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New balance systems, apparatus and weight systems

THE IMPACT OF CONTROL ON THE DEVELOPMENT OF RECORDING BALANCES

Th. Gast

Fachgebiet für Mess- und Regelungstechnik der Technischen Universität Berlin
D-10787 Berlin, Germany

Abstract

I am honored by the invitation to give a lecture at this Conference on Vacuum Microbalance Techniques. I have very good memories of such meetings over 35 years, first in the USA, and then alternating in Europe and Africa. Those who have participated in several conferences of this series know that major developments from manually operated to automated balances have been presented there and documented in the Proceedings of these Conferences. I would like to give a few examples from my own work.

Keywords: beam balance, development of recording balances, magnetic suspension balance, microweighing, self-compensating vacuum balance

Introduction

In comparison with the long history of the balance as a means of mass determination, its development as a recording system took a relatively short time. Its importance increased with the demands on research and industry to develop new materials, processes and products. This involved the examination of the physical and chemical properties in substances corresponding to slow changes in mass.

The balance is a measuring instrument where resolution and accuracy are of special interest, though rapid data acquisition too is important. Basic research in scientific and industrial production-oriented laboratories requires automation of the measurement devices because of the demands concerning the short duration of the experiments, the multitude of measurement data, and the sophisticated methods of data evaluation. Application of feedback control provides optimization of the measuring process both technically and economically, in order to obtain results with an existing balance more rapidly and more accurately.

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Fundamental weighing principles

Three fundamental mechanical weighing principles based on gravity are

- deflection of a physical pendulum without or with a balance beam,
- dilatation of an elastic element, e.g. a helical spring,
- the torsion of a wire, band or fiber.

In all of these cases, the measuring process without feedback control requires a motion of the components of the balance, inclusive of the object. They must be accelerated and brought by deceleration into their final steady state, in which the measured result can be read.

Position-feedback control system

In the balance, e.g. a beam balance, is equipped with a position-feedback control system (Fig. 1), this process is performed more rapidly and more accurately, because the dynamic properties of the measuring instrument can be improved by some orders of magnitude. Hence, feedback control is in many cases a precondition of quasi-stationary recording. The disturbances Z_1–Z_3 signify errors which usually have to be avoided or corrected, e.g. Z_1=buoyancy. This disturbance quantity becomes measurable in gas density balances. Z_2 comprises the errors of the position sensor. These are suppressed by differential systems. Z_3 concerns the error of the current to force relation. Therefore, the actuator was dealt intensively in earlier stages of development. Suitable magnetic materials had to be chosen, and the design had to consider mechanical stability, economic production, and possibly special physical and chemical influences such as pressure, temperature and corrosion. The pot magnet is especially suited for top pan balances; the moving coil may be integrated into the balance beam, as it is sufficiently solid for the transmission of a considerable torque.

Another point of view was the double function of the moving coil as a torque motor and sensor, which could be achieved by carrier-operated inductive measuring methods. An inductive transfer method with a moving coil and a ferrite magnet (Fig. 2) is chosen to minimize eddy currents and to provide excellent long-term stability. Temperature drift needs correction. Later, this balance was improved with more powerful magnets and small rectangular stator coils.

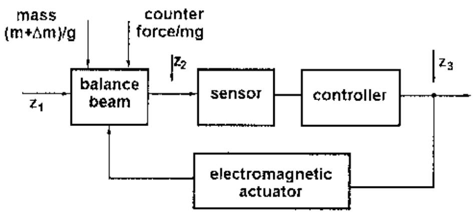

Fig. 1 Closed loop of the electromagnetic balance

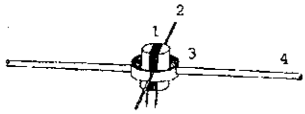

Fig. 2 Combined actuator and sensor: inductive transfer method; 1 field coil on ferrite magnet, 3 moving coil in quartz ring, 4 quartz tube balance beam

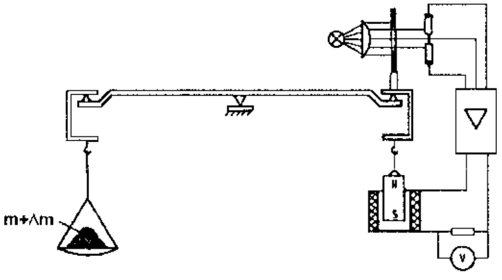

Fig. 3 Scheme of a self-compensating beam balance with optoelectronic position sensor

Figure 3 shows the scheme of an electromagnetic self-compensating balance with an optoelectronic position sensor. The controller generates the exciting current, whose voltage drop at a constant resistor is used for indication. The sensor is a differential one.

Self-compensating vacuum balance

In 1943, the author was commissioned to carry out research on the permeation of water vapour through cable-covering material. This required continuous ob-

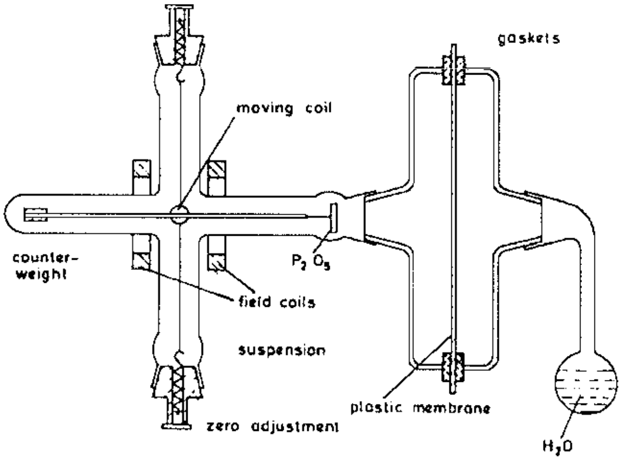

Fig. 4 Measurement of permeation

servation over days and even weeks. He therefore developed a self-compensating vacuum balance in a recording system (Fig. 4). The water permeates through the sample under a constant partial pressure difference. It is absorbed by a drying agent applied to the beam of a special vacuum balance. The recording allowed a survey of the permeation process and the recognition of steady-state conditions. Demands were high sensitivity, good zero stability and minimal error torque by sorption on beam and coil. A pair of Helmholtz coils outside the vessel generated a fairly homogeneous field with outstanding temporal constancy. The balance is insensitive to translations of the ribbon-suspended moving coil. Figure 5 shows such a balance, built in 1943 [1].

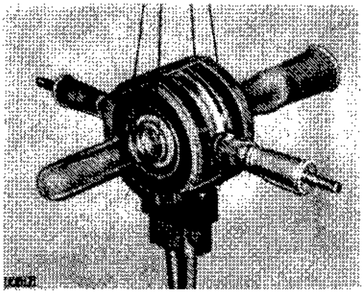

Fig. 5 Permeation balance with Helmholtz coils outside the vessel

For the automatic measuring of dust concentration, a self-compensating balance was developed (Fig. 6). The measuring cycle consists in printing the point of origin, electrical precipitation of the dust particles on a circular metal plate attached to the beam of an electronic microbalance, recording the mass of the precipitated dust and clearing the plate by a strip of velvet, which is simultaneously vacuum-cleaned. During the weighing, the target is completely shielded from the field of the precipitator. The load is compensated by twisting one of the suspension ribbons with the aid of a very efficient servo motor. The mean total power consumption is 1 W, including the precipitator. An example of application was dust measurement in mines.

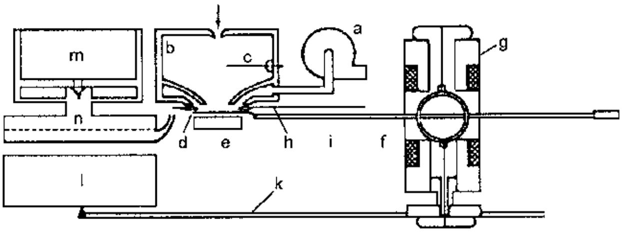

Fig. 6 Scheme of a dust balance; a – aspirator, b – precipitator, c – point, d – electrode, e – arresting plate, f – balance beam, g – microbalance, h – slide, i – velvet strip, k – writing point, l – recording drum, m – auxiliary aspirator, n – paper filter

Electronic nanogram balance

A further application is an electronic nanogram balance (Fig. 7), developed in the Institute for Measurement and Control, Technical University, Berlin, which was designed for the calibration of mg weights. The balance beam is a Zerodur plate, pivoted on edge in torsion bands and provided with etched coils which swing in the gaps of two pairs of horseshoe magnets.

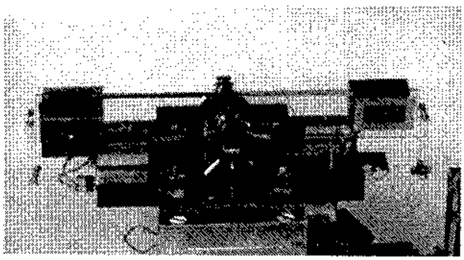

Fig. 7 Electronic nanogram balance

Simultaneous determination of mass and permittivity

The next application to be discussed here is the simultaneous determination of mass and permittivity. This is realizable with the aid of a self-compensating electronic balance. The measuring apparatus determines first the mass of the cylindrical or flat sample. An electrode system is then advanced, which produces a specially-designed electric field around the object. The resulting downward electrostatic force is measured with increased sensitivity and evaluated. A personal computer performs the control of the apparatus and the evaluation of the measured data [3].

Magnetic suspension balance

The special ability of feedback control to stabilize inherently unstable systems allows the hermetic separation of object and balance in physicochemical experiments. According to the Earnshaw theorem, a stable magnetic suspension is possible if one degree of freedom is blocked. This can be achieved by a string, which is of course not a frictionless connection. Magnetic forces, however, fulfil the same purpose if position feedback control corresponding to Fig. 8 is applied. The object is suspended from the lower magnet, and its weight is transmitted through the non-magnetic wall to the upper magnet, which is itself connected to the beam of the balance. Both magnets are partially shielded. An eddy current sensor is used for position control. This consists of a sensor coil around the pole of the upper magnet and a copper disk at the top of the lower magnet.

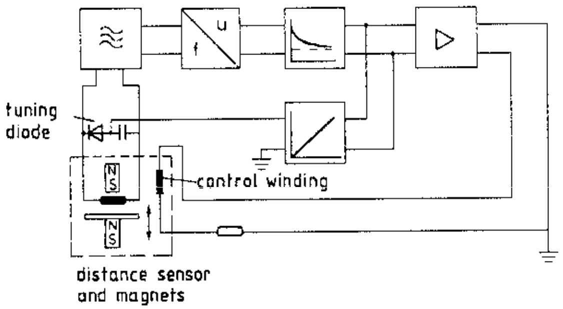

Fig. 8 Control loop of the magnetic suspension

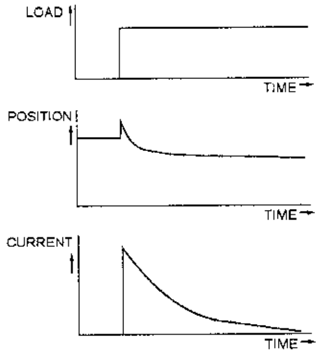

Fig. 9 Load, position and current in a magnetic suspension as a function of time

The quality of the suspension was improved by an auxiliary control loop with an integral step response that brings the exciting current to a set point, preferably zero. Figure 9 shows the decrease of the direct current component to zero, and thereafter only transient alternating currents flow through the control winding. Thus, excessive heating of the electromagnet is avoided. Figure 10 depicts a commercial suspension balance, with the casing removed. Many papers exist on research with the aid of these balances, which were first presented at Achema 1961 [4].

Suspension balance for microweighing

Two thin bar magnets are used for the coupling in order to minimize the weight of the suspended parts (Fig. 11). An optoelectronic feedback control circuit is provided for the magnetic suspension, where the pole distance of the magnets works as an aperture plate. For this reason, the coil has a central gap. In this device, the principle of vanishing direct current is also used. The symmetrical design allows the coil to be fixed at the frame if the current can be reduced far enough in the steady state.

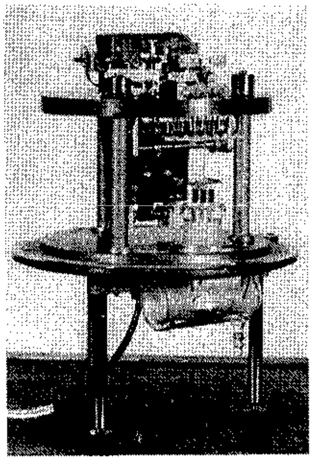

Fig. 10 Sartorius suspension balance with the casing removed

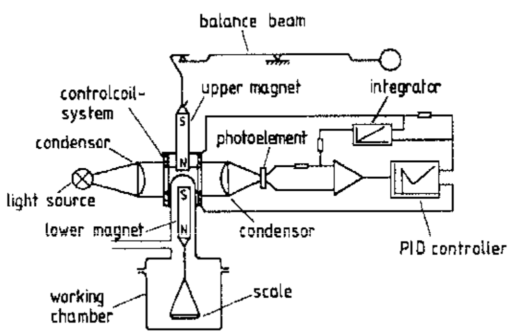

Fig. 11 Suspension balance with bar magnets

Top pan balance

In order to attain a magnetic coupling for a top pan balance (Fig. 12), two degrees of freedom were controlled independently of one another. With the aid of an optoelectronic sensor and four control coils, schematically shown in exploded view, a ring magnet was radially stabilized.

Suspended sphere

For the measurement of gas density with the aid of a freely suspended sphere, feedback control again allows stabilization of the equilibrium of inherently unstable systems on the basis of electrostatic or magnetic attraction. An example is

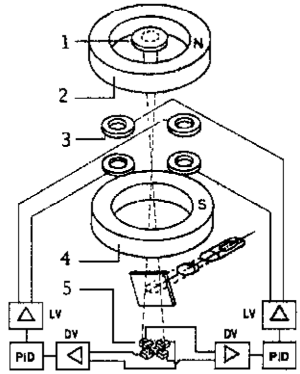

Fig. 12 Radially stabilized ring magnet; 1 – reflector, 2 – suspended magnet, 3 – control windings, 4 – carrying magnet, 5 – sensor diode

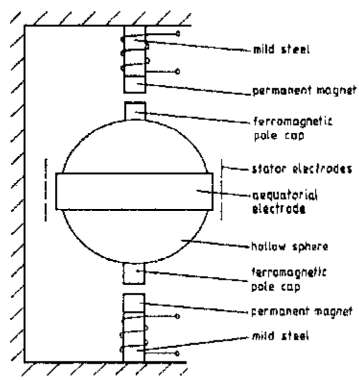

Fig. 13 Magnetic density measurement

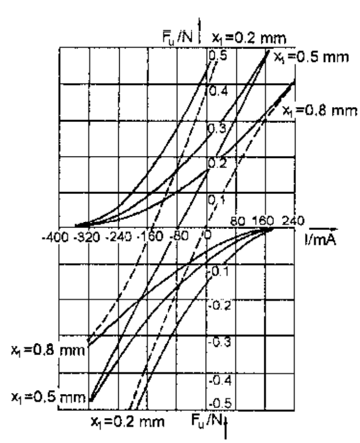

Fig. 14 Static characteristic of the magnetic suspension

presented in Fig. 13 [5]. A hollow glass sphere with attached soft iron poles is freely suspended between two biased electromagnets.

Such a system is stable with regard to radial excursions. It can be stabilized in the vertical direction with the aid of a capacitive sensor for the altitude in a feedback loop with the windings of the electromagnets. The sensor consists of a metal ring, fixed on the equator of the sphere, and three stationary ring-shaped electrodes connected to a differential transformer. It converts the position of the spheres into a linearly dependent signal, which is fed to a PID controller, whose output current excites the electromagnets (Fig. 14). The diagram shows the linear relation between current and buoyancy, which ensures a symmetric position of the sphere between the magnets.

Some years have passed since my co-workers and I have made such and similar developments. I am satisfied to see how well the work has been continued and I am eager to hear of further progress.

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