EXTENSION OF THE MEASURING RANGE OF BALANCES

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The basic principle of comparing the sample mass with the mass of a reference body in equilibrium gives the equal-armed beam balance a unique accuracy. Main parameters characterising the suitability of the instrument are measuring range, resolution and relative sensitivity (resolution/maximum load). The historical development of the values of these parameters achieved depended strongly on the practical need in those times.

Technically unfavourable scales of the oldest Egyptian dynasties (~3000 BC) could resolve mass differences of 1 g and had a relative *sensitivity* of at least 10^{-3}. More sophisticated instruments from the 18th Dynasty (~1567–1320 BC) achieved a relative sensitivity of 10^{-4} independent of the size of the instrument. In 350 BC Aristotle clarified the theory of the lever and at about 250 BC Archimedes used the balance for density determinations of solids. The masterpiece of a hydrological balance was Al Chazini's 'Balance of Wisdom' built about 1120. Its relative sensitivity was $2 \cdot 10^{-5}$.

Real progress took place when scientists like Lavoisier (1743–1794) founded modern chemistry. At the end of the 19th century metrological balances reached a relative sensitivity of 10^{-9} with a maximum load of several kilogrammes. That seems to be the high end of sensitivity of the classical mechanical beam balance with knife edges. Improvements took place by electrodynamic compensation (Emich, Gast).

In 1909 Ehrenhaft and Millikan could weigh particles of 10^{-15} g by means of electrostatic suspension. In 1957 Sauerbrey invented the oscillating quartz crystal balance. By observing the frequency shift of oscillating carbon nanotubes or of silica nanorods, masses or mass changes in the attogram or zeptogram have been observed recently.

Keywords: *balance, history, measuring range, sensitivity*

Introduction

Apart from simple rulers like yardsticks and cups, the balance is the oldest real measuring instrument, invented more than 5000 years ago [1, 2]. The balance is still the most widely distributed instrument in the world. It is used in the household, in industry, in commerce and of course in every laboratory. The basic principle of comparing in equilibrium the sample mass with the mass of a reference body, both influenced by the gravitational field, gives the equal-armed beam balance a unique sensitivity [3].

Parameters

The main parameters characterising the suitability of a balance are [4]:

- measuring range
- maximum load
- sensitivity, resolution
- accuracy, precision, reproducibility

We observed that another value characterises well the state of the art for balances of a special type, independent of measuring range and maximum load [5], namely:

- relative sensitivity (sensitivity/maximum load)

In its historical development the values achieved for such parameters depended strongly on practical need [6].

The beginnings in Egypt

In Fig. 1 we see the oldest known balance beam, made of limestone and 85 mm in length, found in Upper Egypt and dated pre-dynastic [7, 8] (the ropes are added for demonstration). In the tomb of Hesi-re of the 3rd Dynasty (about 2650 BC) a standardisation table can be seen containing cylinders, masses and two balance beams of the same type [9] (Fig. 2). Even those scales of technically unfavourable design could resolve mass differences below 1 g and had a relative sensitivity of at least 10^{-3}.

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Fig. 1 Balance beam made of limestone, 85 mm in length. (The ropes are added for demonstration.) Upper Egypt, pre-dynastic Negade period
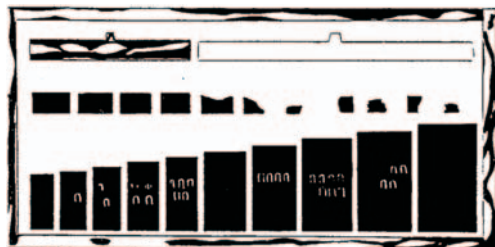
Fig. 2 Tablet with two balance beams, masses and cups. Upper Egypt, Tomb of Hesi-re, ~2650 BC

During the 3000 years history of Old Egypt some progress can be stated in the design of the exclusively equal armed balances. The balance beam becomes smaller, reducing its mass. Fulcrum and the points of application of the pan suspensions were arranged in a line increasing the sensitivity. Besides primitive types, a characteristic of balances of the New Kingdom (1567–1085 BC) and later was the suspension of the scale pans by four cords which were introduced laterally into the balance beam and a plummet (Figs 3–5).

Fig. 3 Death tribunal. Papyrus pLouvre 3079 (Ptolemaic)

**Fig. 4** Model of a large balance of the 18th Egyptian Dynasty

Fig. 5 Hand balance, Egypt, 18th Dynasty

We have many drawings of balances of a man's height in Egyptian tombs from 18th Dynasty (~1567–1320 BC) [10]. The Egyptians believed that in a death tribunal the heart or the soul of a deceased person would be weighed against an ostrich feather which was the symbol of truth [11–13] (Fig. 3). We reconstructed such a balance in order to determine its sensitivity and to understand its operation and realised a maximum load of more than 30 kg and a resolution of about 1 g [14, 15] (Fig. 4). We may assume a relative sensitivity of 10^{-4} independent of the size of the instrument but depending on the load. So, indeed the Egyptians were able to weigh that feather which has a mass of about 2 g and we learn that the mass of the soul is about 2 g.

Greeks, Romans and Arabs

In 350 BC Aristotle [16] clarified the theory of the lever and in about 250 BC Archimedes used the balance for density determinations of solids [17, 18]. His balance was improved by Al Chazini, a muslim scientist of Greek origin, which taught at Merw (Turkmenistan). His masterpiece of a hydrological balance was 'Balance of Wisdom' [19–21] built about 1120 (Fig. 6). It achieved a relative sensitivity of $2 \cdot 10^{-5}$.
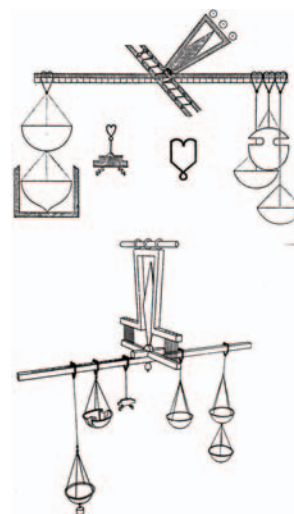
**Fig. 6** Balance of Wisdom of Abụ-Fath Abd-ar-Rahmān al-Chāzinī, Merw (Turkmenistan) 1120

Fig. 7 Above – sketches of gravimetric hygrometers of Leonardo da Vinci, below – sketches for the Last supper. In the middle a balance loaded with a sponge to be used as a hygrometer

Further improvement of the balance involved the use of metal and the development of Roman type single armed balances and besemers which had, in general, a lower relative sensitivity. Progress with regard to sensitivity and accuracy was very slow. Leonardo da Vinci at the end of the 15th century designed several gravimetric hygrometers (Fig. 7) [22]. That means he measured water adsorption. The balances were very poor; nevertheless he used them for weather forecasting.

Modern times

Real progress took place when scientists like Lavoisier (1743–1794) founded modern chemistry. At that time, end of the 18th century, the French revolution took place. Lavoisier was beheaded, but his work survived including the introduction of the new metric system of units. Beginning in 1791, the standardising of the new metric units required more than ever before, a far higher accuracy of weighing [23]. Special balances of outstanding accuracy and the first vacuum balance were built. At the end of the 19th century a relative sensitivity of 10^{-9} was achieved of metrological balances with a maximum load of several kilogrammes. That seems to be the upper limit of sensitivity of the classical mechanical beam balance with knife edges [24]. The Bunge balance (Fig. 8) designed for weighings in vacuum was used at the Bureau International des Poids et Mesures at Sèvres from 1878 until the 1950s.

In 1833 Talabot at Lyon equipped a laboratory with 39 thermobalances for quality control of Chinese silk (Fig. 9); this is the beginning of thermogravimetry [25, 26]. In 1914 Petterson performed sorption measurements resolving 10^{-10} g, the balance beam be-
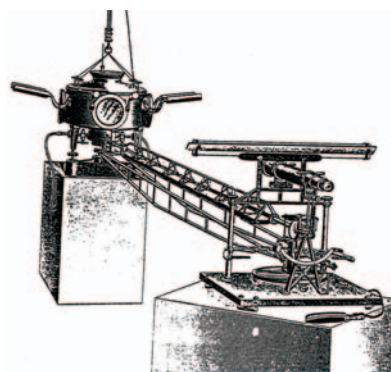

Fig. 8 Paul Bunge's kg-prototype balance, Hamburg 1878. Reproducibility: $2.5 \cdot 10^{-9}$

Fig. 9 Desiccators Talabot Rogeat at the Lyon laboratory. The ovens are decorated with Chinese enamel and were heated first with coal, later with electricity

ing suspended with quartz fibres. Electromagnetic and electrodynamic compensation was introduced successfully and here the extensive work of Gast has to be noted [27]. The upper limit of sensitivity of such balances was achieved by Czanderna using a quartz frame beam (Fig. 10) for a vacuum ultramicrobalance with optical deflection sensor and electrodynamic compensation [28]. The capacity was more the 10 g at each side and it had 10^8 scale divisions per gram.
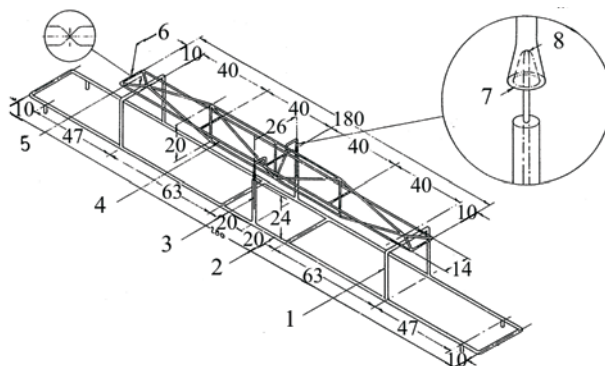

Fig. 10 Quartz frame beam of Czanderna's electrodynamic vacuum ultramicrobalance (1965). 1 – beam arrest, 2 – frame, 3 – tungsten wire, 4 – 3-dimensional trussed beam, 5 – yoke, 6 – suspension wire support, 7 – quartz cup, 8 – tungsten point. Dimensions in mm

The sensitivity of such beam balances is limited by the effect of Brownian gas motion and it seems that this limit is attained by several types of electrodynamic nanogram balances. So let us have a look at other types of balances besides beam balances.

In 1665 Robert Hooke invented the spring balance [29]. The relative sensitivity of spring balances is poor in comparison with beam balances. However, its simple design provides advantages, e.g. for sorption experiments in a corrosive atmosphere. In connection with strain gauges it is used widely in industry and in household.

In 1909 Ehrenhaft and Millikan could weigh particles of 10^{-15} g by means of electrostatic suspension [30]. Straubel improved that method by application of an alternating electric field (Fig. 11). We used his apparatus to measure water adsorption isotherms on suspended particles in the range of 0.1 nanograms [31].
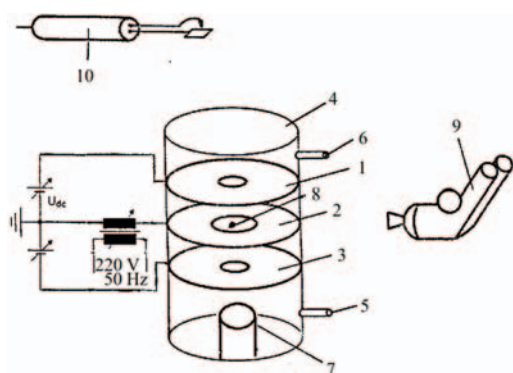

Fig. 11 Scheme of a three-plate capacitor according to Straubel for positioning of charged particles. Determination of *e*/*m* of particles suspended in an alternating electric field. 1 and 3 – DC operated Millikan plates, 2 – AC operated plate, 4 – perspex cylinder, 5 and 6 – gas supply, 7 – lamp, 8 – suspended particle, 9 – stereo microscope, 10 – spatula with corona discharge

Dynamic measurements

A gravitational balance attempts to measure a static equilibrium value, mostly by comparison of masses. During seven millenniums this principle was applied, allowing very sensitive measurements. Further progress was obtained by dynamic measurement of the inert mass. An inert mass balance produces its own gravitational field by accelerating the sample to be weighed. The equivalence of gravitational and inert mass was confirmed only recently. In 1916 Einstein published the general theory of relativity [32] in which the distinction between inert mass and passive gravitational mass was abolished.

In 1957 Sauerbrey invented the quartz crystal balance [33, 34]. The intensity of the high frequency field generated on the crystal surface can be several million times higher than that of the gravitational
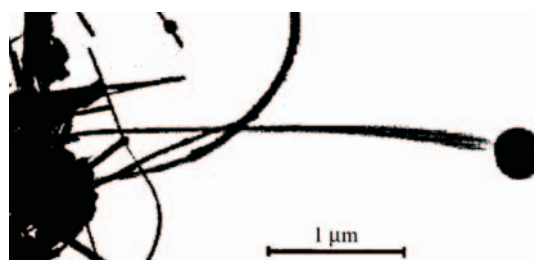
Fig. 12 Resonating carbon nanotube with a carbon particle to be weighed. Mass: 22 Femtogram. Courtesy of W. de Heer

field on Earth [35]. Thus, the sensitivity of that sensor is remarkably higher but the method is restricted to measuring mass changes of samples which are firmly connected to the sensor. Observing the frequency shift of oscillating carbon nanotubes (Fig. 12) or of silica nanorods it is possible to weigh the absolute mass or mass changes in the attogram [36] and even in the zeptogram region [37].

Recently cantilever systems, as used in the scanning tunnel microscope, have been used to determine masses down to that of a few molecules [36–39]. A micromechanical cantilever sensor consists of two major components, the cantilever that is used as transducer element and a coating [40]. The sensitivity of the sensor to different stimuli is specific to the type of coating. Arrays of micromechanical cantilever sensors can be integrated on a single chip in a small package of only a few cubic millimetres. Such an array of several micromechanical cantilevers may be made as a polymer brush. A nanomechanical resonator has been used to measure quantum effects of thermal Brownian motion [41, 42].

Conclusions

For seven millenniums the gravitational balance was the most sensitive measuring instrument. Measuring range and sensitivity were increased significantly within the last two centuries. Important progress has been made recently by application of vibrational systems. Up to now, no limitation of the application of instruments for direct mass determination has been found.

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