XXI IMEKO World Congress "Measurement in Research and Industry"
August 30 – September 4, 2015, Prague, Czech Republic

PROCESSING AND EVALUATION OF BUILD-UP SYSTEM MEASUREMENT DATA

Michael Wagner [1], *Falk L. Tegtmeier*[2]

[1] Physikalisch-Technisch Bundesanstalt, Braunschweig, Germany, michael.wagner@ptb.de
[2] Physikalisch-Technisch Bundesanstalt, Braunschweig, Germany, falk.l.tegtmeier@ptb.de

Abstract **–** Build-Up systems (BU systems) are parallel combinations of force transducers for realizing a large range of rated loads using one type of transducer. As yet there is no uncertainty budget for these devices. Creating such, makes it necessary to detect the significant influencing parameters of BU systems by measurements and to prepare appropriate methods for the processing of the collected data. This paper will regard this processing.

Keywords: Build-Up systems, processing, uncertainty

1. COLLECTION OF DATA

There are two standards, for 'calibrating force transducers' (ISO 376) and 'verification of static uniaxial testing machines' (ISO 7500-1). The metrological examination of large-scale Build-Up systems represents a particular application which is not clearly covered by these standards. Firstly, BU systems should be used as transfer standards for the traceability of testing-machines, which is the main idea of using them. In this case the evaluation following ISO 7500-1 comes into consideration and the force which is indicated by the BU system then applies as the 'correct force' F [1].

The largest force standard at PTB generates a maximum force of 16.5 MN, beyond that a traceable calibration of BU systems is not possible in an uncertainty range below 0.1%. A standardized procedure for extrapolation of BU system measuring values does not exist yet. For the mentioned reasons, BU systems are considered as force transducers according to ISO376 in the range above the traceable force scale of PTB. Force transducers along with an indicator provide a 'deflection' X but not a 'correct force' F [2].

For these reasons a consistent linguistic usage is needed for the investigation of BU systems, which describes the signals and the derived quantities independent of their usage.

Table 1.1 shows the quantities, which are similar to the standards as far as they are assignable. In the following sections the acquisition and processing of these quantities will be described. Furthermore, a preliminary interpretation of the information content of these values will be given.

Table 1.1 designation of BU system quantities

Symbol / Unit [source]	**(short) english designation**
F_R / N	real acting force
F_i / N [DIN EN ISO 7500]	indicated machine force
F_{LS} / N	load step
F_{IS} / N	indicated single transducer force
F_{IB} / N	indicated build-up system force
F_S / N	sum force
F_{RS} / N	reference sum force
d_S	summation deviation
d_L	real single-indication deviation
$d_{L,i}$	ideal single-indication deviation
d_I	indication deviation
d_K	connection deviation

In order to obtain the set of data, which is necessary for the complete evaluation of BU systems, the single transducers that are part of the BU system have to be calibrated individually. Also the BU system has to be calibrated as a whole ('in sum'). For comparison purposes it is helpful if the load steps for single calibration equal the load steps used for sum calibration, divided by the number of transducers the BU system consists of. Also the number of load steps of each calibration shall be equal if possible.

2. FORCE VALUES OF BU SYSTEMS

The calibration of a single force transducer, whose purpose is to determine the characteristic and the uncertainty of the device, follows the ISO 376. However, the measurement according to this standard does not consider the particular characteristics of the BU system. For this reason, a measurement method and a method of evaluation must be developed which can detect the various parameters which characterize a BU system.

A BU system consists of at least three force transducers. The single calibration results of these force transducers form the basis for evaluation of the overall system. These results allow the calculation of a force by a compensation polynomial according to ISO 376, which will be hereinafter referred to as indicated single transducer force, F_{IS}.

For a complete evaluation of a BU system four parameters are defined, each representing a force.

The indicated machine force is used as reference. In contrast, the indicated force of the BU system is provided, which can be determined in two different ways.

One way is to calibrate the system providing a single signal. This happens either by the use of a summation box (an electrical component comprising the arithmetic mean of the input signals at the output by a suitable interconnection of these) or by arithmetic averaging of the signals from the single transducers. This signal can be evaluated according to ISO 376 which results in a polynomial that enables the calculation of a force based on the mean signal of the BU system. For this force "indicated BU system force" is agreed, because this force value is indicated by a commercial BU system after calibration using a summation box. The indicated BU system force is considered as the force value primarily displayed by a BU system.

The second way is to use the already existing calibration results of the single transducers to determine three individual force signals, which are then summed. This way, for example, is appropriate when the BU system is not calibrated in the rated load range because its nominal load exceeds the force traceability range or the calibration capability. For this force, the term "BU system sum force" is used because this value is mathematically determined by summation.

When force transducers are calibrated individually they experience fundamentally different boundary conditions of force compared to a calibration of the entire system. To quantify this difference, it is necessary to establish another reference value. For this quantity, the term "reference sum force” is agreed. It applies as the sum of the indicated single transducer forces gained during independent single calibration.

3. DETERMINATION OF MACHINE FORCE

Force generating machines generate forces according to different principles. These forces are set by the operator in advance and are displayed by the display device of the machine. There are three different force values that are not necessarily identical.

Firstly, there is the target force which is set by using machine controls. For this value, the term ‘load step’ is agreed. This quantity is affected by an uncertainty.

Secondly, there is the physically acting force between loading machine and force transducer. This force value is the true value of the measured variable force, which is unknown. For this force, the term ‘real acting force’ is agreed. For this value there is no uncertainty specified.

Thirdly, there is a specified force of the display device of the loading machine. For this force, the term "indicated machine force" is agreed. This designation is based on the specified name in the ISO 7500-1 "Verification of static uniaxial testing machines".

In force standard machines the load step and the indicated machine force are systematically identical within the limits of uncertainty. In testing facilities or reference calibration machines these differ from each other, particularly because test forces are often only approached approximately.

To get the force value, which is considered as the indicated machine force it is to care for deviations between the indication of the machine itself and maybe existing calibration results of the particular machine.

4. CHARACTERISTICS OF BU SYSTEM

After computing the four force values that are provided by a BU system or its components, the deviations between them are to be calculated. This applies as follows.

For the deviation between the indicated BU system force and the BU system sum force, the term "relative deviation of BU system sum force" or shortened within an appropriate context "summation deviation" is agreed, what applies

$$d_{\mathrm{S}} = \frac{F_{\mathrm{IB}} - F_{\mathrm{S}}}{F_{\mathrm{S}}} \cdot 100\%$$
$$d_{\mathrm{S}} = (d_{\mathrm{I}} - d_{\mathrm{L}}) \frac{F_{\mathrm{LS}}}{F_{\mathrm{S}}} \cdot 100\% \,. \quad (4.1)$$

For the deviation between the sum force of the BU system and the load step, the term "relative deviation of load and sum force" is agreed or shortened within an appropriate context "real single-indication deviation" for which the following applies,

$$d_{\mathrm{L}} = \frac{F_{\mathrm{S}} - F_{\mathrm{LS}}}{F_{\mathrm{LS}}} \cdot 100\% \,. \quad (4.2)$$

Since this quantity describes the deviation of the indicated BU system force under real conditions, there is a similar quantity which describes the deviation of the indicated BU system force under ideal conditions. This quantity is called the ideal single-indication deviation. It applies as

$$d_{\mathrm{L},i} = \frac{F_{\mathrm{S},i} - F_{\mathrm{LS}}}{F_{\mathrm{LS}}} \cdot 100\% \,. \qquad (4.3)$$

For the deviation of the indicated BU system force from the load step, the term "relative deviation of indicated BU system force" is agreed, for which applies

$$d_{\mathrm{I}} = \frac{F_{\mathrm{IB}} - F_{\mathrm{LS}}}{F_{\mathrm{LS}}} \cdot 100\% \,. \qquad (4.4)$$

The actual benchmark for assessing the deviation between the individual and the sum measurements is the relative deviation of the reference sum force from the BU system sum force. Since there is a systematic deviation that arises from combining force transducers to a BU system by parallel interconnection, for this quantity, the term "relative deviation by parallel combination of force transducers" is agreed or shortened within an appropriate context "combination deviation", for which applies

$$d_{\mathrm{K}} = \frac{F_{\mathrm{S},i} - F_{\mathrm{S}}}{F_{\mathrm{S}}} \cdot 100\% \,. \qquad (4.5)$$

5. PROCESSING OF OBTAINED DATA

Since exactly given force values cannot be reached precisely when performing measurements in testing machines, which is due to their individual principle of generating forces, the actually achieved force values must be interpolated to those rounded force values that are used for the respective comparison, usually these are the load step values primarily agreed.

Also, due to the individual capacities of the machines used for the respective comparison, it is not possible to realize the same number of load steps for each measurement series as well as the needed ratio of load steps. This means, load steps for single transducer measurement may not be realized in the necessary ratio of e.g. one third since the loading machine is not capable of providing each of these load steps.

Another important issue is, however, the individual forces acting on the single transducer within a BU system are unknown. Therefore, the load distribution, which is shown by the indicated single transducer force in BU system measurement is used for the computation of the distribution of the indicated machine force. This means that the indicated single transducer forces are calculated using their individual single calibration results and the indicated machine force is assumed as acting on the transducers in the same ratio.

After the load distribution on the individual load cell inside the BU system is determined, there are now individual force values according to each measurement value. The force values are always different, however, and thus are not comparable.

Therefore, the force values must be interpolated to comparable, rounded values, the corresponding measured values are converted according to the same context. We distinguish between two fundamentally different approaches to interpolate the given data.

First, there is the method to interpolate each recorded value separately. That means, the given deflection value is divided by the indicated machine force and then multiplied by the desired load step. As a result, an interpolation deviation occurs which will contribute to the uncertainty of the BU system's indicated force. This is done for each value. Subsequently, a zero point correction is performed, afterwards the resulting data can be used to calculate the characteristics discussed above. The main advantage of this method is, that discontinuities of the machine characteristics as well as the BU system will not be lost. One disadvantage of this method is, as mentioned before, that the conditions regarding the number and ratio of load steps need to be respected.

The second way of realizing the interpolation is to firstly compute a compensation polynomial for each row of the measurement series. In total there are six records. Three resulting from the single calibrations, three more will follow from the BU system measurements. Each contains six rows, the result is 36 polynomials. These can now be used to compute any deflection value for any desired force value. The most important advantage of this method is that there is no need to care for the number of performed load steps as well as a constant ratio of these. The main disadvantage is that discontinuities will not be reproduced, as there are force introduction effects within the 20% range of the characteristics as well as discontinuities such as bends or jumps.

Figures 5.1 and 5.2 show the indication deviation of a 3 × 2 MN BU system computed by discrete and polynomial interpolation of values. As mentioned before, the force introduction effects as well as the nonlinearities in the curve can very well be seen using the discrete interpolation method.

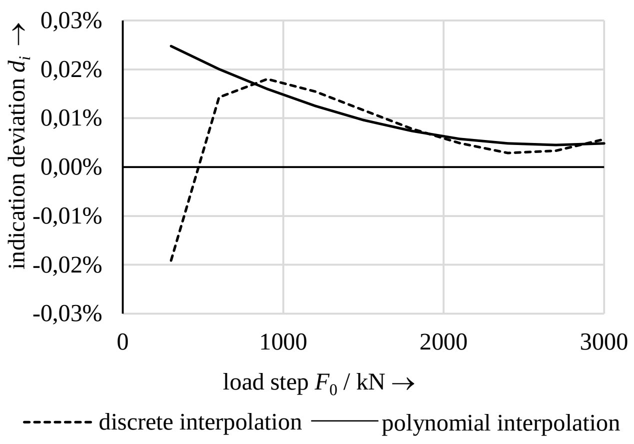

Figure 5.1: deviation between discrete and polynomial interpolation

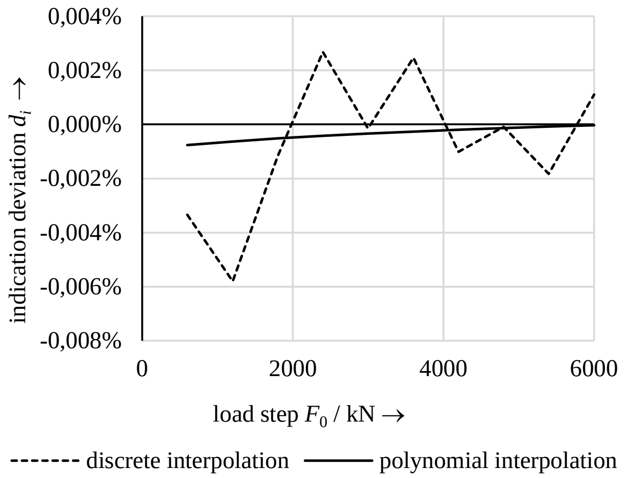

Figure 5.2: deviation between discrete and polynomial interpolation

6. LOAD CENTER

An important aspect which has been shown as part of the evaluation of measurement data from BU systems is the load distribution on the involved transducers. As a result, the absolute lever lengths of the introduced bending moment which in the following will be referred to as the load center. In order to create a widest possible data base, also this load center is calculated. This calculation is performed as follows.

Each force transducer is placed in a defined distance from the geometric center of the system and faces an individual acting force. The load distribution in the BU system has already been evaluated based on the calibration results. The results from this calculation are assumed as the force load on each individual transducer.

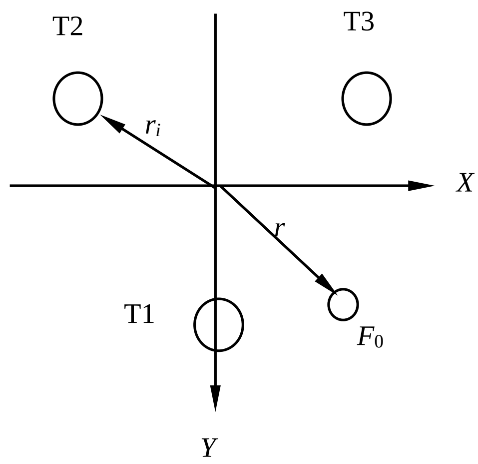

Figure 6.1: calculation of load distribution

An ideal resulting force, equaling the sum of the individual forces of the utilized transducers, which thus according to the above, always equals exactly the load step is assumed to act over an unknown distance from the geometric center of the BU system. By means of a moment balance, this distance can be determined. If this distance is multiplied by the corresponding load step, the bending moment, introduced into the system will result. Figure 6.1 shows the transducers T*i* representing the three individual forces, as well as the resulting force F_0 acting over the distance *r*.

The Cartesian components $\{r_x,\ r_y\}$ of the distance *r*, according to this, apply as

$$r_x = -\frac{(F_1 - F_2) \cdot r \cdot \cos\frac{\pi}{6}}{F_0} \tag{6.1}$$

and

$$r_y = \frac{-(F_1 + F_2) \cdot r \cdot \sin\frac{\pi}{6} + F_3 \cdot r}{F_0} \tag{6.2}$$

Not taken into account is here that the load distribution within the BU system is not ideal, which means that the emergence of parasitic forces and their influence on the actual distribution is not reflected in these results.

7. PRESENTATION OF RESULTS

Finally, this section will show some example results. At this point no particular information on the used equipment will be given. The aim is to show how the discussed quantities can be interpreted.

The evaluation of BU systems is twofold, on the one hand there is the information about the characteristics of the device itself, and on the other hand these systems are to be used as transfer standards.

According to this, Figure 7.1 shows the indication deviation d_I of a BU system together with the real single indication deviation d_L, based on the calibration results of a given measurement. This method can be considered as a transfer standard calibration. As expected, the indication deviation of the system is constantly below $1 \cdot 10^{-6}$ and equals the combined interpolation error resulting from the individual calibration results of each load cell.

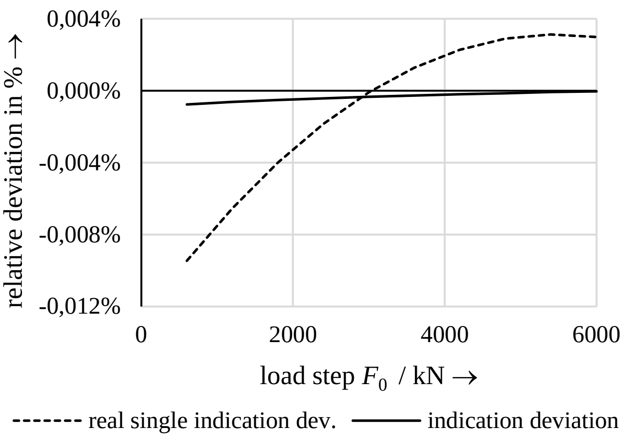

Figure 7.1 indication deviations performing BU system calibration

In contrast, the same calibration results are applied to measurement results gained in another machine, what can be, for example construed as a comparison to another NMI, in which the BU system is meant to be an already calibrated transfer standard. The indication deviation in Figure 7.2 then shows the deviation between the primary force standard and the compared loading machine under regard of the transfer standards uncertainty. Since the difference between the both curves in each diagram is only a result of the difference of processing the same single transducer signals, this difference is constant.

According to Eqn. (4.1), this constant deviation which is agreed to be called summation deviation d_S can be computed from the both values shown in the discussed diagrams.

BU systems sensitively react on the layout of the force introduction parts due to the generation of parasitic forces. The quantity which is able to show the influence of force introduction parts is the combination deviation d_K. As an example, one system has been used with two different load introduction layouts providing different mechanical stiffness.

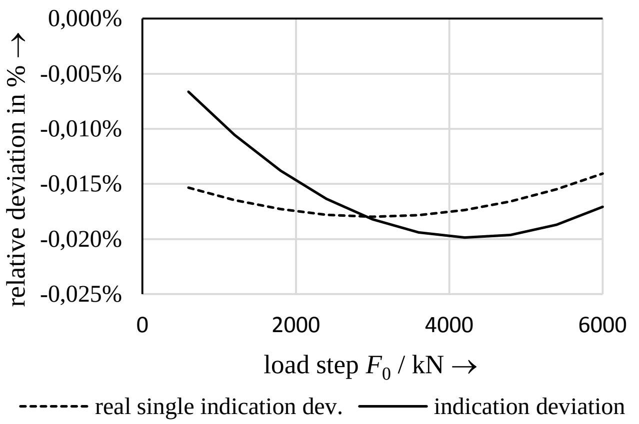

Figure 7.2: indication deviations performing intercomparison

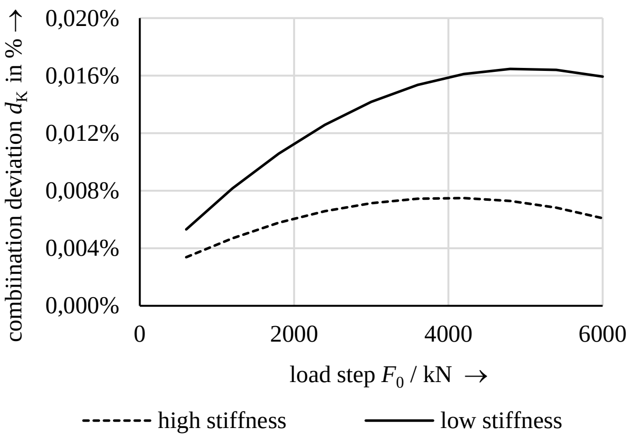

Figure 7.3: combination deviation using different load introduction parts

The results show very clearly the influence of the force introduction on the measurement results. It is noteworthy that a change of this deviation by a factor of two can be achieved by the simple reinforcement of the force introduction layout.

Finally, the calculation of the absolute lever lengths of acting bending moments according to the equations (6.1) and (6.2) is discussed. It is striking that both the machine characteristics and the characteristics of the BU system are reflected in the results.

This phenomenon can be explained as follows. A standard machine, for example, has a load frame which is attached to the force transducer. The mass stack then acts like a pendulum and is in equilibrium always aligned vertically.

The geometrical center of the machines cross head will not necessarily be in the geometrical center of the machine frame when unloaded. When applying a load, the cross head is forced to the geometrical center of the machine frame, because this position has the lowest potential energy.

Due to this, the discussed lever length shall show a movement from the outside towards the center of the machine frame.

Assuming the BU system has two plane-parallel contact surfaces, so these actually show always an angular deviation. The mass stack thereof will be particularly not affected regarding its alignment.

A rotation of the BU system leads to a changed orientation of the gradient of the upper surface of the system. However, this will not affect the alignment of the mass stack.

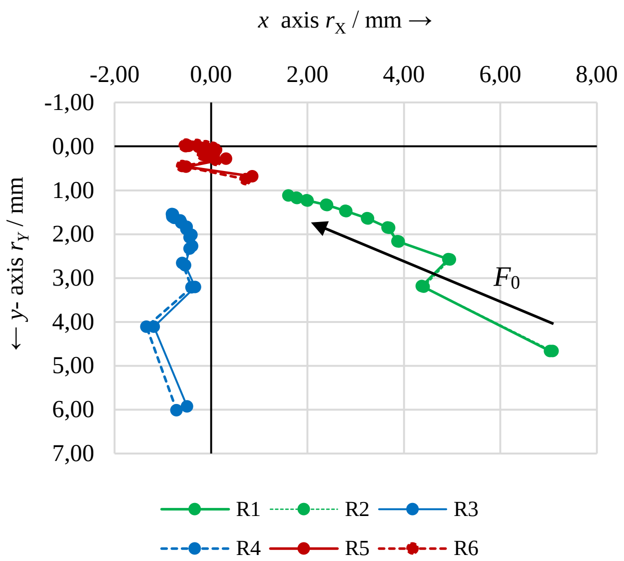

Figure 7.4: movement of the load center in a force standard machine

Figure 7.4 shows the result of the computation of the load center in a force standard machine as described above. The rows one to six herein are recorded according to the ISO 376 standard which means, after every second row there is a rotation of the entire system by 120 degrees. As can be seen, the load center moves as expected: with increasing load, the lever length of the acting moments decreases because the load center moves to the center of the machine. The orientation of the curves describing the direction from which the point moves to the center is almost equal.

The same system investigated in a force standard machine using hydraulic amplification shows a completely different behavior. As can be seen in Figure 7.5, the effect of the rotation of the system is very notable. The kinematic difference is, that the load frame of the hydraulic machine is attached to the bottom surface of the transducer so that the BU system is able to induce a geometric deviation at small loads.

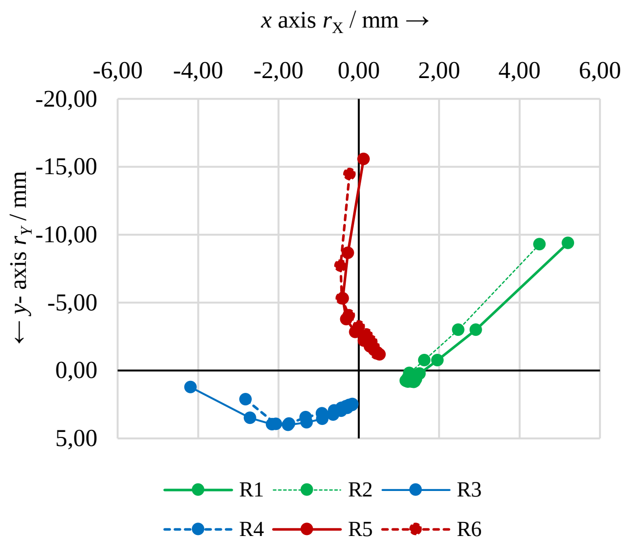

Figure 7.5: movement of the load center in a hydraulic machine

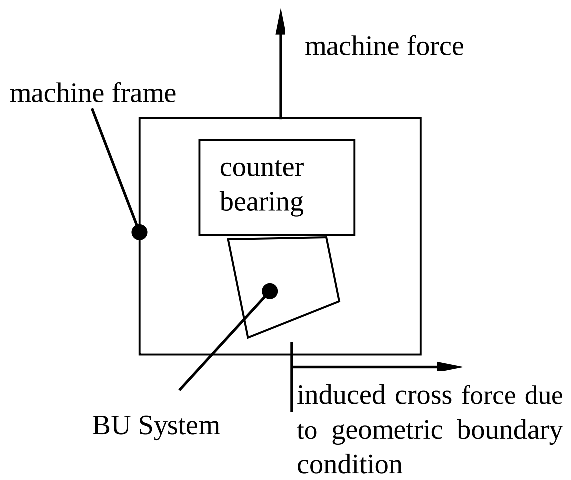

Figure 7.6: geometrical boundary condition in hydraulic machines

Figure 7.6 shows the reason for the deflection of the load frame.

This effect correlates to the direction of the BU system, therefore the curves in Figure 7.5 do not show the same orientation as in the case of the use of a direct loading machine. The reason why the curves do not show an angle of 120 degrees to each other, seemingly is that the machine itself has its own characteristic similar to the direct loading machine which is additionally overlaid.

Another combination which has been investigated is the use of a hydraulic machine combined with a BU system providing a spherical cap. According to the present results, the movement of the load center is expected to be oriented in the same direction. This result can be seen in Figure 7.7.

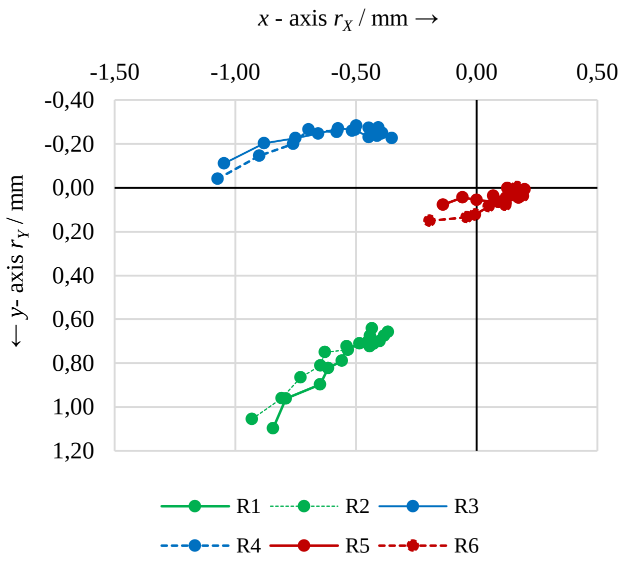

Figure 7.7: load center in a hydraulic machine with spherical cap

8. CONCLUSIONS

For the evaluation of BU systems at least a number of measurements is necessary that equals the number of transducers plus one. In order to compare the results of measurements performed in different machines, the indicated forces of the transducers as well as that of the whole BU system have to be computed as a basis for the computation of the load distribution on the single transducers.

For a comparison, these individual forces as well as the corresponding signals can either be interpolated to force values that are equal or a set of compensation polynomials is used. This results in a loss of information regarding nonlinearities in the characteristics but enables the calculation of any intermediate values and, at the same time, much less stringent conditions on the measurement procedure. In order to improve the reproduction of the characteristic curve by the polynomial, it is possible to neglect the area of load introduction effects in the calculation of the polynomial.

It could be shown that the discussed parameters can describe the behavior of the BU system when it is used as a force transducer, calibrated according to ISO 376 by providing two force values which have a systematic correlation. Likewise, assuming an uncertainty budget for BU systems, it is possible to evaluate the measurement data when using the BU system as a transfer standard by providing information about the deviation of the primary force standard to the machine to be calibrated.

Moreover, the force introduction effects can be detected qualitatively as well as the mutual influence of machine kinematics and geometry of the BU system on the measurement results.

ACKNOWLEDGEMENT

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

REFERENCES

[1] ISO 376:2011, *Metallic materials - Calibration of force-proving instruments used for the verification of uniaxial testing machines*

[2] ISO 7500-1, *metallic materials - Verification of static uniaxial testing machines - Part 1: Tension/compression testing machines - Verification and calibration of the force-measuring system*