NEW-DESIGN DUAL-BALANCE GRAVIMETRIC REFERENCE SYSTEM WITH PTB's NEW 'HYDRODYNAMIC TEST FIELD'

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Abstract:
PTB's new 'Hydrodynamic Test Field', which represents a high-accuracy water flow calibration facility, will serve as the national primary standard for flow measurands: volumetric and mass flow rate, respectively, and total flow measurement, i.e. the quantity of fluid (volume or mass) passing a flowmeter. As most accuracy determining component parts, it comprises three different-size dual-balance gravimetric reference systems: 300 kg, 3 tons and 30 tons. This type of gravimetric references were realized as a combination of a strain gauge based and electromagnetic force-compensation load cell based balance, each. Though each of these two weighing principles fulfils the individual accuracy requirements that have been derived from the total measurement uncertainty budget of the calibration facility as a whole, the electromagnetic force-compensation load cells reveal several advantages concerning linearity error, hysteresis error and sensitivity.

Introduction

High-accuracy liquid flow calibration facilities, generally, are based upon static weighing gravimetric systems applying flying-start-and-finish measurement method. In such a calibration facility the weighing system with a flow diverting device [2] represents a highly accuracy determining component part for precision flow metering. In the case that volumetric flowmeters are to be calibrated, density measurement of the test fluid is also an essential part of the gravimetric calibration technique.

Gravimetric reference system of the 'Hydrodynamic Test Field'

Accuracy requirements and general setup

PTB's new high-accuracy water flow calibration facility, the 'Hydrodynamic Test Field' (***Fig. 1***), incorporates 3 different-size dual-balance weighing systems (30 tons, 3 tons, and 300 kg) with integrated calibration capabilities. The accuracy requirements for these weighing systems result from the calibration facility's total expanded measurement uncertainty of 0,02 % which was one of the central design goals. This very low value of the expanded measurement uncertainty will have been reached after the Hydrodynamic Test Field's full commissioning.

Figure 1. *View of the test hall*
(in the background: 30-tons weighing system)

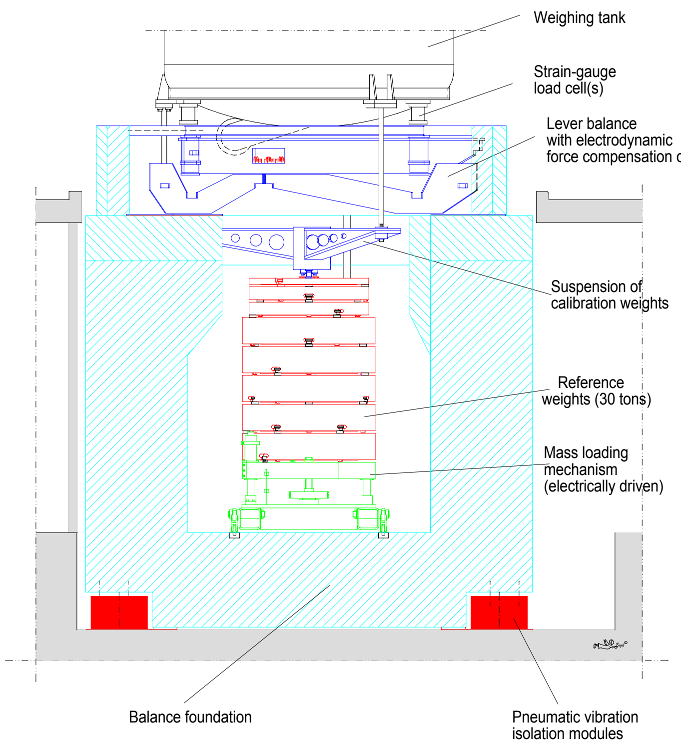


Figure 2. *30-tons weighing system with integrated calibration facility(side view, principle)*

Due to these requirements, the main design goal of the weighing systems was to achieve a resolution of 3 million increments with the guarantee that the expanded measurement uncertainty would not exceed 0,01 % [1]. Owing to this goal, the decision fell in favor of a dual-balance weighing system that combines two different principles of weighing or force metering, respectively: a "classic" beam scale with electronic readout (electromagnetic force-compensation load cell or EFC load cell) and, above this, three strain-gauge transducers (SGT) are arranged that support the weighing tank. This design principle can be seen in **Fig. 2**, exemplified by the 30-tons weighing system.

The design of the 300-kg weighing system distinguishes from those of 30-tons and 3-tons weighing systems. Though also combining strain-gauge and EFC force metering techniques, the construction of the 300-kg balance consists of a center-pole supported weighing tank equipped with one single load cell on top of this pole of steel. This installation was erected on an industrial platform balance using EFC technique.

The signal outputs of both weighing devices in each weighing system are read out coincidentally by the dedicated control computer, which is part of the calibration plant's Supervisory Control and Data Acquisition (SCADA) system [7] (see **Fig. 4**).

Figure 3. *30-tons balance: view of the calibration weights loading system*

1) *Suspension of the calibration weights*
2) *Calibration weights*
3) *Mass loading support*
4) *Balance foundation, i.e. "mass of inertia"*

Generally, the utilization of two different-type force metering principles, as it was realized with PTB's 'Hydrodynamic Test Field' provides the capability to benefit from the fast dynamic response behavior of the strain-gauge cells and from the stability and good repeatability of the electronic beam scales (EFC load cell). In addition to that, the integrated calibration facility (see **Figures 2** and **3**) implies the general possibility to re-calibrate the both components of the three weighing systems at any time it might be considered to be necessary. Due to this fact, the reliability of the calibration results can be increased tremendously. Of course, the balance calibration procedure is fully automated and operable via the operator console of the calibration plant's computer-based control system.

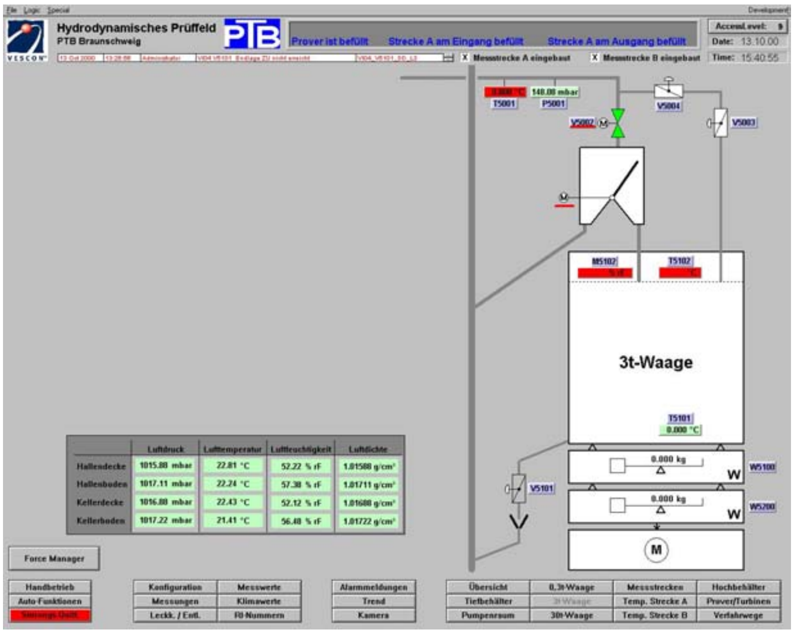


***Figure 4**. Video graphics display: 3-tons dual-balance weighing system*
***(**with measurement value readout and virtual buttons for operator intervention capabilities, e.g. to initiate balance calibration)*

General features

The strain-gauge transducers that were applied with the Hydrodynamic Test Field's gravimetric-reference system represent a double-ring-shaped spring-body design. In order to minimize measurement errors, these force sensors were specially chosen from the supplier's off-the-shelf products under the point of view to find and select specimens which provide minimum error effects due to varying measurement and environmental conditions.

For instance, relative measurement deviation due to sensor creeping is less than $5 \cdot 10^{-5}$ within 30 minutes of operation. According to the sensor specifications by the manufacturer, the temperature coefficients of zero and span are less then 10^{-6}/°C. Additionally, resistive temperature sensors were attached to the strain-gauge transducers to compensate for error effects due to varying ambient temperature.

Disturbing factors as sources of error

Ambient temperature

Due to the high-accuracy requirements for the weighing system, several provisions were made to reduce the effect of varying ambient temperature as a source of measurement error:

- with SGT load cells, thermal isolation of the force transducers and active temperature compensation by means of measuring the transducer's temperature (see above);

- with EFC load cells, a combination of thermal isolation and temperature stabilization of the load cell through electric constant-temperature heating in the force transducer housing at a temperature which is above ambient temperature;
- closed-loop temperature control of the radiators of the central heating in the test hall;
- "calm" conditions through keeping closed all entrance doors and gates to the test hall before and during calibration runs as a preventive measure (also avoiding forces on the weighing tank caused by ambient air flows as a source of error).

Of course, ambient temperature, barometric pressure and relative air humidity are measurands that are acquired via the SCADA system [7] to provide the capability of automated air buoyancy compensation due to the actual environmental conditions during balance calibration and on measurement.

Vibration excitation due to running machinery and flowing water

While the test field is in operation, pumping machinery and the water that is circulated in the plant's pipework are sources of mechanical vibrations. In order not to reduce the weighing system's high resolution, vibration isolation and active vibration damping are essential measures that were applied to utilize the full range of measurement at a low measurement uncertainty level.

It should be mentioned that these measures of mechanical vibration isolation and active damping where necessary as electromagnetic force-compensation (EFC) load cells are used in the weighing systems, in combination with strain-gauge transducer (SGT) load cells. The functional principle of EMC load cells implies several non-linear signal transfer characteristics [3]. Thus, harmonic vibrations acting at the load cell's base(i.e. at an "irregular signal input" in case the balance was installed on a vibrating foundation) generate additive contributions to the load cell's steady-state output signal that cannot be separated from the steady-state signal which originates from the weighing signal at the "regular" input of the load cell. This effect is the same like in an electric circuit with a rectifying device which generates constant (direct current) and harmonic output signals when an alternating input voltage is applied to the rectifying device (e.g. a semiconductor diode).
In the case that only SGT load cells would be utilized in a weighing system, i.e. only linear signal characteristics are effective in the measurement device, the application of signal filtering techniques would be sufficient and no addition measures of mechanical vibration isolation would be necessary.
Though not being part of gravimetric reference system, the vibration-isolated installation of the pumps of the flow generation system is an essential measure to prevent mechanical oscillations being induced into the weighing system.

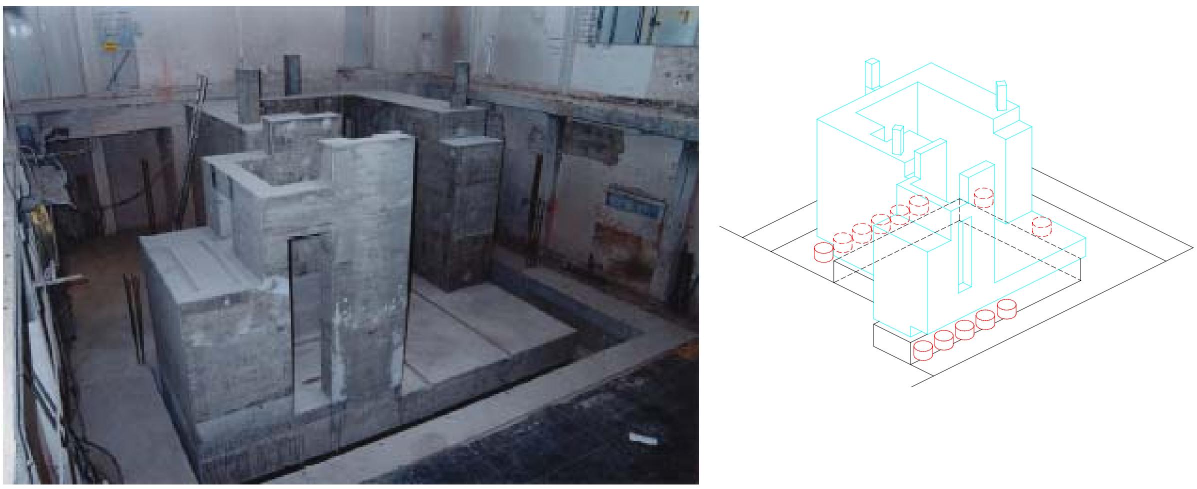


Figure 5. *Balance foundation ("raw conditions") with vibration isolation system (right-hand side: location of the vibration isolators)*

<u>Measures provided for vibration isolation</u>

Owing to the facts presented above, special interest and careful attention were directed towards the design and the construction of the foundation of the weighing systems, taking into consideration the boundary conditions given by the existing building, the properties of the soil below the foundation and the expected disturbing influence of the water current in the calibration plant's pipework.

Analytical and application studies [4][5] were carried out in order to analyze the characteristics of different system designs and to find a practicable solution for this problem. Extensive computer-based finite element calculations were performed to find an optimum system design. The most important task was to determine the eigenvalues of the mechanical system, i.e. the resonance frequencies at which oscillations will occur on the event of mechanical excitation. The lowest natural frequency (i.e. eigenvalue) had been estimated to be 2 Hz.

These investigations resulted in a system design shown in **Fig. 2**: a seismic mass of about 300 tons of concrete as the balance foundation which is supported on a construction comprising 13 pneumatic vibration isolating modules (see **Fig. 5**). These modules provide capabilities to "tune" the whole system that its lowest resonance frequency is below 2 Hz. Additionally they serve as actuating devices in an active level control loop for the balance foundation. This system guarantees a leveling (vertical position) accuracy of ± 0,05 mm.

This passive system of vibration isolation (level/position control) is combined with an active dynamic damping system, which comprises velocity sensors, multi-loop controllers and electric linear drives as three-axis actuators for dynamic system activation.

Thus, the component parts of the complete vibration isolation system are: the concrete foundation as a mass of inertia, pneumatic isolation modules for passive vibration isolation, and electronic devices for active vibration damping.

<u>Test and measurement results</u>

To verify the designed system parameters of the weighing systems, a comprehensive testing program was carried out to ensure a reliable and high-accuracy operation of the balances with the water being circulated in the pipework of the calibration plant. The balances were tested based upon comprehensive procedures with the test field's water flow in operation and stopped, respectively. Thus the performance of the weighing systems was determined under ideal, i.e. there was no water flow being circulated through the plant's pipework, and under operating conditions with water flowing. Essential measurement and test procedures were:

- calibration of the balances by means of calibrated weights applied in a repeated series of measurements;
- verifying the discrimination threshold, sensitivity, stability and hysteresis;
- performing measurements and tests under operating conditions with the vibration isolating system switched active and inactive, respectively.

The calibration procedures are performed automatically under the supervision of the process control system (see **Fig. 5**), calibrated mass pieces being applied, e.i. being suspended below the balance to provide defined loads as input quantity to the balance. The calibration loads to the weighing systems were increased in steps:

- with the 30-tons weighing system, 1 t, 2 t, 2 t, 5 t, 5 t ... up to a total load of 30 t (see **Fig. 3**);
- with the 3-tons weighing system, 100 kg, 200 kg, 200 kg, 500 kg, 500 kg ... up to a total load of 3 t;
- with the 300-kg weighing system, 10 kg, 20 kg, 20 kg, 50 kg, 50 kg ... up to a total load of 300 kg;

and decreased in the reverse succession, with the respective weighing system.

It has practically proven, after having been started up and before high-accuracy measurements will be started, the weighing system in use should be loaded and unloaded in, at least, three duty cycles with the calibration weights being applied up to full scale.

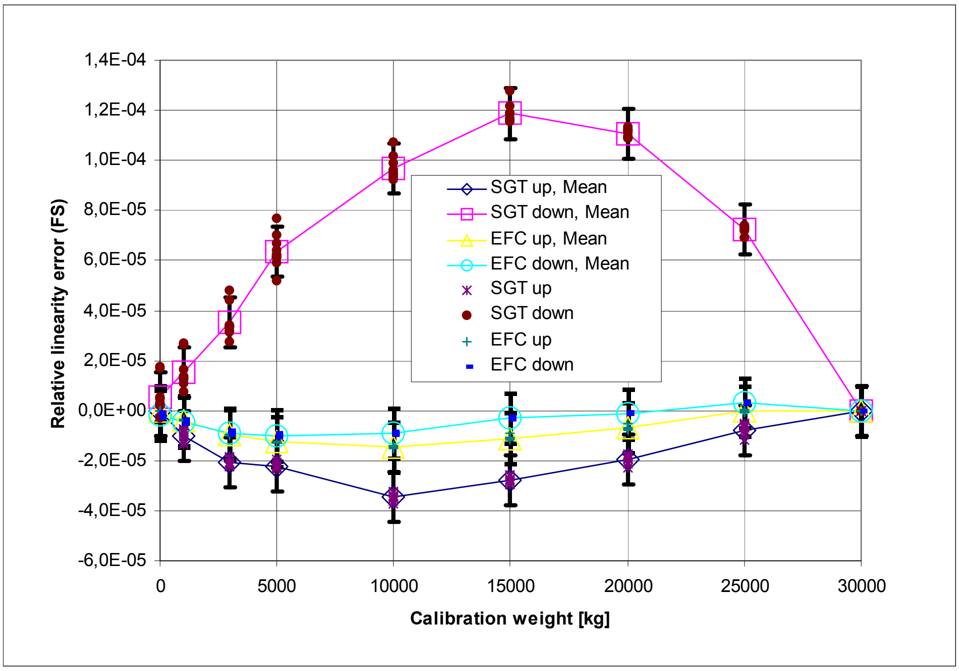


Figure 6. *Characteristics of the 30-tons weighing system (comprising strain-gauge transducer (SGT) and electromagnetic force-compensation (EFC) balances)*

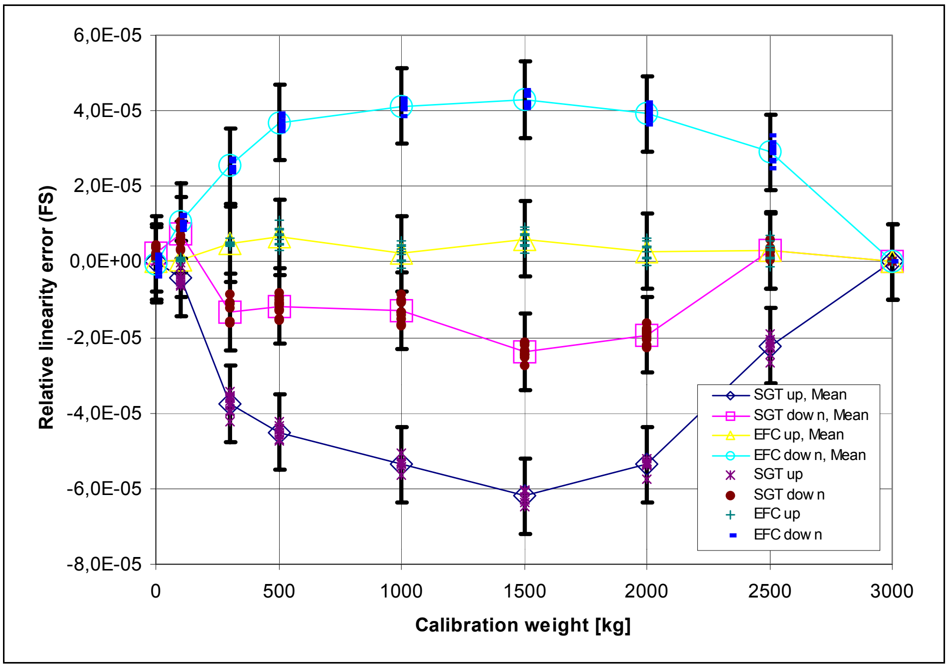


Figure 7. *Characteristics of the 3-tons weighing system (see also Fig. 6)*

Characteristics of the weighing systems

Results of these tests and calibration measurements that were gained in calibrating the 30-t balances are depicted in **Fig. 6**, i.e. relative linearity deviation related to full scale(FS) vs. calibration weight: **a)** for strain-gauge transducer (SGT) based balance and **b)** for electromagnetic force-compensation (EFC) load cell based balance, respectively. Coincidentally, **Fig. 6** summarizes measured values of the calibration runs during 10 succeeding up and down loading cycles and the respective mean values. The bar-type line marker represents a relative deviation of $\pm 1 \cdot 10^{-5}$ FS.

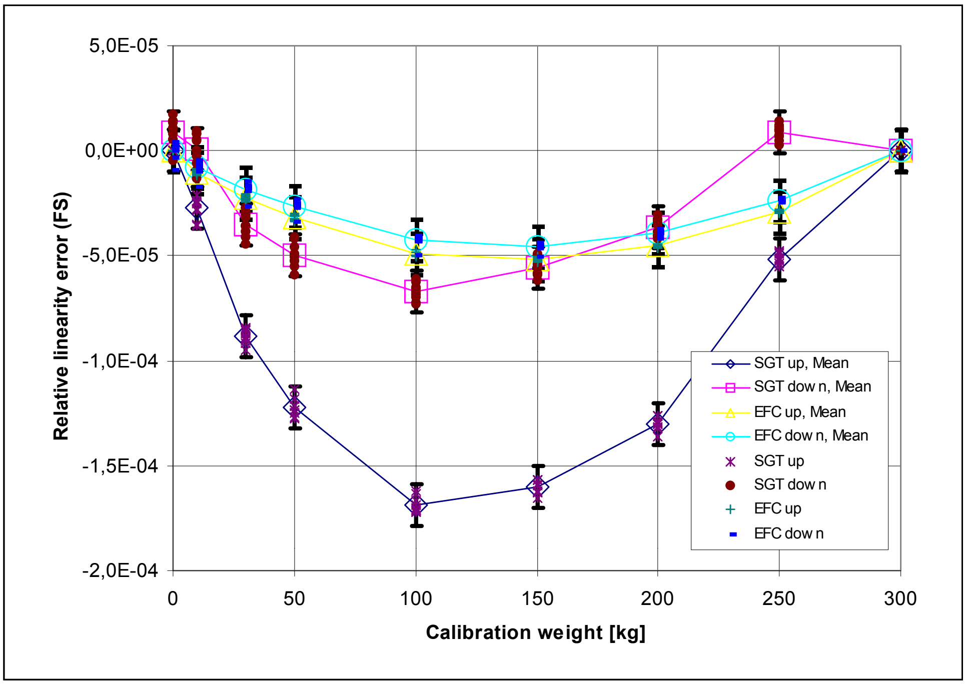


Figure 8. *Characteristics of the 300-kg weighing system (see also Fig. 6)*

Fig. 6 provides a complete overview of the most important characteristics of the two types of load cells of 30-tons balances, and it can be recognized:

- the repeatabilities of the 30-tons balances under investigation are reproducible within the required value of $1 \cdot 10^{-5}$ FS [1],
- the hysteresis is less than $1{,}5 \cdot 10^{-4}$ FS and, thus, it lies within the required constraint values of less than $2 \cdot 10^{-4}$.
- there is a significant difference in the characteristic of the two different types of balances (SGT and EFC), but the operating range of both does not exceed the permitted tolerances.

Fig. 7 depicts the results of investigation of the same characteristic features of 3-tons balances, **Fig. 8** those of the 300-kg balances, respectively.

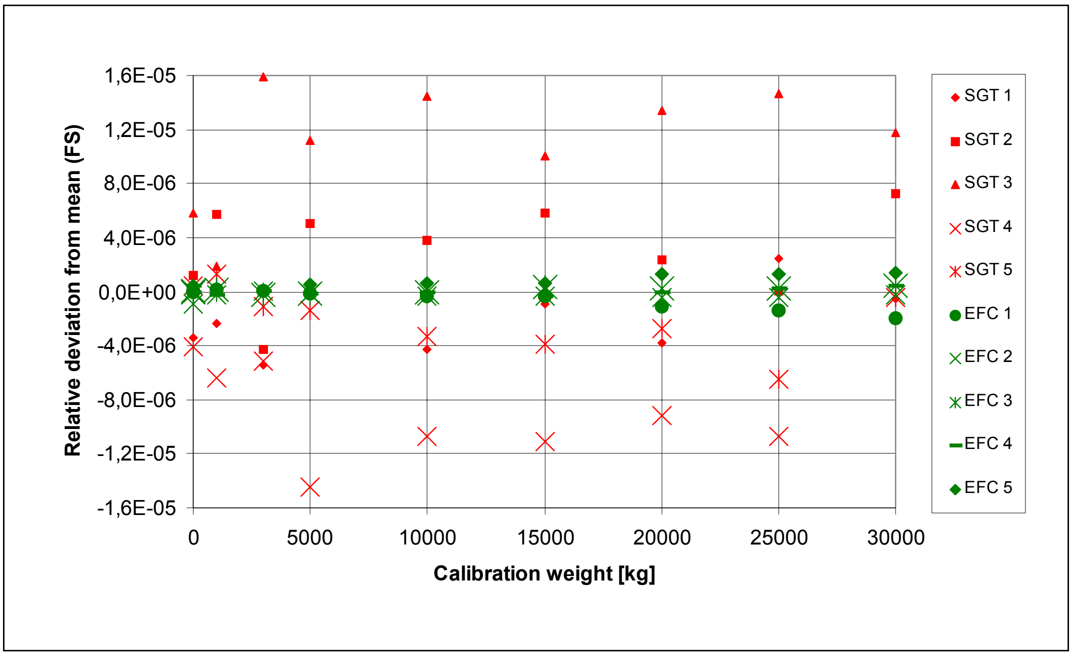


Figure 9. *Performance stability of the 30-tons weighing system vs. time (5 repeated load cycles over a period time of 12 h)*

Long term stability

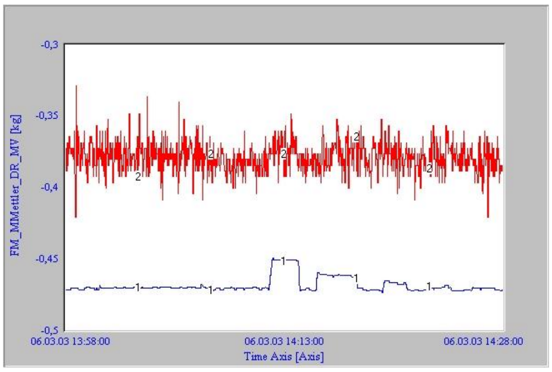
Long term stability over a period of one day's measurement was checked to acquire knowledge about the necessity of the balance's re-calibration intervals. The résumé is: one calibration per day is sufficiently (see **Fig. 9**).

Sensitivity

By applying tiny calibration weights (3-tons balances: 1 g through 5 grams) the measurement sensitivities and the discrimination thresholds of the balances, respectively, were determined. A decrease in sensitivity vs. time will be an indicator that the balances have lost measurement accuracy, e.g. due to increased friction of the knife edges on the stones as joints in the mechanical beam scales. For that reason, the sensitivity measurement is a preventive measure to sustain the balances' measurement accuracy. Test and measurement results for the 3-tons balances are depicted in **Fig. 10a** through **c**. These figures present an impressive imagination of the weighing system's sensitivity, demonstrated by the small pieces of mass placed as a "load" on a fastening plate of the 3-tons weighing tank. The resulting system responses of the balances are shown in **Fig. 10c**: a screen printout that was generated by utilizing the process visualization capabilities of the SCADA system [7].

a) *Test weight: 5 grams*

b) *3-tons weighing system of the calibration plant (**above**)*



c) *Balance response on mass pieces being applied (**left side**): 20 g, 10, 5 g, 2 g and 1 g, respectively*
(SCADA system's on-screen trend display:
- upper/red curve: readout of the strain-gauge sensors
- lower/black curve: readout of the electromagnetic force-compensation load cell)

Figure 10. *Sensitivity test: 3-tons weighing system*

Resistivity against vibrational system excitation

The damping effect of the vibration isolating system is shown in **Fig. 11**: the load applied by 15 tons of calibration weights was determined with and without the damping system in operation. These signal outputs were related to the steady state of "quietness", where the disturbing impacts of the vibration excitation caused by the running pumps and the circulated water flow is not present. It can be seen that the disturbing scatter of the readout of the SGT based balance, while the test field is run at maximum flow rate (2100 m^3/h), was reduced by a factor of about 3 when the vibration isolation system was active.

In case of the vibration isolating system being active, measurements with both types of balances were made to compare the readout signals and to check whether disturbances caused by the water flow result in different weighing results. These measurements were carried out with the test field being run at maximum flow rate of 2100 m³/h.

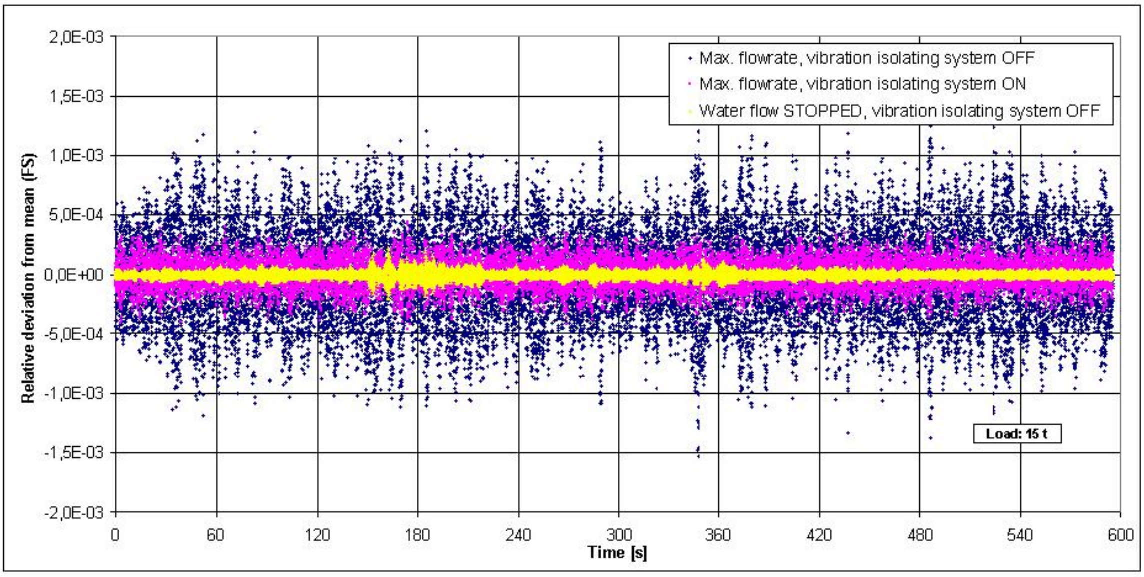


Figure 11. *Error reducing effect of the balances' vibration isolation system*

'Auxiliary' facilities of the gravimetric reference system

Flow diverter

Fluid flow diverters are essential elements in liquid flow calibration facilities utilizing flying-start-and-finish method and static weighing. A special flow diverter design was developed for this standard facility, offering several new features: electrically actuated servo-controlled diverter transition and continuous-position signal acquisition for precise timer actuation. For further details see [2] and [8]. Those papers describe, in detail, the accuracy requirements, the design and test results of the first prototype of this new-design diverter that is applied in the test field.

In-process water density metering facility

The density metering facility, acquiring density data of the test fluid water in the calibration plant, comprises a high-precision laboratory-type density meter (vibrating U-tube density meter) and a peristaltic pump for automated sampling. So the water density can be determined online. The sampling and metering procedures are wholly supervised and controlled by the computer-based SCADA system. For further details see [7].

Docking facility

Measurement (temperature, humidity transducers, and SGT load cells) and data communication devices, attached to the weighing tanks, are energized by battery-backed power supplies, which will be disconnected from external mains system during measurements, i.e. when the balances are read out. Data transmission from and to this measurement "islands" were realized via "wireless" optical links. Additionally, the pressurized-air power supply for actuating the weighing tank's drain valve is connected or disconnected via this docking facility. Thus, any accuracy reducing mechanical influence via connecting wires or hoses to the weighing tank is avoided.

Conclusions and final remarks

Verifications (comprising measurements and function tests) of the gravimetric system's components: weighing systems, flow diverting devices [2], and density metering device [7], have proven that these component parts meet their individual measurement uncertainty specifications that were derived from the measurement uncertainty budget of the whole calibration facility. Thus

as a result of these verifications it can be established that the 'Hydrodynamic Test Field' in its entirety will achieve the claimed expanded measurement uncertainty better than 0,02 % on total volumetric flow-rate measurement, i.e. the metered volume that has passed through the flowmeter under calibration.
Continuous monitoring of all relevant process quantities (e.g. sensor output signals and actuator driving signals) by means of the calibration plant's computer-based Supervisory Control and Data Acquisition system [7] provides the capability to guarantee low-uncertainty calibration during the entire plant operation.

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