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# CONSTRUCTION OF A STANDARD FORCE MACHINE FOR THE RANGE OF 100 µN – 200 mN

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**Abstract** – A new force standard machine (FSM) for the range of 100 µN – 100 mN has been developed [1]. The machine is based on the comparison of a force transducer with the indication of an electromagnetic compensated balance (ECB). Construction details as well as first measurements will be presented. To guarantee traceability to the established deadweight force machines, the new facility was compared with the PTB 200 N FSM.

**Keywords:** force standard machine, small forces, force transducer, ISO 376, electromagnetically compensated balance

## 1. INTRODUCTION

The well-established method for force calibration is the application of dead-weight machines based on masses suspended in the Earth's gravitational field. In this way, the traceability within the International System of Units (SI) is given directly from a traceable mass artefact combined with a precise determination of the local gravity according to Newton's Law: $F=m\cdot g$, with $F$: Force, $m$: mass and $g$: gravitational constant.

A wide range of forces reaching from 20 N – 2 MN can be realized by this machine, e.g. at PTB. Nevertheless, the extension of forces to higher or smaller regions requires other concepts, because the use of mass artefacts becomes unmanageable. Larger forces in the MN range can be realized, e.g. by hydraulic amplified machines [2] or by the assembly of so-called build up systems, where the force is distributed along several (generally 3-4) precisely calibrated force transducers.

Small forces below 1 N could also, in principle be realized by dead weights as shown, e.g. in [3]. On the other hand, the smallest official mass artefact used in legal metrology is, e.g. in Germany, 1 mg, corresponding to a 10 µN force. These small weights are specially shaped wires which are difficult to handle in an automatic procedure. Especially the stacking of these masses for the stepwise increase of the force and the realisation of an extremely precise perpendicular force vector seems to be a micromechanical challenge.

Another route for measuring small forces is the comparison method by the application of very precise ECBs. Using this method the force transducer is pressed in a controlled way against the balance and according to Newton's principle, action equal reaction, the force equivalent mass indication on the balance is taken as the reference.

A very crucial point is that the calibrations which will be performed with the new FSM should be possible within the framework of the international standard ISO 376. This automatically implies that at least 8 force steps for the loading and unloading of the force as well as a change in the mounting position of the force transducer should be possible (e.g. a rotation of 120°).

Besides the new facility described here, two other set ups for measuring small forces where tested at PTB. Both instruments where based on the application of ECBs. The first one [2] used a piezoelectric adjustment device (PIFOC, piezoelectrical focus), where the force transducer was mounted overhead. The PIFOC was able to position the transducer with nanometer resolution and a maximum displacement of 100 µm. On the other hand, commercially force transducers usually reach their maximum force via strain or stretch within a range of 200 – 300 µm. This limiting factor and a quite large rotational effect of this machine, led to a completely new construction described in [3]. Thereby the ECB is mounted overhead on a movable traverse. The weighing pan is removed and a special piezoelectric stretching element is directly coupled to the balance mechanics. The transducer is mounted on a rotating table and stands on a goniometer to adjust the force vector. By stretching the piezoelectric element (max. displacement ≈500 µm), an equal force is generated on the transducer and the balance. So far only one transducer, with a nominal range of 2 N, was measured with this machine according to ISO 376, whereby uncertainties around 1 part in $10^4$ were reached.

## 2. TECHNICAL DETAILS

The main concept of the new force machine [1] is seen in Fig. 1. One of the core items is a nano-positioning table (NPT). The ECB stands on the table platform. In contrast to the previous concepts, this has the great advantage that the balance can be changed very easily and thus the force range can be adjusted. The NPT itself is a combination of servo motors and piezoelectric actuators. This arrangement

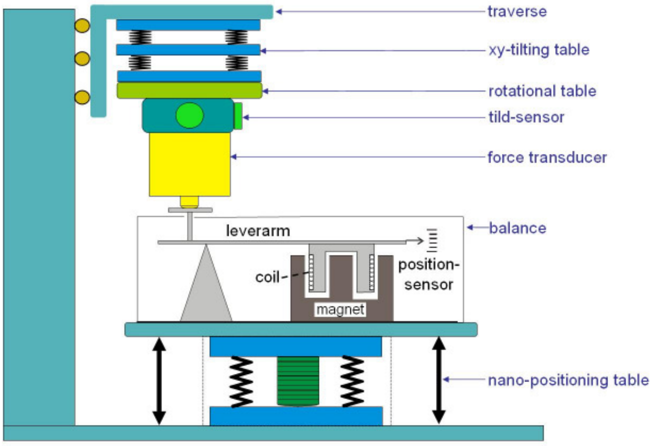



Fig. 1. Construction principle of the new FSM. The ECB is located on a platform mounted on a NPT and can thus be driven against the force transducer. The transducer itself hangs on a rotational and tilting table for precise adjustment. The tilt table can be changed in x and y direction, whereby the tilt angle is measured by 2 appropriate tilt sensors. The rotational table allows a rotation of 360°. All hanging components are mounted on a vertical moveable traverse.

ensures a wide positioning range of 7 mm combined with a very precise absolute positioning of 4 nm.
The interaction of the servo motors and the piezoelectric actuator is controlled by an appropriate controller. The table is also equipped with an internal incremental linear encoder for position measurement. This sensor has a resolution of 2 nm. Due to the two different positioning concepts the table can be driven in a wide velocity range so that the positioning range of 7 mm, e.g., can be driven in 70s.
For the designed force range from 100 µN – 100 mN, an ECB with a nominal range of 20 g is used. The balance has a readability of 1 µg and a standard deviation of 3 µg. Depending on the data filters which are switched on internally, the balance can be read out with frequencies between 5 – 100 Hz. Besides this balance, there are two other balances available, originating from the above-described machines. In Table 1, the parameters of all balances are summarized together with estimated achievable uncertainties. Looking on the smallest force, e.g. 100 µN, one has to keep in mind that following an ISO 376 calibration, the smallest force step is 1/10, thus 10 µN.
If the transducer is pressed on the balance its lever arm moves downwards (see Fig. 1), which causes this position change to be detected by the position sensor located on the opposite side of the lever. The internal controller of the balance is increasing the current through a coil mounted below the lever. The coil itself is surrounded by a permanent magnet. Hence, the coil produces a magnetic field which repels it from the static magnetic field of the permanent magnet. The produced deflection compensates the lowering of the balance lever. The higher the mass/force, the higher the current and the higher the Lorentz force produced by the coil. As a result, the weighing pen is always kept at the same position. The coil current goes through a resistor, which is part of a Wheatstone bridge. The produced voltage signal, resulting from the bridge detuning, will be amplified and transformed to the balance indication.

Table 1. ECBs and their associated force ranges with estimated uncertainties.

| Balance | No. 1 | No. 2 | No. 3 |
|---|---|---|---|
| Weighing capacity | 20 g | 200 g | 1200 g |
| Readability | 1 µg | 100 µg | 1 mg |
| Repeatability (σ) | 3 µg | 100 µg | 1 mg |
| F-max | 200 mN | 2 N | 12 N |
| rel. U (k=2) | $< 10^{-5}$ | $<10^{-5}$ | $<10^{-5}$ |
| F-min | 100 µN | 10 mN | 100 mN |
| rel. U (k=2) | $< 10^{-2}$ | $<10^{-3}$ | $<10^{-3}$ |

A further main construction part is the suspension of the force transducer. The transducer can be adjusted using the rotational and tilt table perpendicular to the weighing pen. The tilt can be adjusted in the range of ±7° separately for the x and y axis. The adjustment of this table can be done manually by micrometer screws, whereas the smallest step size is 65 µrad. The rotational table can be adjusted by a stepper motor. This ensures an automatic rotation, necessary for a calibration according to ISO 376. A rotational range of about 360° with a smallest step size of 21 µrad of the table is more than sufficient.

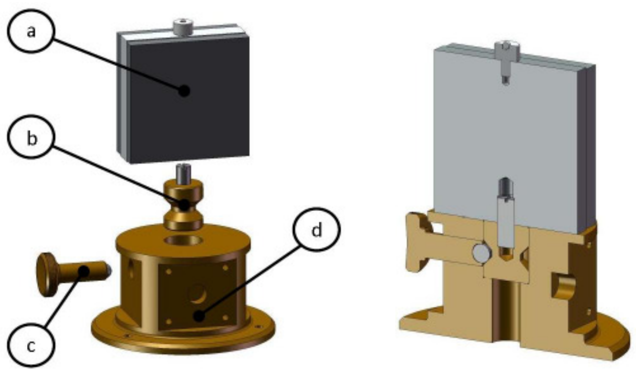



Fig. 2. The principle of mounting the force transducer (a) on its special adapter (b-d). The force transducer (a) is connected with the adapter via a special connector (b) which is equipped with a UNF-screw fitting the transducer. The connector is fixed with a ball-head screw (c). The side planes (d) of the adaptor are designated for the tilt sensors.

A special adapter was constructed to mount the force transducer, see Fig.2. One requirement was a quite universal adapter, which can be used for different kinds of force transducers. For that reason, the adapter was supplied with a special connector (b) having a neck in the middle. In this way, the ball-head screw (c) fits exactly in this neck and holds the transducer, see Fig. 2 right part. If another type of transducer is calibrated only, the connector (b) has to be

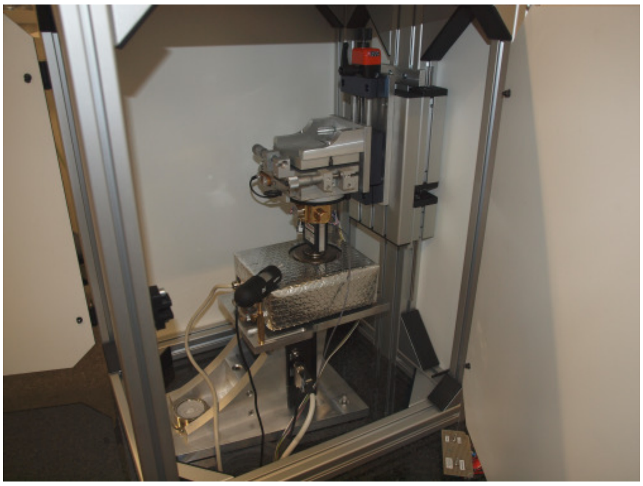
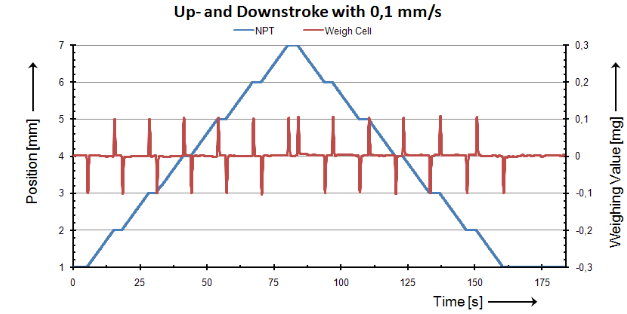


Fig. 3. Photograph of the new FSM. In the lower part one can see the NPT and the balance, surrounded by a foil to reduce thermal influences. Above the balance, the transducer, with the adapter mounted on the rotational and tilt table.

changed. On the side of the adapter there are two plane areas to mount the tilt sensors. Due to the close location of the sensors to the transducer, a very precise adjustment can be guaranteed. The tilt sensors are applicable for ±20° and have a resolution of 0.001°. The rotational and tilt table is directly connected together and hangs on a vertical movable traverse. The traverse mechanics consist of two movable linear stages mounted together. The first one, which is part of the whole frame, is for coarse adjustment. The vertical mounting position can thus be changed within ≈15 cm. The second stage is for fine adjustment in a range of 5.5 cm. A pitch of 2 mm can be realized with one turn of the integrated spindle. The adjustment must be done manually via a rotary knob and can be controlled by a digital indicator.
The complete frame of the machine is housed by special plates to reduce thermal influences and air turbulences. All environmental parameters like temperature, air pressure and humidity are measured inside the machine housing and recorded parallel to the calibration procedure. In addition, the machine stands on an active dumping table to reduce vibrations.

## 3. MEASUREMENTS

First measurements were performed to examine the behaviour of the different components. An important piece of information is whether the balance will be disturbed during the movement of the NPT. Hence, the NPT was driven with the slowest and the fastest velocity. Figure 4 shows the results of both measurements. Thereby, the step function is the position measurement of the internal sensor of the NPT. In the case of the fastest velocity (0.1 mm/s), distinct spikes in the signal of the ECB are seen. These spikes are over- and undershot, originating from the acceleration and deceleration process of the NPT. During a calibration procedure these spikes can be ignored because their duration is roughly 1 s and according to the ISO 376 norm, the first usable data would be recorded after 30



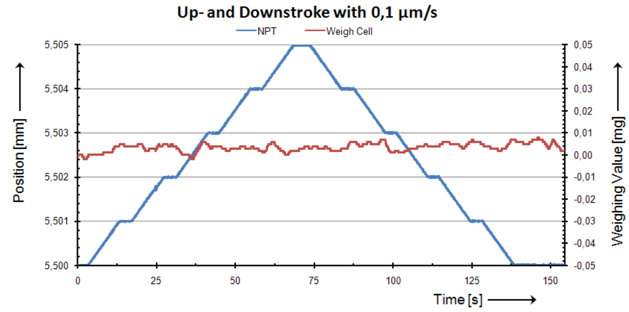




Fig. 4. Interaction between NPT and ECB measured during the positioning procedure. The first figure shows the behaviour using the fastest velocity of 0.1 mm/s, the second one, with the lowest velocity of 0.1 µm/s. The step like curve is the measured position from the internal position sensor of the NPT.

seconds. On the other hand these spikes vanish by using the smallest velocity, as shown in Fig. 4, lower part. Speaking, one would drive a force step in such a way that the table is be slowed down when reaching the target position, instead of jerking to a stop, as shown in the upper part of Fig. 4.
A first measurement was performed to compare the new machine with the 200 N FSM of PTB. For this comparison a 2 N strain gauge transducer from INTERFACE® was used. The 200 N FSM can realize 4 force steps (0.5, 1, 1.5, 2N) in the range of 2 N. To produce these steps, special stainless steel discs are stapled together. The masses of these discs are adapted to the certain force values. To increase the resolution, an E2-standard mass set was used to obtain 8 additional force steps. In this way, force steps corresponding to the masses reaching from 2 – 20 g, in steps of 2 g, could be realized. In Table 2, the coefficients of a linear fit to the data are shown. With these coefficients, the transducer signal in mV/V can be calculated as a function of the load mass in kg. Both measurements fit together on a level of 1 part in $10^4$.
The given uncertainties for the parameters are derived from the diagonal elements of the covariance matrix obtained by the fit.

Table 2. A linear regression of the transducer signal as a function of the mass load.

| | Slope | | Offset | |
|---|---|---|---|---|
| | Value | Unc. | Value | Unc. |
| 200N-FSM | 0.95644 | $8.12\cdot10^{-6}$ | $-2.0\cdot10^{-5}$ | $1.1\cdot10^{-5}$ |
| E2 set | 0.95624 | $3.38\cdot10^{-6}$ | $-2.6\cdot10^{-5}$ | $2.7\cdot10^{-5}$ |

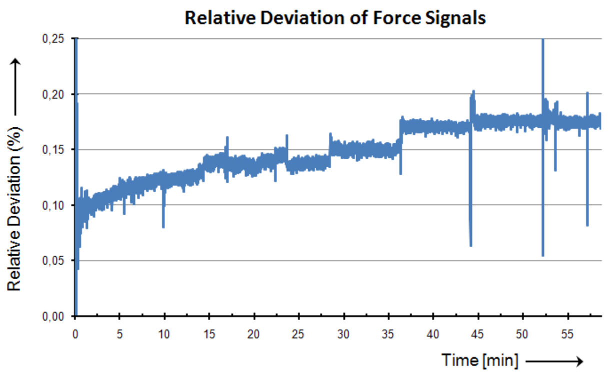



Fig. 4. Deviation between the calculated force signal, using the parameters obtained for the E2-set of Table 2 and the indication of the transducer amplifier, normalized of the indication and given in percent.

First measurements were performed to investigate the behaviour of the system if a force is created by pressing the transducer and the ECB together. In a first check a force around 100 mN was created and the transducers as well as the balance signal were recorded with 20 Hz over a period of roughly one hour. With the parameters of Table 1, one can now convert the balance indication to a value in mV/V, which can be directly compared with the amplifier indication of the force transducer. Figure 4 shows the difference between both signals normalized relative to the transducer signal. First of all, one can note that the signals are not time stable. This is due to the normal drift immanent to the devices. In addition, there is a certain softness connected with the micromechanical components which can be lead to different relaxation processes. Especially the ECB is equipped with an overload protection in the form of an additional spring below the weighing pen. Removing this protection was done in the work of [4] could clearly improve the balance behaviour. According to fig. 4, the deviation of the measured force signal is smallest (0.05-0.1%) directly after reaching the force step. By introducing a controlled operation incorporating the NPT, ECB and the transducer signal, the absolute precision of the created force should be considerably improved.

## 4. CONCLUSIONS

A new force standard machine for the range of 0.1 – 200 mN has been developed. The machine is based on state of the art micromechanical commercial components, whereby the core pieces are a nano-positioning table and an electro-magnetic compensated balance. The force transducer hangs over head on a special adapter which can be tilted in x and y direction as well as rotated around 360°. With this equipment a very precise force feed-in is possible. Thus, the machine is able to perform a calibration according to the ISO 376 standard. After a calibration of the used force transducer with the 200 N FSM and an E2 standard mass set the force stability was measured. It could be shown that at the beginning of the force created the deviation between the calibration and the measured force by the machine is between 0.05- 0.1%. Due to drift and relaxation processes, the deviation increased over time and converged approximately to 0.17% after one hour.
The precision of the machine can be drastically improved if a controlled operation is implemented to reach uncertainties estimated in Table 1.

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