The measurements for the evaluation have been performed using PTB´s 5 MN and 16.5 MN facilities and Ukraine´s 30 MN machine in Odessa. First, a preload test up to 17 MN was realized in Odessa. Afterwards the system was investigated in several full and partial load measurements at PTB. The transducers were calibrated individually and in the overall system in the 16.5 MN FSM up to 15 MN. The essential results show, also concerning the uncertainty model of the EMRP project, that the uncertainties measured in the whole system may be even smaller than the uncertainties measured with the single transducers. The reason for this is the much smaller rotational error of the whole system compared with the single transducer. Due to that reason, the single transducers can be confirmed with ‘class 05’ according to ISO 376. The complete system enables a ‘class 00’ confirmation.

Fig. 7. Photo of the 15 MN BU system mounted in PTB´s 16.5 MN FSM

Some other interesting results were obtained: Instead of all surfaces were manufactured very precisely, the so-called force introduction effect shown in nonlinearities in the lower force steps of the calibration occurred much higher, even more than already known from smaller 3 MN or 6 MN BU systems. The manufacturing process of these large elements is more challenging than it is for smaller systems. In addition, the bigger surfaces of all contact areas that are realized due to the demand of high safety against mechanical failure lead to areas with higher force introduction effects in the lower force steps. They show a very good reproducibility, proven by the very good reproducibility of the entire system, but they cannot be described with an interpolation polynomial of the third degree. It is the aim to use a polynomial of a higher degree - as already used by some NMI´s for their internal evaluations.

The three transducers show a strong deviation between the sensitivity measured during single calibrations of each. In addition, measuring the single transducer signals with a multi-channel amplifier during a BU system use, a load distribution between the single transducers in the percent range between every series can be obtained.

Table 1 shows the uncertainties as stated in Annex C of ISO 376:2011 established in a calibration at PTB´s 16.5 MN up to the nominal load of the system. Especially the uncertainties for the rotational error are much smaller than for a single transducer of the system.

The measurements were done using a six channel DMP 41 amplifier to measure simultaneously all the channels of the system. They were noted separately and analysed with an Excel template which calculates the sum of the signals of the BU system and deviation between the single transducer calibration and combined use within the BU system. It also calculates the centre of the force introduction, comparing the signals of the single transducers after the geometrical dimensions are entered in the template. This template and the evaluation of BU systems is presented in [2].

Tab. 1. ISO 376:2011 uncertainties of the 15 MN BU system

Force	w_1	w_2	w_3	w_5'	w_6	w_8	w_{rev}
kN	applied force	reproducibility	repeteability	creep	drift zerosignal	interpolation	reversibility
1500	0.01%	0.0057%	0.0057%	0.0128%	0.0075%	0.0882%	0.0383%
3000	0.01%	0.0040%	0.0040%	0.0128%	0.0075%	0.0044%	0.0383%
4500	0.01%	0.0032%	0.0041%	0.0111%	0.0075%	0.0080%	0.0334%
6000	0.01%	0.0022%	0.0037%	0.0082%	0.0075%	0.0067%	0.0246%
7500	0.01%	0.0021%	0.0026%	0.0052%	0.0075%	0.0038%	0.0155%
9000	0.01%	0.0021%	0.0022%	0.0030%	0.0075%	0.0001%	0.0089%
10500	0.01%	0.0021%	0.0023%	0.0011%	0.0075%	0.0021%	0.0034%
12000	0.01%	0.0027%	0.0020%	0.0001%	0.0075%	0.0022%	0.0004%
13500	0.01%	0.0031%	0.0018%	0.0003%	0.0075%	0.0016%	0.0009%
15000	0.01%	0.0032%	0.0013%		0.0075%	0.0019%	

Figure 8 shows interesting behaviour about the BU system presented. The series depicted in the figure were the first series taken in the machine at PTB. After the series in zero degrees (R1 and R2), the position of the upper load cup was checked and it was found, that there was a deviation in the range of approximately 3 mm. That was nearly exactly the value marked in Fig. 8 for the green series R1 and R2 at full load. At lower forces, however, the values are much bigger. The reason is - certainly amongst others - the contact area between the two spherical surfaces between the upper plate and the upper load cup. Due to geometrical effects of the double spherical contact area, the relative disorientation is larger at lower forces than at higher forces.

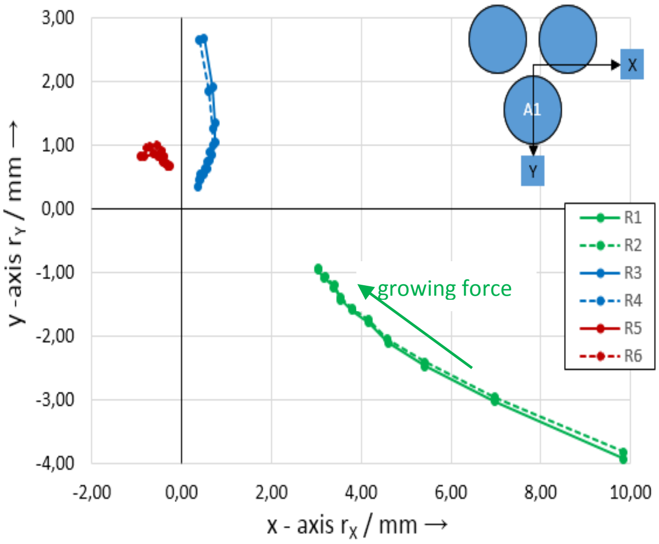

Fig. 8. Load shifting of the force centre introduced in the BU system

But force introduction effects might also be the reason for this behaviour. In Fig. 8, it can clearly be seen that the dislocation changes especially in the lowest range. These force introduction effects can be reduced if the contact areas are as small as possible. Many manufacturers max the material properties out to keep these effects low using the smallest contact areas with the highest mechanical stress. But this does not conform to the purpose, to generate a BU system with the highest dependability under rough conditions during the calibration of material testing devices. Hence the decision was made not to optimize the system in that direction. Lower stress also reduces the risk of plastic deformations if the system might be partially overloaded by mounting conditions which are not optimised. This guarantees the stability of the calibration values.

Table 2 shows the single uncertainty components of ISO 376:2011 measured within a calibration of a single transducer and the whole system. In both cases, the calibration is done up to 5 MN to compare the proportion of the uncertainty components. Repeatability, zero drift and reversibility are within the same range. This demonstrates the good quality of the design, material and manufacturing of the system - remembering that it is only loaded to one third of its nominal load.

As predicted before, the force introduction effects are clearly visible. The system shows higher nonlinearity than the single transducers or other BU systems with a higher utilization of the material to reduce these effects. The higher nonlinearity causes an interpolation error which is larger in the BU system than for the single transducers. To reduce this uncertainty to negligible values, it can be recommended that BU systems should use polynomials of the fifth degree for the interpolation.

Looking at table 2, it can be clearly perceived that the reproducibility of the BU system is much better than for the single transducer. This is a typical effect of many BU systems. The mechanical stability of the complete system reduces the effects of parasitic forces within the calibration facility.

Force / kN	w2 (repro.)	w3 (repeat.)	w6 (zero)	w8 (interp.)	w5´ (rev.)
single transducer calibrated up to 5 MN					
500	0.027%	0.005%	0.008%	0.003%	0.009%
1000	0.016%	0.003%	0.008%	0.008%	0.020%
1500	0.014%	0.005%	0.008%	0.006%	0.019%
2000	0.011%	0.004%	0.008%	0.006%	0.015%
2500	0.010%	0.003%	0.008%	0.002%	0.008%
3000	0.009%	0.003%	0.008%	0.001%	0.001%
3500	0.008%	0.003%	0.008%	0.003%	0.005%
4000	0.008%	0.001%	0.008%	0.000%	0.006%
4500	0.007%	0.002%	0.008%	0.001%	0.004%
5000	0.007%	0.001%	0.008%	0.001%	
complete BU system calibrated up to 5 MN					
500	0.005%	0.008%	0.006%	0.352%	0.006%
1000	0.004%	0.006%	0.006%	0.030%	0.004%
1500	0.002%	0.005%	0.006%	0.028%	0.002%
2000	0.002%	0.004%	0.006%	0.032%	0.001%
2500	0.001%	0.004%	0.006%	0.019%	0.001%
3000	0.001%	0.005%	0.006%	0.002%	0.001%
3500	0.001%	0.005%	0.006%	0.009%	0.000%
4000	0.001%	0.005%	0.006%	0.012%	0.001%
4500	0.002%	0.005%	0.006%	0.006%	0.001%
5000	0.002%	0.005%	0.006%	0.009%	

Tab. 2. Uncertainty components according to ISO 376:2011 comparing a single transducer and the complete 5 MN BU system calibrated up to 5 MN

4. CONCLUSIONS

An ISO 376 ‘class 00’ BU system has been made from three single transducers using extensive numerical simulations to optimize the structure of the adaptation parts.

All the properties desired have been achieved: The material is not exploited to its limit to enable a high degree of safety against material failure even under possible applications which are unfavourable, such as when calibrating material testing facilities.

It is shown, that it is important to minimize cross forces and bending moments to reduce uncertainty.

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