SENSITIVE MEASUREMENTS OF DISPLACEMENTS AND MASSES

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Introduction

Modern electronic balances use automatic compensation, that means, they work according to a closed loop. This loop, shown in fig.1, comprises a mechanical comparator, as f.i. a balance beam, converting

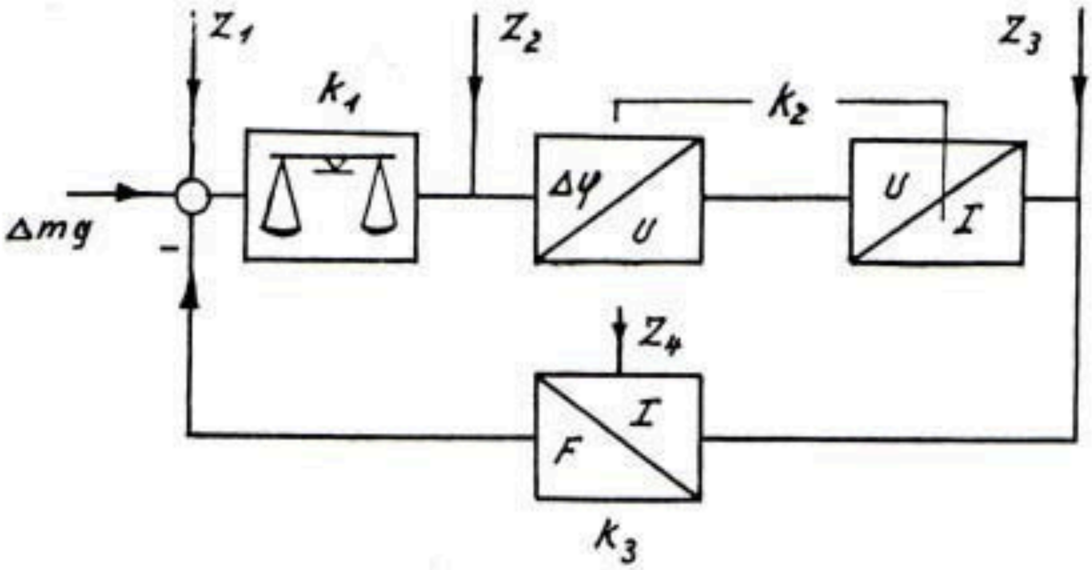

Fig.1 *Closed loop of the automatically compensating balance*

differences of force into angular displacements, a force motor, supplying a counterforce and a displacement sensor, converting angular deflections or translational displacements into electric signals. The sensor is usually followed by an amplifier with certain desired transfer functions.

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The output current of the system shown in fig.1 obeys the equation

$$I = \frac{1 - \frac{1}{k_1 k_2 k_3}}{k_3(1 + Z_4)} \{ \Delta m \cdot g + Z_1 + \frac{1}{k_1} Z_2 \} + Z_3 \qquad (1)$$

where k_1 is the sensitivity of the balance beam (rad/N)
k_2 is the conversion constant of sensor + amplifier (A/rad)
k_3 is the conversion constant of the force motor (N/A)
Various causes may exist for the disturbance quantity Z_1 which could be an additional electrostatic, magnetic or convection force. Such forces cannot be distinguished from the weight to be measured and therefore are not corrigible. (1)

Further causes may be thermal expansion of the balance beam under constant load, or variations of length by relaxation processes. This has to be considered in design of the beam and choice of materials. Newtonian friction is avoided in modern balances with elastic joints or taut band suspension.

The disturbance quantity Z_2 arises from drift in the sensor or the amplifier. It can be refered to the input of the sensor. According to equation (1), the influence of Z_2 decreases with increasing k_1. Indifferent equilibrium would be optimal in this respect. This should be also considered in design.[1]

Z_3 is a disturbance signal acting upon the output and cannot be distinguished from the wanted signal. Insulation and shielding is helpful in this respect.

The disturbance quantity Z_4 is due to the influence of temperature on the magnetic flux of the force motor. It is usually corrected by a magnetic shunt with temperature dependent permeability.

The second member of the numerator in equation (1) contains the transfer coefficients of the balance beam, the sensor + amplifier and the force motor. We assume, that all disturbance quantities are zero and that $\frac{1}{k_1 k_2 k_3} \ll 1$ holds. Logarithmic differentiation yields

$$\frac{dI}{I} = \frac{kd_i}{k_i} \cdot \frac{1}{k_1 k_2 k_3} \qquad (2)$$

the influence of variations in each coefficient k_i decreases with increasing product of the coefficients. Because k_3 is determined by the desired sensitivity of the balance

$$\frac{dI}{dm} \approx \frac{1}{k_3} \qquad (3)$$

by reasons of load capacity and durability, the constant k_2 should be made as large as possible.

Thus, high sensitivity and small drift of the sensor are required for automatically compensating balances of high quality. Efforts in the development of sensors for this special purpose could provide solutions for displacement measuring problems in general.

Selected examples of displacement sensors are treated in the following section in connection with balance systems.

Capacitive displacement sensors The parallel plate capacitor appears at first sight as a very simple and cheap sensor. If fringing is neglected, the capacity C obeys the equation

$$C = \varepsilon\varepsilon_o A/a \tag{4}$$

where A is the area, a the distance of the electrode, ε_o the field constant and ε the permitivity of the material between the plates. The sensivity to variation of distance increases with approaching plates.

$$\frac{dC}{da} = -\frac{C}{a} \tag{5}$$

Because the maximum deflection depends on the clearance between the electrodes and the area of the electrodes is restricted by reasons of design, the capacity of such sensors is in the picofarad range. Thus, changes in cable capacitance can present serious problems, if no special measures are taken.

Such transducers are suitable for modern electromagnetic balances with parallel movement of pan and force coil by guiding levers.

A serrated cylindric capacitor as used in an experimental top balance is shown in figure 2. The sensitivity is given by the equation[2]

$$\frac{dC}{ds} = 2\pi\varepsilon\varepsilon_o \left(\ln\frac{r_a}{r_i}\right)^{-1} n \quad 2\pi r_i \varepsilon\varepsilon_o \frac{n}{r_a - r_i} \tag{6}$$

where n is the number of grooves. In the differential capacitor shown in the figure, two stator tubes are arranged in such a manner, that the capacitances vary in opposite sense, if the inner electrode is deflected. The stationary electrodes are connected to the ends of the symmetrical secondary winding of a transformer which is excited by an alternating voltage source. The center tapping of the secondary winding is grounded. Opposed currents flow over the partial capacities of the sensor to the input of the amplifier. In the neutral position of inner electrode, the currents cancel. By deflection, a signal arises at the output of the amplifier which converts current to voltage and has a negligible input impedance. The conversion constant shall be Z.

$$U = (\Delta I)Z = U_o \omega\varepsilon\varepsilon_o \, 4\pi \left(\ln\frac{r_a}{r_i}\right)^{-1} Z n \Delta l \tag{7}$$

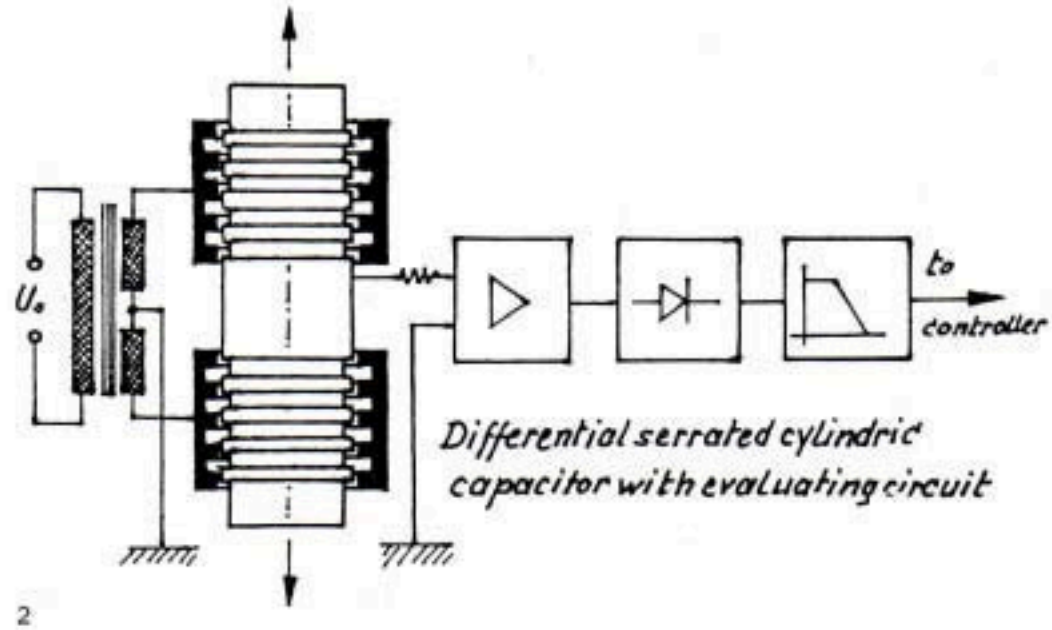

Fig. 2

The transformer has a ratio 1 : 1 : 1.

The signal is rectified with respect to phase and filtered. It can serve for indication and control purposes. The capacities between core and metal sheaths of the cables connecting stationary electrodes and transformer do not influence the indication, because they only shunt the secondary windings. There is also no influence of the cable capacity of the connection between the movable electrode and the amplifier, because this capacity shunts an input with zero impedance. The transformator can be replaced by an amplifier plus inverter. In order to eliminate the influence of ω, capacitive feedback of the amplifier can be applied, i.e. $Z = 1/\omega C$.

Differential capacitive sensors can serve simultaneously as displacement indicator and electrostatic force motor for ultramicrobalances. A very sensitive circuit for measuring the displacement of the central electrode in a differential parallel plate capacitor is shown in fig.3. Two sources of equal and opposed voltages $+U_o$ and $-U_o$ are connected in series. The sum 2U is applied to the outer electrodes of the sensor by the switches S_1 and S_2 during one half period of a controlling square wave voltage.[3]

During the next half period, the electrodes are connected to ground. Thus, a signal arises between the central electrode of the capacitor and

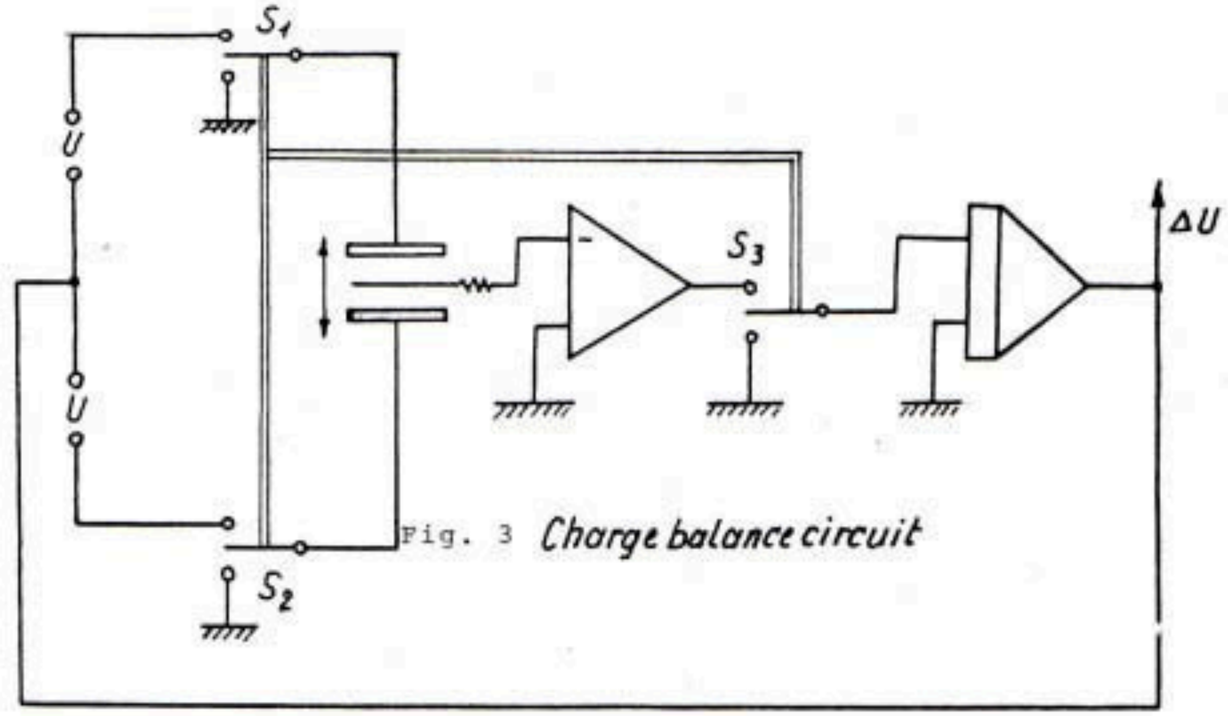

Fig. 3 *Charge balance circuit*

ground, which depends on the partial capacities of the sensor and the potential of the connection between the voltage sources.[3] In the first half period of the controlling voltage, this signal is fed to the input of an integrator by way of an amplifier and the switch S_3. During the next half period, the input of the integrator is grounded. The output of the integrator is connected to the junction of the voltage sources. The charges on the partial capacitors are equal, if S_1 and S_2 are in their upper position. In the steady state, no signal arises at the input of the integrator, therefore

$$Q_1 = U_1 C_1 = Q_2 = U_2 C_2 \qquad \text{and} \tag{8}$$

$$U_1 = U + \Delta U \; ; \; U_2 = U - \Delta U \tag{9}$$

Combining (8) and (9) and equation (4) we obtain

$$\frac{U + \Delta U}{a + \Delta a} = \frac{U - \Delta U}{a - \Delta a} \tag{10}$$

resulting in

$$\frac{\Delta U}{U} = \frac{\Delta a}{a} \tag{11}$$

Because $$\frac{U + \Delta U}{a + \Delta a} = E_1 = \frac{U - \Delta U}{a - \Delta a}$$

the electrostatic forces on the central electrode corresponding to the respective field strengths E_i cancel in the steady state, whereas the circuit of fig.3 sould generate negative restoring forces if applied to a differential plate capacitor.

With equal voltages $U = \pm 10$ V and an assumed drift of the amplifier of ± 1 µV, a resolution of 10^{-6} is attainable, which corresponds to a displacement of 1 nm = 10^{-9}m, if the distance between the electrodes is 1 mm.

Inductive displacement transducers

In balances with resolutions down to 1 mg, inductive displacement transducers with movable ferromagnetic cores can be used, because the forces onto such cores caused by external magnetic fields can be kept in an innocous range. If, however, micrograms have to be detected, no highly permeable moving parts are tolerable in the inductive sensors. Some examples of differential inductive displacement sensors without movable permeable material are discussed in the following section.

The sensitivity of these devices is enhanced by high carrier frequencies, small bandwith being ensured by a lock in amplifier.

The first example is a sensor for angular displacement, currently in use for commerical ultra microbalances. It is shown in figure 4. A rectangular coil, which is attached to the balance beam and suspended by thaut-bands is movable in a permanent magnetic field. The winding con-

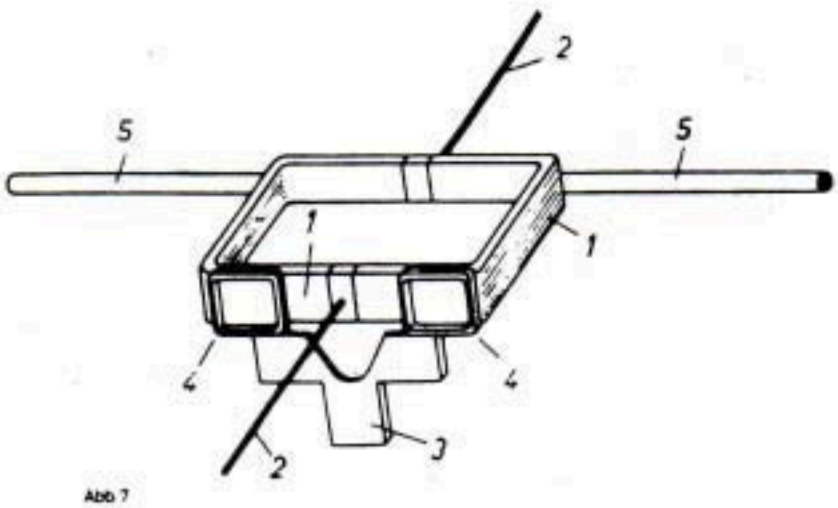

Fig. 4 Position Sensor of a Ultramicrobalance
1) Moving coil 2) Taut band suspension
3) Support 4) Sensor coils
5) Balance beam

stitutes not only the essential part of a torque motor, but it serves also as the secondary winding of a transformer with variable mutual inductance. Two small square coils acting as primary windings are attached to the base plate of the system by a common support. The distance between these coils and the front of the moving coils is about 0.2mm.

The square coils are antiserially connected. Thus, if the moving coil is in its horizontal position, the mutual inductance between the set of small square coils and the moving coils is zero. Small horizontal and vertical displacements of the moving coil produce no effect. If the moving coil is however tilted, a mutual inductance proportional to the deflection arises. Thus, if the small coils are excited by a high frequency current, a synchronous voltage at the leads of the moving coil, proportional to the inclination of the balance beam is obtained. By amplification and phase sensitive rectification, one can detect deflections as small as 10^{-5} rad. A balance based on this principle has a sensitivity of 10 digits per µg. It serves for gravimetric experiments in controlled atmospheres and also as a symmetric ultra-microbalance for weight determination in air.[4]

Another type of ironless inductive sensor is shown in fig.5. The primary winding is horizontally mounted and excited by a high frequency current, while the secondary winding is vertically mounted. Because of the symmetrical arrangement of the two coils the mutual inductance is zero.

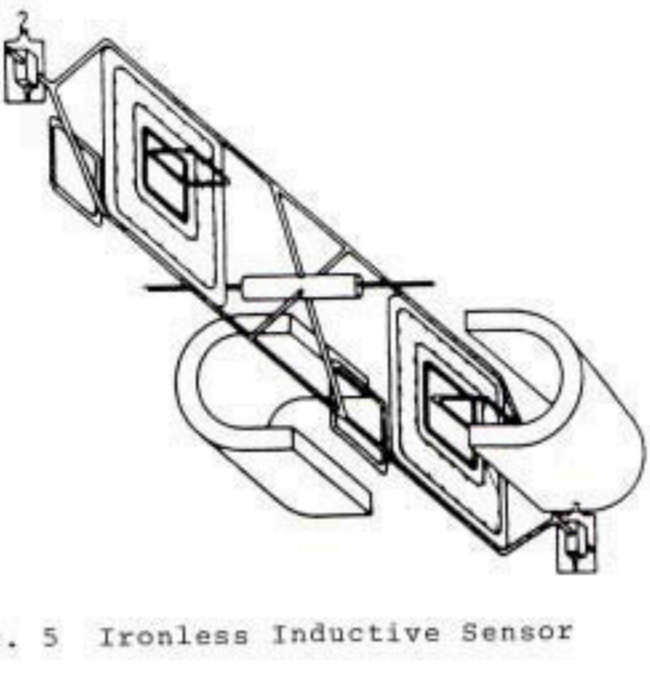

Fig. 5 Ironless Inductive Sensor

A displacement sensor can be derived from this arrangement by inserting a vertical short circuit-ring between primary and secondary winding, parallel to the secondary. This ring is photoetched on a quartz plate, which is incorporated in the frame work of a balance beam. The quartz plate also serves as substrate for an etched winding as a moving coil in the magnetic field of two horseshoe magnets. The beam is symmetrically designed, i.e. one quartz plate with ring and coil is mounted on each end. If the beam is tilted, an alternative current is induced in the rings and this current induces a signal in the secondary windings.

Again, a direct current voltage proportional to the deflection is obtained by amplification and phase sensitive rectification of the induced signal. Because of the symmetrical arrangement, horizontal or vertical displacement of the beam in its taut-band suspension also rotation of the beam around a vertical axis produces no signal.

A balance of this design has a sensitivity of 100 digits per microgram.[1]

Differential variable reluctance sensor

For another measuring system, that is a very sensitive differential manometer, a displacement sensor had to be developed[5] Fig.6 is a schema-

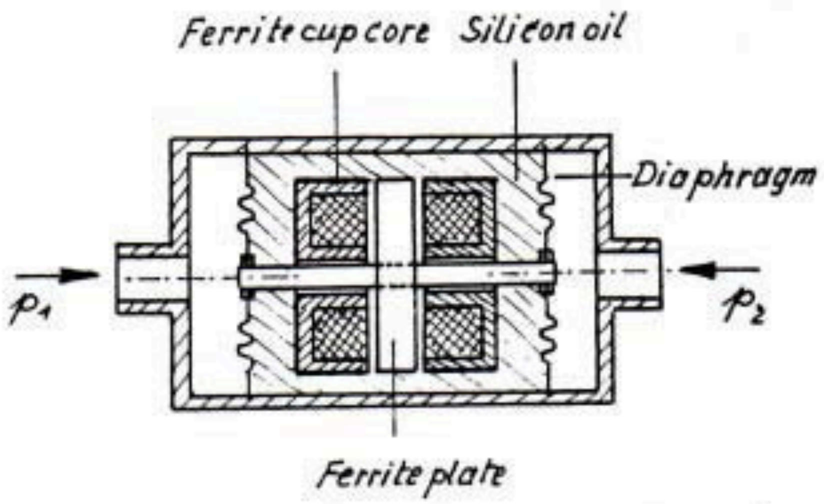

Fig. 6 Inductive differential pressure transducer

tic drawing of the sensor. It consists of two ferrite cup cores, mounted with open ends opposed. A disc of ferrite is fastened to a shaft which traverses the central holes in the cores. The disc is held in position in the gap between the cup cores by two membranes which are exposed to the pressure to be compared. With equal pressures, the disc is held in the middle of the gap between the cores.

Thus the reluctances are equal in both cores and likewise the inductivities of both windings. The windings are connected as branches of a

Wheatstone bridge. They are tuned by capacitors in such a way, that the frequency of the supply voltage corresponds to points of inflection on the same side of the resonance curve in both resonant circuits. In order to avoid fine adjustment of the inductivities, the frequency of the oscillator can be digitally adjusted. The bridge is highly symmetrical. Common mode disturbances by the influence of temperature on dimensions, permeability of the cores, resistivity of the windings and permittivity of the dielectric in the capacitors are suppressed. The sensor can detect displacements down to 1nm which correspond to pressure differences in the range of 1 μm water column or 10 m Pa. If the ferrite disc is replaced by a copper plate the displacement sensitivity is reduced, but the system is now insensitive to magnetic fields acting on the movable part, and could be utilized for balances. Calibration of the displacement sensor has been carried out by utilizing the elastic line of a beam, which is clamped at one end and deflected at the other end by a micrometer screw as shown in Fig.7.

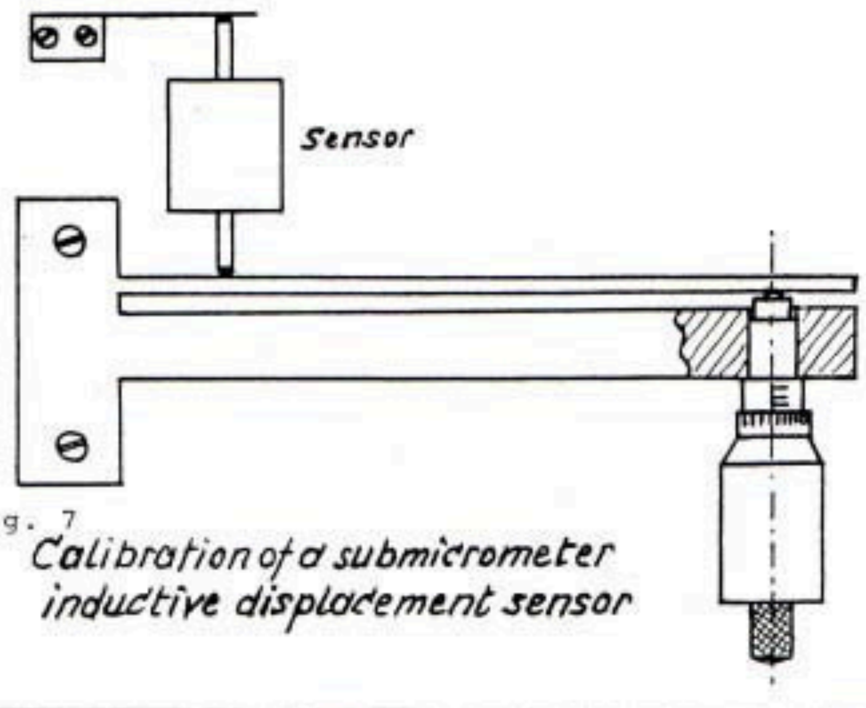

Fig. 7
Calibration of a submicrometer inductive displacement sensor

The sensor is pressed against the beam at such a distance from the end of fixation, that a reduction of 1 : 100 is obtained.

Because of the parabolic shape of the elastic line, a reliable reduction can be performed without exacting the mechanical system.

Photoelectric displacement sensors

These sensors have been applied in electromagnetic balances very early. They excel by the absence of reaction forces, if light pressure and radiometer forces are excluded. These would disturb only very highly sensitive instruments, because a first order compensation by symmetrical arrangement can be usually provided.

Three types of photoelectric displacement sensors will be discussed. With the first, a parallel bundle of rays from a light source, f.i. a light emitting diode is directed against a differential photo-diode, as it is shown in fig.8. A narrow reed, fixed to the object, is displaced across the surface of the diode, so that its shadow falls in each half of the cell.[6]

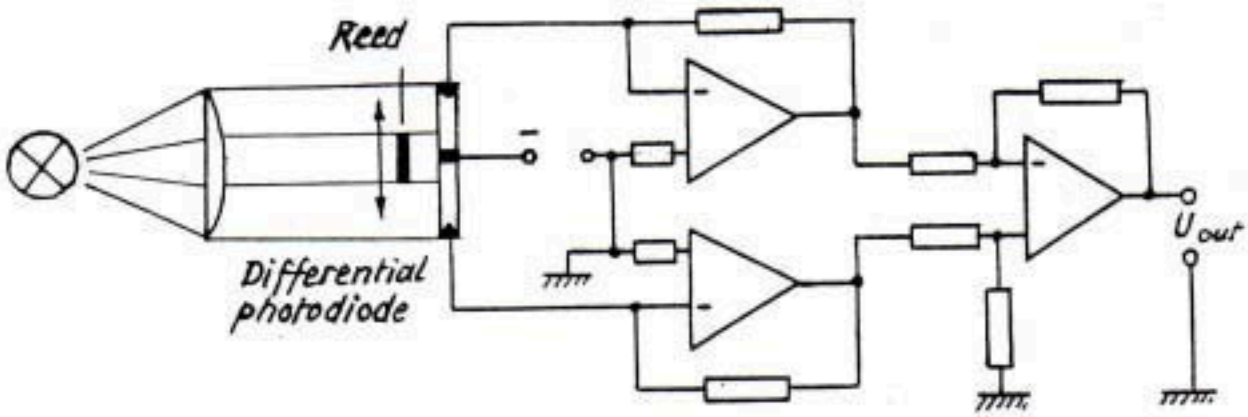

Fig. 8 Differential photoelectric displacement sensor

The difference of the photocurrents is formed with the aid of an instrumentation amplifier. The height of the diodes is h, the width of each diode d, the width of the reed s, the width of the insensitive section between the diodes e, the illumination of the surface of the diodes E_v and the sensitivity of each diode E_d. On the assumption, that the illumination and the sensitivity are constant over the surface of the differential diode, we obtain a difference of currents

$$\Delta I = E_d E_v \Delta A = E_d E_v h \{(d - \frac{s-e}{2} + x) - (d - \frac{s-e}{2} - x)\}$$

$$= E_d E_v h \, 2 \, x \qquad (12)$$

If we utilize the device for a selfcompensating balance with integral action, the load is always fully compensated, ΔI will be zero, x disappears, there is no influence of the illumination E_v or the sensitivity of the diodes on the indicated weight. In order to eliminate any changes in I caused by a variation of E_v, E_d and the transparency of the optical path even for finite deflections, a control circuit could be set up, which keeps the sum of the currents I_l and I_r constant. The current supplied to the light source serves as correcting variable. The sum of the currents of the differential diode is

$$\sum I = E_d E_v \sum A = E_d E_v h \{ 2d-(s-e) \} \tag{13}$$

and for the ratio of ΔI and $\sum I$ we obtain

$$\frac{\Delta I}{\Sigma I} = \frac{x}{d-\frac{(s-e)}{2}} \tag{14}$$

If ΣI is kept constant, no influence of the discussed parameters exists. The linearity is very good, the zero stability is excellent. Drift is in the range of nanometers for carefully designed sensors of this kind. The same results are obtained, if the reed is replaced by a slit diaphragm.

Gratings can be also used for sensitive measurement of small deflections. If two gratings of the same period are put together with the respective stripes parallel to one another, periodic brightening and obscuration accurs with relative displacement. The displacement necessary for one period of intensity variation depends on the angle between the direction of displacment and the elements of the gratings. Theoretically it is variable between one and infinite as shown in fig.9.

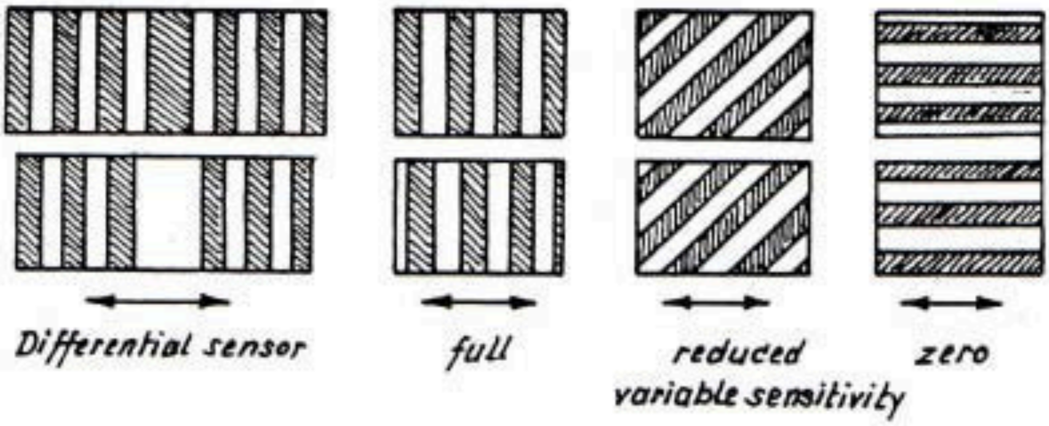

Fig. 9 *Optical displacement sensor with gratings*

The system can be as well used for analogous sensing as for digital measurement. A differential arrangement with a phase jump in one of the gratings allows rather large photodetectors to be used.

Because of the averaging in the formation of the signal, such devices can be very accurate.

If the respective lines of the gratings include a small angle, moire fringes are observed. The fringe pattern moves in a direction perpendicular to displacement. For small angles α of inclination, the magnification is $m = 1/\alpha$. The moire fringes can be detected by photoelectric devices. Analogous and digital evaluation is possible.

Optical interferometers belong to the most accurate measuring devices for translational and angular displacements. In connection with balances, they are f.i. used for prototype weighing. A new device for the comparison of kg-prototypes also uses an interferometer. The principle is shown in fig.10. A system of 6 floats is submerged in water which is contained in a ringshaped vessel. The floats are attached to a ring, which is connected to a platform above the vessel by three stainless steel wires. The wires penetrate the surface of the water. The system is balanced in such a way, that the water level intersects the mid of the wires if a 1 kg piece is put on the scale pan. The sensitivity is determined by the diameter of the wires and the density of the water according to the equation

$$E = \frac{\Delta h}{\Delta m} = \frac{1}{\rho q} \tag{15}$$

Because the total cross section q of the wires is about 2.5mm, it results

$$E = 0.4\ \mu m/\mu g$$

If 1 μg is to be detected, the altitude of the platform has to be measured to fractions of micrometers. A Michelson interferometer is used for this purpose, the triple mirror attached to the platform as it is to be seen in fig.10.[7]

The deflection of the platform can be measured in the following way: A two frequency laser emits a right-hand polarized and a left hand polarized wave with a frequency difference of 1.8 MHz. The laser beam is expanded by a telescope and passes a beam splitter, where a reference beam is branched to a photodiode. The diode forms the difference signal f_1-f_2 which is amplified, doubled and fed to a forward counter. The undeflected beam is split by a second beam splitter. As we see, the horizontal beam passes a polarizing filter which selects one direction of circular polarization and is reflected to the beam splitter. As we see, the horizontal beam passes a polarizing filter which selects one direction of circular polarization and is reflected to the beam splitter by the reference triple mirror while the downard beam passes a polarization filter which selects the other direction of polarization and is reflected by the movable triple mirror attached to the platform. The reflected beam is reunited with the first beam and both are received by the second diode. A signal is produced, whose frequency depends on the velocity of the movable reflector according to the Doppler effect. The signal is processed in the same way as the first one. If the difference of the two counts is taken, a measure for the displacement of the movable reflector results.

Because the light source is stationary, a Doppler frequency

$$\nu = \nu_o \left(1 + \frac{W}{C}\right) \tag{16}$$

i obtained, where ν_o means the frequency of the light source selected the polarizing filter, w is the apparent velocity of the detector

$$w = 2\, w_R \tag{17}$$

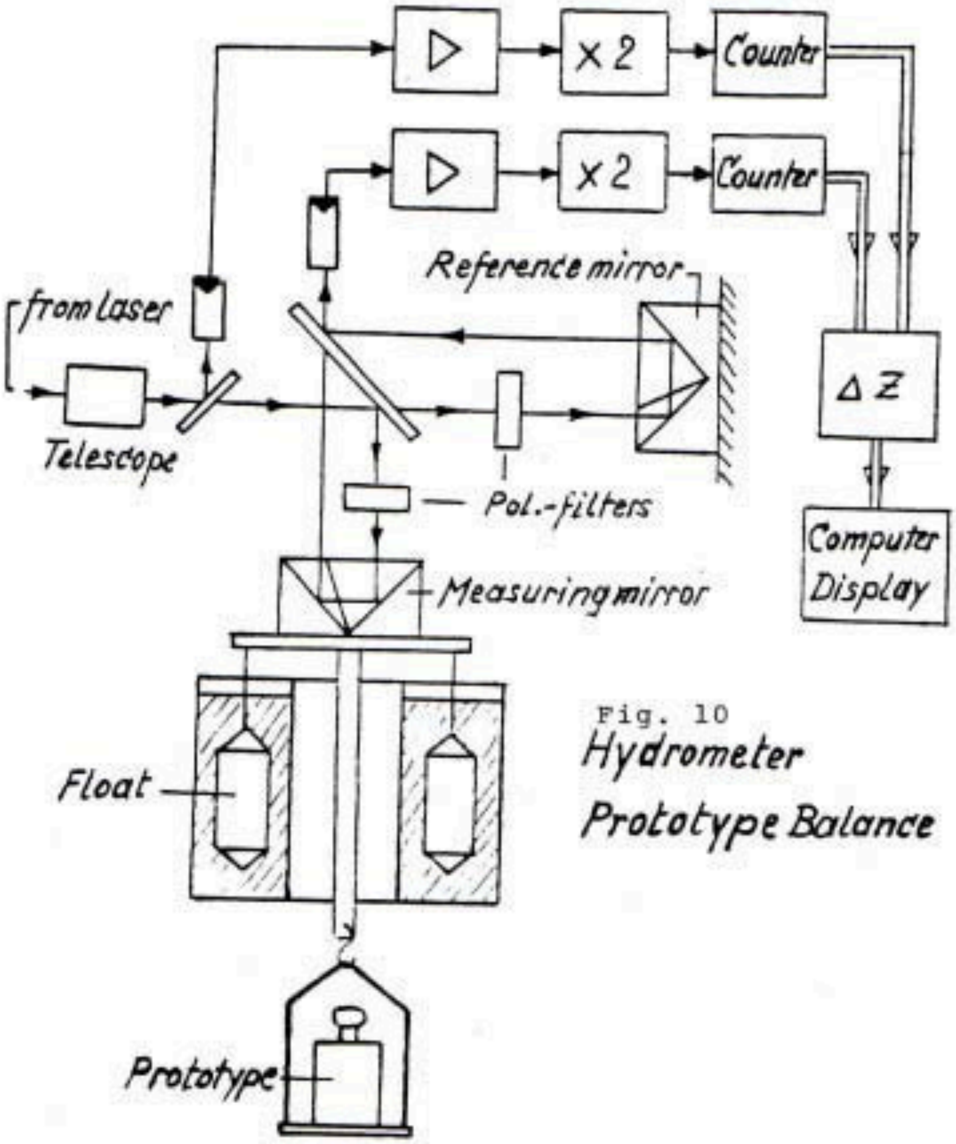

Fig. 10
Hydrometer
Prototype Balance

where w_R is the velocity of the triple mirror at the platform. Thus, the frequency difference of the measuring beam and the reference beam will be

$$\nu_1 - \nu_o \left(1 + \frac{W}{C}\right) \tag{18}$$

The frequency of the corresponding signal is doubled and the periods are counted. The result is for a time interval Δt

$$Z_2 = 2\{\nu_1 - \nu_o(1 + \frac{W}{C})\}\,\Delta t \tag{19}$$

Likewise we obtain for the signal from the first diode

$$Z_1 = 2\,(\nu_1 - \nu_o)\,\Delta t \tag{20}$$

The difference of the counts is

$$Z_2 - Z_1 = 2\,\nu_o\,\frac{W}{C}\,\Delta t \tag{21}$$

Considering, that

$$W \cdot \Delta t = 2\,\Delta 1 \tag{22}$$

where 1 is the displacement of the triple mirror and

$$\frac{2\,\nu_o}{c} = \frac{2}{\lambda} \tag{23}$$

we obtain

$$\Delta 1 = (Z_2 - Z_1)\,\frac{\lambda}{4} \tag{24}$$

The wavelength of the laser is approximately 0.63 µm and the resulting resolution of 0.16 µ is sufficient for the comparison of prototypes with the aid of the described device.[7]

A look at fig.11 will observe the moving coil system already discussed, a bar magnet in a cylindric coil operating as force motor, the electrodynamic system, used in the modern precision top pan balances and a promising flat coil system with cobalt-samarium magnets which produce high flux density in a very simple arrangement.

Suspension balances

With the balances consisered, the moving parts of the force motor are mechanically guided by a balance beam, parallel springs or other devices.

Electronic microbalances have been widely used for physical and physicochemical experiments, measuring sorption, diffusion, reaction kinetics and pyrolysis.

There are however cases, where the atmospheres in such experiments or the decomposition products of the sample are corrosive or contaminating. Thus it would be desireable to separate the balance and the sample completely.

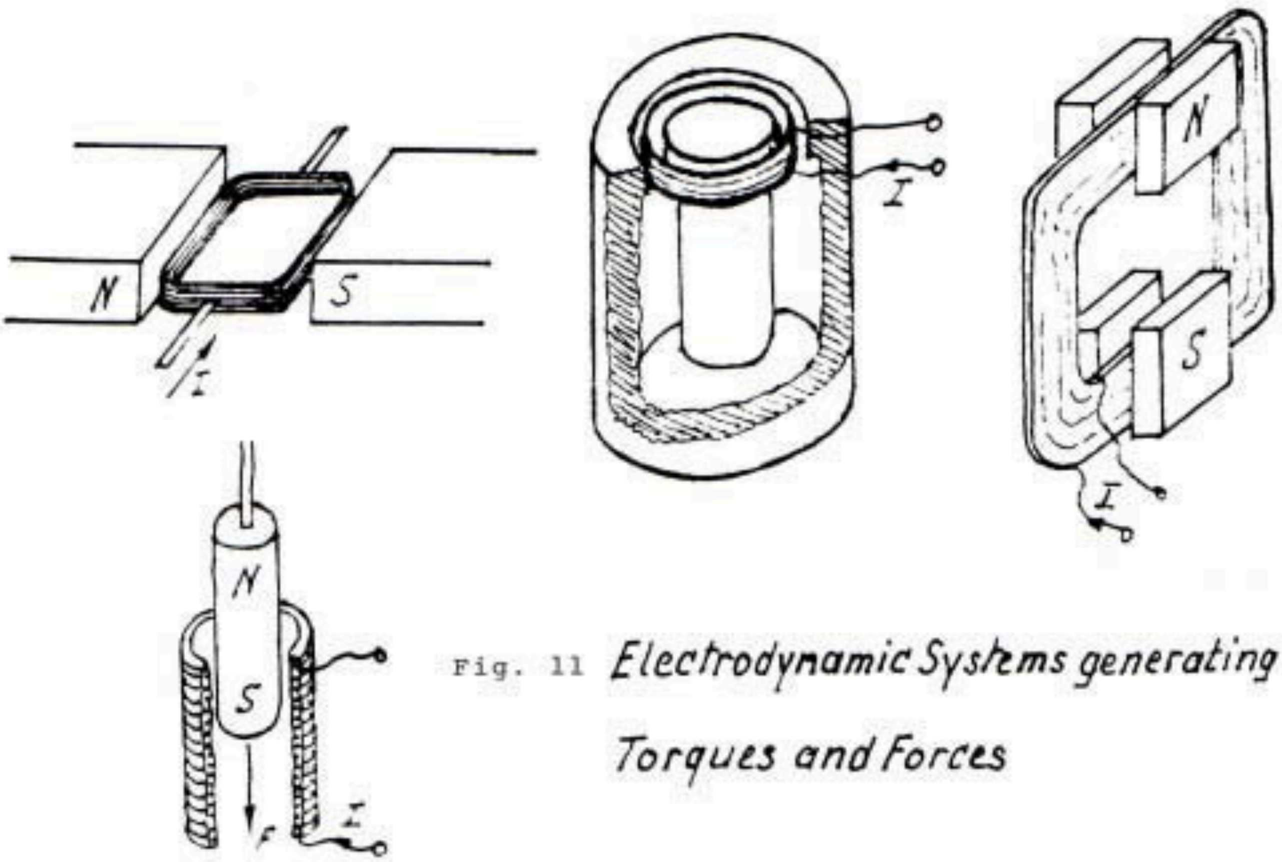

Fig. 11 *Electrodynamic Systems generating Torques and Forces*

Free magnetic suspension is the solution to such problems. Fig.12 shows examples of conceivable suspensions.[8]

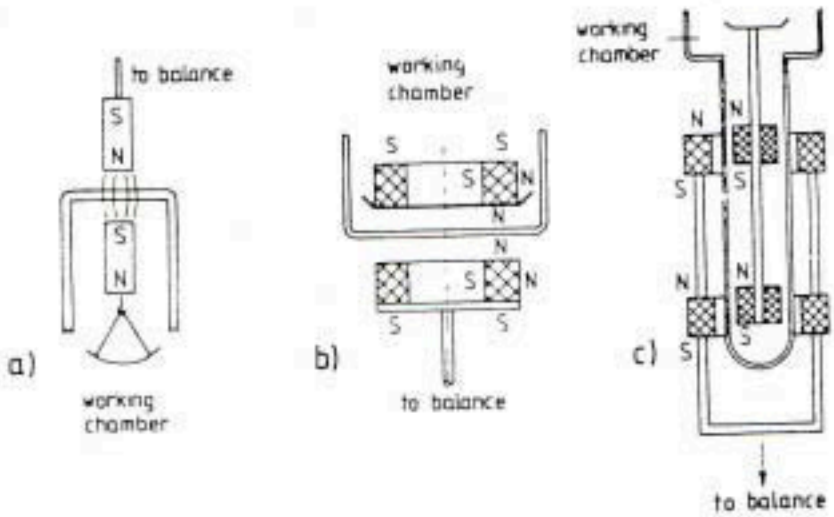

Fig.12 Modes of magnetic suspension as device for weighing

The first is based on attraction, the second on repulsion, the third on repulsion or attraction in different coordinates. In the case of the attracting magnets, the force distance-relationship is a hyperbola as shown in fig.13 and the superposition of the magnetic forces by gravity leads to a curve of potential energy as a function of distance with a maximum. This indicates instability. At least one degree of freedom has to be stabilized by an independent restoring force, to obtain a stable magnetic suspension. If, for example, a section of the force distance curve is inverted, as the dotted line indicates, a minimum in the curve of potential energy appears, which signifies stable suspension. This can be realized by automatic control.

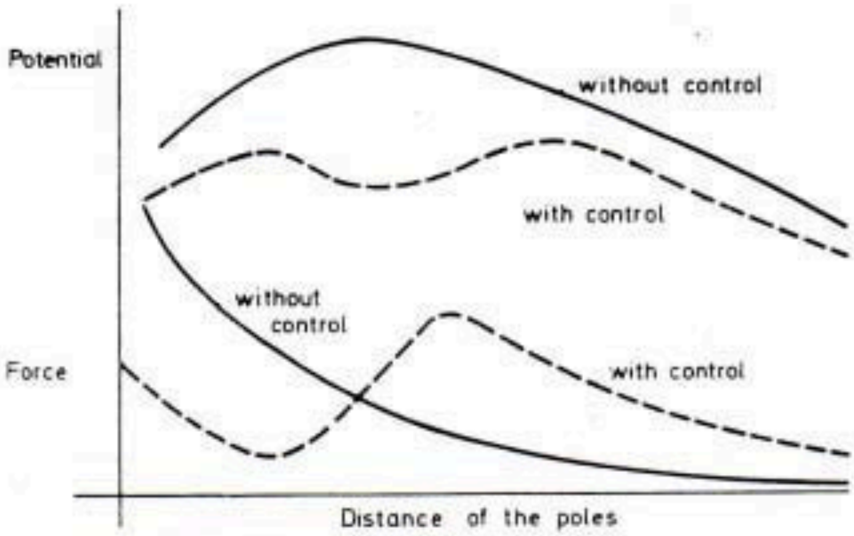

Fig. 13 Forces and potentials with magnetic suspensions

We will now discuss a suspension system according to fig.12a used as a coupling between a recording balance and a balance pan. The reaction vessel is provided with a glass window at the upper side. It is shown in fig.14, that the upper bar magnet is provided with a control winding and an iron mantle. The controlling current through this winding decreases or increases the attraction force onto the lower magnet. In order to measure distance, a pair of flat coils is used, acting as a transformer with variable mutual inductance. One coil encircles the lower pole of the upper magnet, the other the upper pole of the lower one. The upper coil is included in the resonant circuit of an oscillator whose frequency consequently depends on the distance on the coils. The relationship depends on the load applied to the lower coil. If the coil is shorted or replaced by a copper ring, the frequency rises with approaching coils. The reverse relationship is obtained by capacitive tuning of the lower coil. Both are shown in Fig.15.

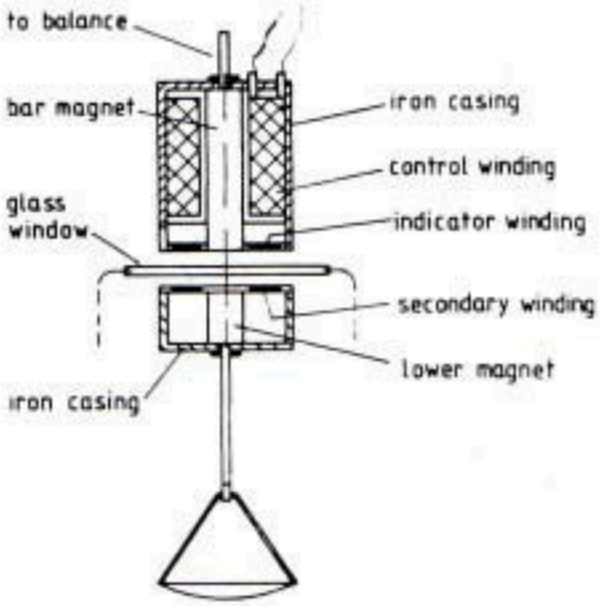

Fig. 14
Suspension system with two-coil distance sensor

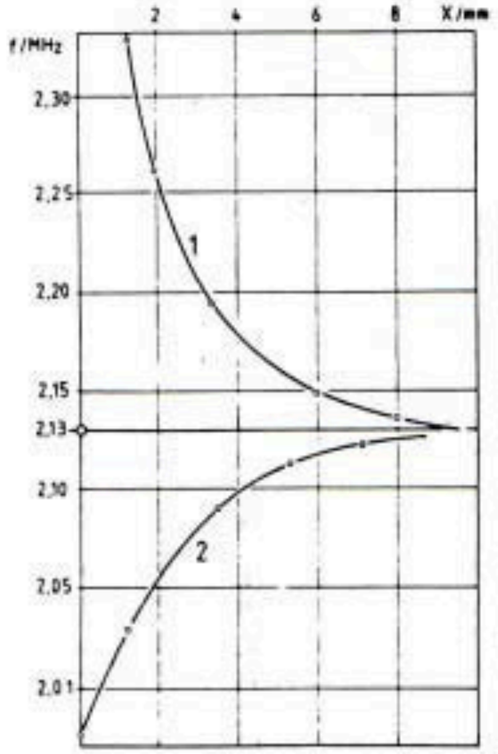

Fig. 15
Frequency as function of distance
1 Coil disc-arrangement
2 Disc replaced by tuned coil

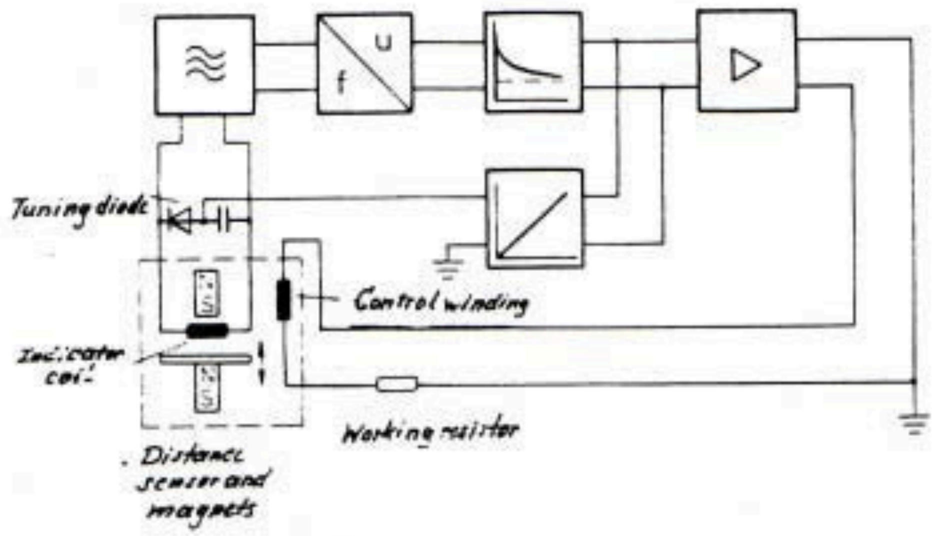

Fig 16 Distance control of the suspension system

Figure 16 represents the distance control circuit of the described magnetic suspension. The signal of the oscillator is fed to a discriminator, where the deviation from the set value is converted to a voltage as input of a PD-controller which is followed by an amplifier. Its output current controls the winding of the displacement sensor decreases with increasing distance. Provided that the discriminator, the controller and the amplifier are linear, a nonlinear relationship between distance and force results. The output of the controller is also fed through an integrator to a varactor diode connected in parallel to the sensor coil. By this measure, the set value of the distance is adapted to load. If the load is changed, the PD controller at first varies the control current in order to maintain equilibrium. The corresponding signal at the output of the controller now causes the voltage at the varactor diode to alter until the distance has attained the value, where the upper magnet carries the lower without any aid by the control winding.

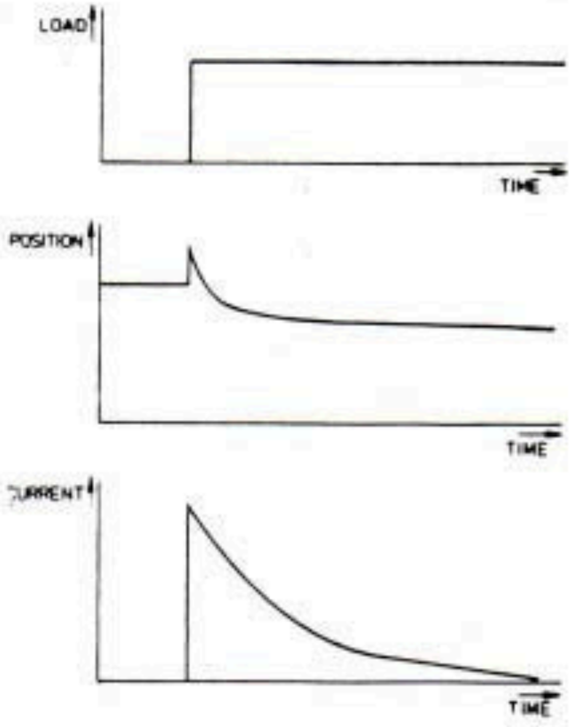

Fig. 17 Additional Control Operation

The course of this additional control operation is presented in Fig.17. A positive step in weight causes a slight increase in distance which effects a pronounced rise in current. Immediately, the integrator varies the control voltage of the varactor, the distance decreases and reaches an equilibrium where the current is zero again. Fig.18 shows, how the magnetic coupling is attached to a balance beam. The balance is

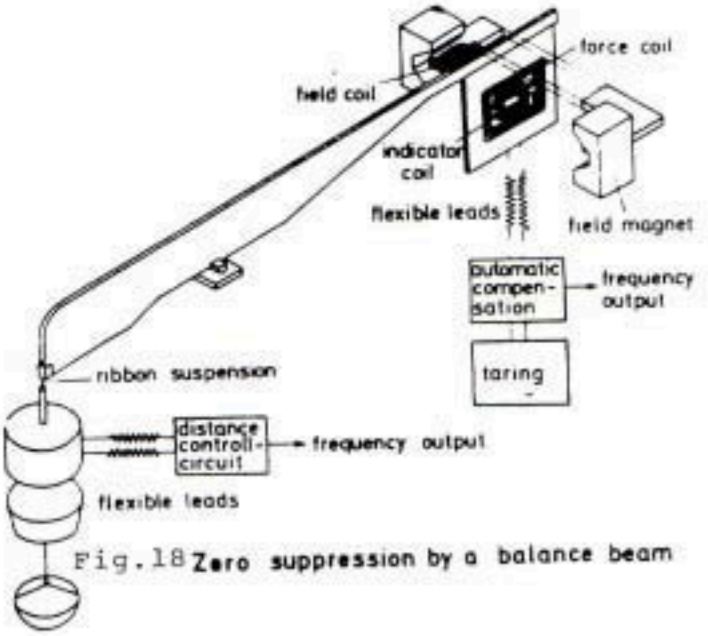

Fig.18 Zero suppression by a balance beam

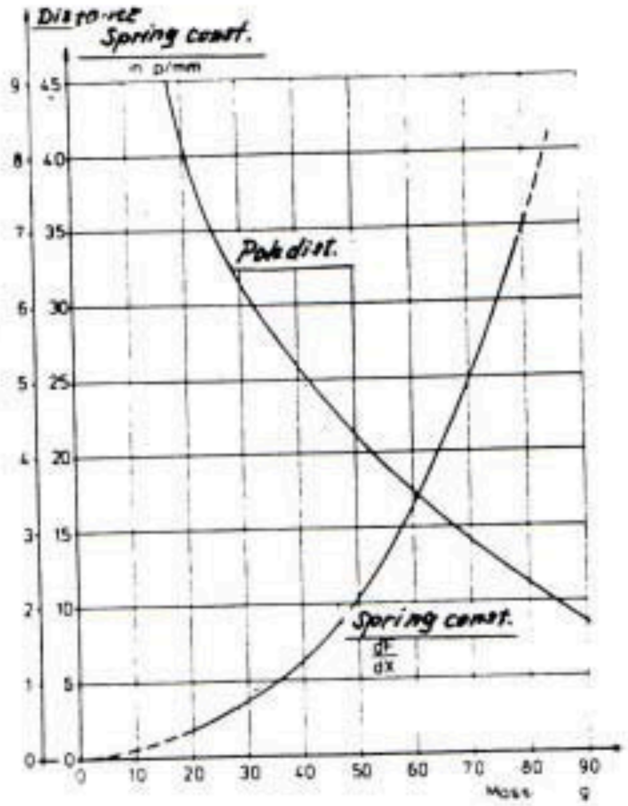

Fig. 19
Parameters of the Suspension

selfcompensating. For this purpose, a force coil and a sensor coil are affixed to the opposite ends of the beam. Frequency outputs are indicated as a hint to telemetry. The balance beam allows to compensate the weight of the magnetic system inclusive balance pan by a counter-weight. In this way, only the actual load has to be balanced by additional weights and electromagnetic compensation. Balances of this kind possess an electrical measuring range of ±10 g, a useful sensitivity of 100 digits/mg and a mechanical range of compensation of 30 g.

In fig.19, the distance of the magnets and the electromagnetic "spring constant" as functions of the actual load are presented. According to the changes in mass and distance, the natural frequency of the magnetic system which is an essential parameter in the automatic control, changes also. Y.C. Chen has treated this problem with the aid of adaptive control.[9]

If a magnetic suspension balance is subjected to vertical vibrations, disturbing torques arise for two reasons: First, the wanted mass is determined by electromagnetic compensation. Thus, a mass is suspended from the beam at the load side and no corresponding mass is attached to the other side. This arrangement acts like an accelerometer. The second reason is due to the quasielastic magnetic suspension of the lower magnet and the balance pan plus sample at the load side and the rigid attachment of the counterweight to the beam at its other end.

Y.C. Chen has proved that the torques which are generated in such a system by vibrations, can be compensated. The magnetic suspension is used as an accelerometer. The output signal of the distance sensor will be fed to the force coil of the electromagnetic balance over a special filter. The problem is simplified if the natural frequency of the magnetic suspension is kept constant by adaptive control.

Magnetic coupling for small loads, using a stationary control winding.

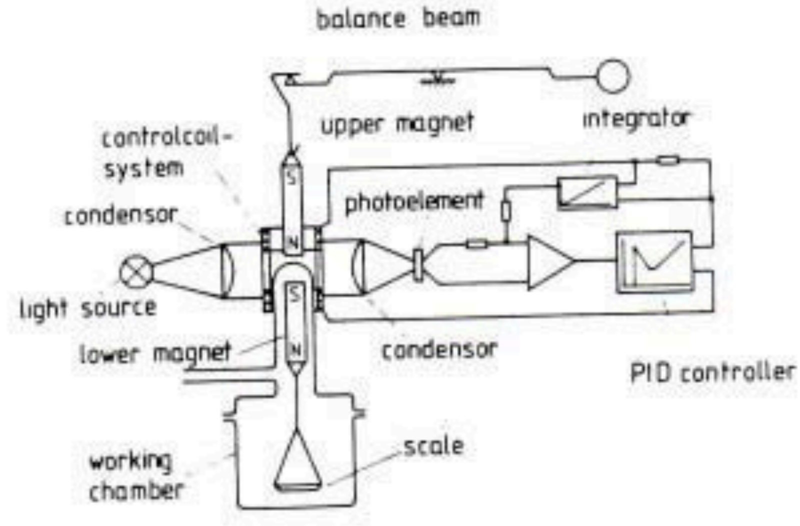

Fig.20 Suspension balance with bar magnets

In order to provide a magnetic coupling for microbalances of low load capacity, the iron mantles of the bar magnets have been omitted and a stationary control winding has been used. Fig.20 is a schematic drawing of the balance. The beam carries a counterweight on the right side and the upper magnet on the left. The magnet consists of a cylindric rod made from nickel iron or ferrite with a small disc of cobalt samarium cemented to its lower end. This magnet attracts the freely suspended lower magnet which is equally designed and carries the balance pan. It is enclosed by an inverted test glass tube which is attached to the reaction vessel.[10]

A parallel bundle of rays traverses the gap between the halves of coil partially obstructed by the ends of the magnets. The distance of the magnets influences the free cross section and bears upon the luminous flux to a photovoltaic cell. The photovoltage controls an amplifier, whose signal is fed to a PID controller which supplies the current to the control winding. If the distance between the poles of the bar magnets increases, the luminous flux also increases and the controlling current rises as high, as to restore the original position. The set point for the distance is given by the output voltage of an integrator, whose input signal corresponds to the voltage drop across a resistor included in the circuit of the control winding. Symmetrical arrangement of the latter with regard to the gap between the magnets means, that the forces exerted onto the magnets by the halves of the control winding cancel. A lack in symmetry causes errors in weighing, because a part of the weight is taken up by the winding, or the latter adds a force in proportion to the weight. This is shown in fig.21 for various deviations

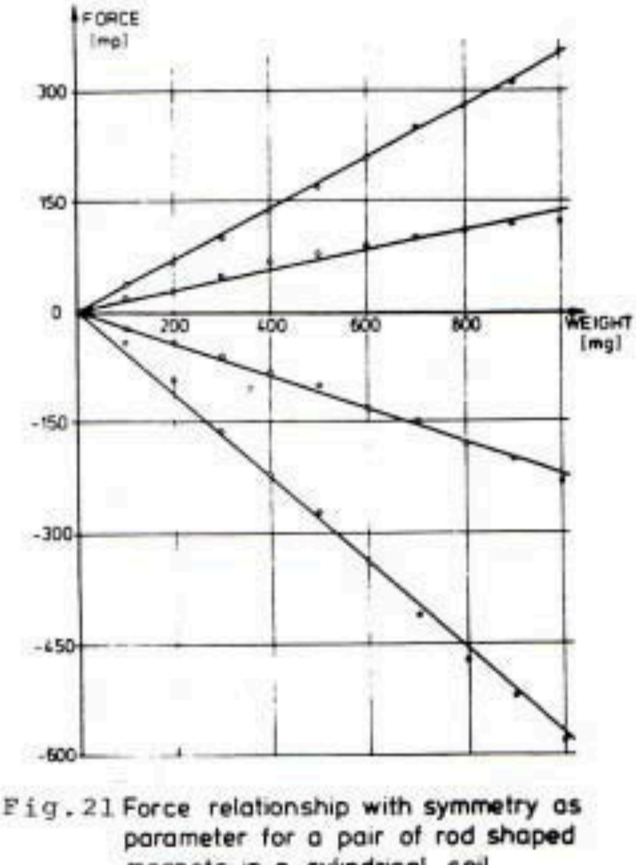

Fig.21 Force relationship with symmetry as parameter for a pair of rod shaped magnets in a cylindrical coil

from symmetry. With the aid of the above mentioned set point variation, the controlling current is always reduced to a very low value. The influence of a small deficiency in symmetry is thereby supressed. If symmetry is carefully adjusted and the controlling current is reduced by the additional control loop, the residual errors are very small.

The fact, that the distance between the poles decreases with increasing load, disturbs the symmetry. Correction is possible by a spring of suitable constant which is inserted in the suspension of the upper magnet. If the spring constant equals double the derivative dF/ds of the force distance-relationship of the pair of magnets, symmetry is maintained for small changes in load. A nonlinear sping could provide the correction over the full load range.

Simultaneous measurements of weight and torque by free magnetic suspension

Molecular weight can be measured according to the effusion method after Knudsen by simultaneous determination of weight and torque for a cylindric cell which contains the sample and is suspended by a diametral shaft. Two small bore holes are arranged in central symmetry with respect to the shaft. If the cell is heated, the vapor of the sample effuses through the openings and a reaction torque is produced. From the mass rate, the torque and the temperature, the molecular weight can be calculated. In order to apply the method in nuclear experiments, an experimental set up with free magnetic suspension has been designed and built, with which no sensitive and expensive parts can be contaminated. The principle is presented in fig.22.[11]

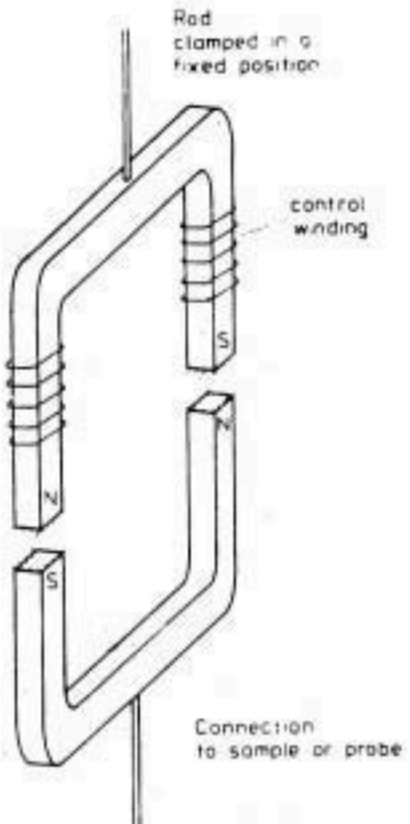

Fig. 22 Freely suspended horseshoe magnet

A horseshoe magnet carries a second one in freely suspended state. Therefore it is provided with a control winding. The lower magnet carries a nonmagnetic cross arm with a square copper plate attached to each end. The vacuum vessel has a flat cover of nonmagnetic and poorly conducting material. Four inductive sensors are affixed to its outer surface. The sensors detect displacements of the copper plates as well in altitude as in angular position, the shafts of the magnets considered as axes of revolution. They are connected to form a Wheatstone bridge according to fig.23,

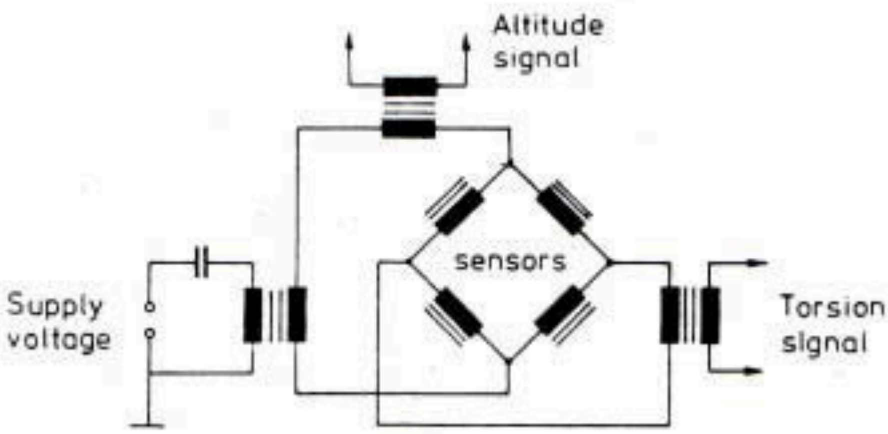

Fig. 23 Bridge connection of the sensors

where the configuration in the circuit corresponds to the actual position on the cover of the vessel. The bridge is fed by an audio frequency oscillator. The current flows through the primary winding of a transformer and generates a signal

$$U_1 \sim I = \frac{U_o}{S} = U_o \,(S_T + S_s)^{-1} \tag{25}$$

where S_T is the impedance of the transformer, S_s the impedance of the sensors, connected in the Wheatstone bridge. The impedance of the bridge can be expressed by

$$S_s = \frac{(S_1 + S_2)(S_3 + S_4)}{S_1 + S_2 + S_3 + S_4} \tag{26}$$

the block diagram of the complete system is shown. The load detection channel consists of the above mentioned transformer, whose primary winding is included in the circuit of the Wheatstone bridge, an impedance converter, a rectifier with filter and amplifier, a set point adjustment for the altitude, a PID controller and a voltage controlled current source which supplies the exciting current for the control winding of the upper magnet. The channel for the measurement of torsion contains the already mentioned second transformer, a preamplifier and amplifier, a synchronous demodulator, a multiplicator and an output state which supplies the indicating signal.

The interrelationship between the wanted torque and the measured torsion has as yet not been treated. It is connected with the horizontal component of the attraction under torque and therefore depends on load. This is the reason, why the load signal is fed to the multiplicator in the path of the torsion signal.

If the lower magnet is deflected from its equlibrium position by a small angle, its poles oppose those of the upper magnet with a reduced surface. Thus a larger current is necessary to carry the load. The resulting error can be corrected by feeding the torsion signal to the altitude set point-adjustment as disturbance variable compensation. The dotted line indicates the signal path.

Suspension balance for high pressures

Sorption and solution at very high pressures are of high interest for catalysis research, for the storage of hydrogen in metals, also for the investigation of geophysical phenomena. Therefore, a balance has been developed, which will allow, to study such processes without contact between the balance and the compressed gases. Of the systems presented in fig.12, the third appears to be the most suitable. It is a top pan system, that means that an oven to heat the sample is mounted above the balance. Therewith a positive temperature gradient arises, which suppresses convection. Moreover, the partition between the reaction chamber and the balance can be made cylindric and will withstand higher pressure differences than a flat one.[12]

Fig.25 is only a rather schematic drawing of a high pressure balance. The balance proper is selfcompensating. It consists of a moving coil system as in normal electromechanic balances and works together with a displacement sensor which is not included in the drawing. The sensor is entirely nonmagnetic and consists of a short circuit ring, moving in the field of two coils, and changing their inductivities in opposite sense. A frame is connected with the moving coil, which is guided by levers with flexural pivots. The frame contains two axially magnetized ring shaped magnets from cobalt-samarium. It also carries a differential sensor winding for the magnetic coupling. A glass tube is fixed to the casing in such a manner, that it freely penetrates the bores of the magnets and the winding. It serves as partition, is tightly connected with the cover, closed at the lower end and encircles a rod, which carries the balance pan.

where S_i is the impedance of the single sensors. If the copper plates are positioned fully symmetrically with respect to the sensors and in equal distances from these, all impedances are equal, and

$$S_s = S_i \text{ as well as } U_1 = U_o\ (S_T + S_i)^{-1} \text{ hold.}$$

Small equal varirations of S_1, S_2 in opposite sense as well as S_3, S_4 in opposite sense do not change the signal. The voltage across the horizontal diagonal which is detected via the transformer at the right hand side obeys the equation

$$U_2 \sim U_o\ \left(\frac{S_1}{S_1 + S_2} - \frac{S_3}{S_3 + S_4}\right)\ (S_T + S_s)^{-1} \tag{28}$$

If the impedances of the sensors are varied by parallel elevation or lowering of the lower magnet, $S_1 = S_2 = S_3 = S_4$ holds, but if a change of S_s occurs, the current through the bridge is changed. Thus, the signal U_1 is altered. By comparison of U_1 with a set value, an error signal is obtained which controls the current through the winding of the upper magnet with the aid of a PID controller. The loop for altitude control is now closed. In order to determine the mass rate, we have go measure and differentiate the exciting current through the control winding.

If the lower magnet is rotated in constant altitude with respect to the upper magnet, S_1 and S_3 are varied in the same sense, S_2 and S_4 in opposite sense with respect to S_1 and S_3. These variations cancel in the equation for U_1.

The variable U_1 is insensitive to angular displacements while sensitive to altitude. The variable U_2, however, is markedly sensitive to rotation and less sensitive to variations in altitude. In figure 24,

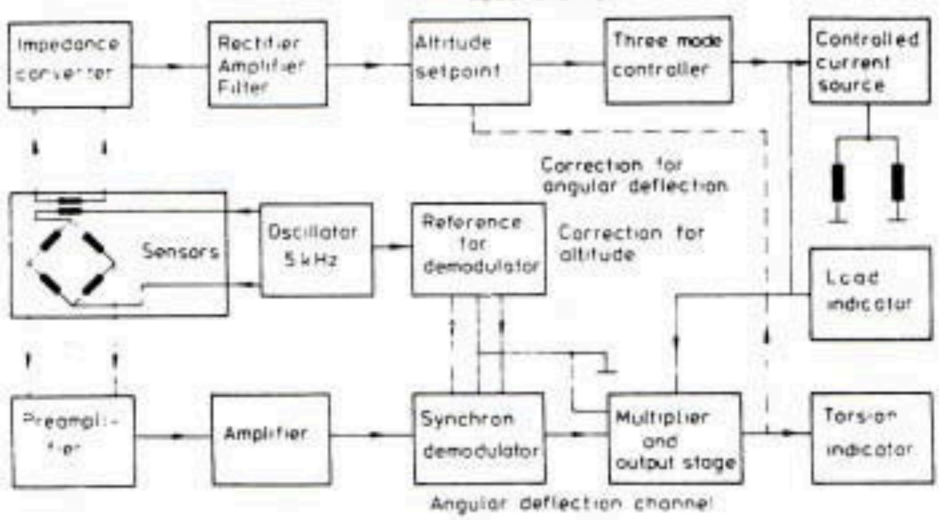

Fig. 24 Block diagram of the complete system

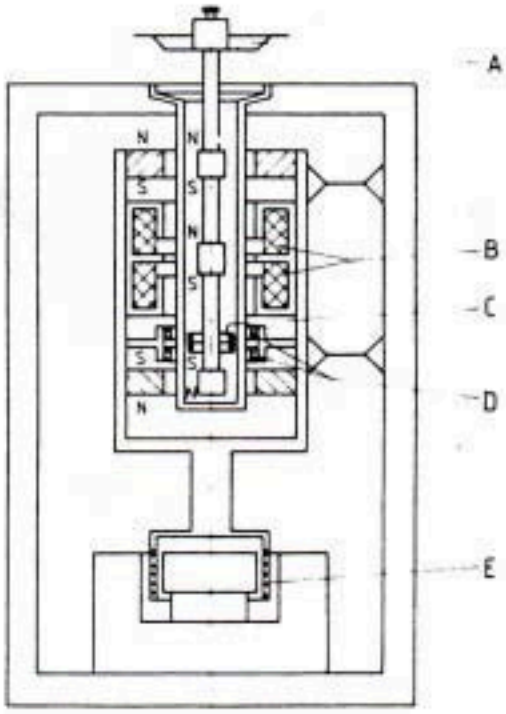

Fig. 25
Axial stabilization in a high pressure-suspension balance

A Working chamber B Force coils
C Metal ring D Sensor coils
D Moving coil of the balance

Two cylindric magnets are fixed to the rod inside the ring shaped magnets. The cylindric magnets are also axially magnetized. They are centered in the ring magnets by repulsion. An axial stabilization is performed with the aid of a third cylindric magnet fixed midway between the two magnets on the rod and a differential force coil which together form a force motor. A short-circuit ring attached to the rod and the above mentioned differential winding serves as displacement sensor. The casing is filled with an insulating liquid, which has to remain fluid at high pressures. It communicates with a metal bellows exposed to the pressures. It communicates with a metal bellows exposed to the pressure of the atmosphere around the sample. The oven and the upper section of the casing are not drawn. Fig.26 shows the complete casing of the high pressure balance. For the experiments, it is contained in an autoclave. The balance is provided with a mechanism, which allows to calibrate the system while the pressure is already applied. For this purpose, the balance pan, also an additional weight, can be placed or relieved. Pressure and temperature are measured with the aid of electrical sensors. A desk calculator controls the measuring process, makes the necessary corrections and displays the results.

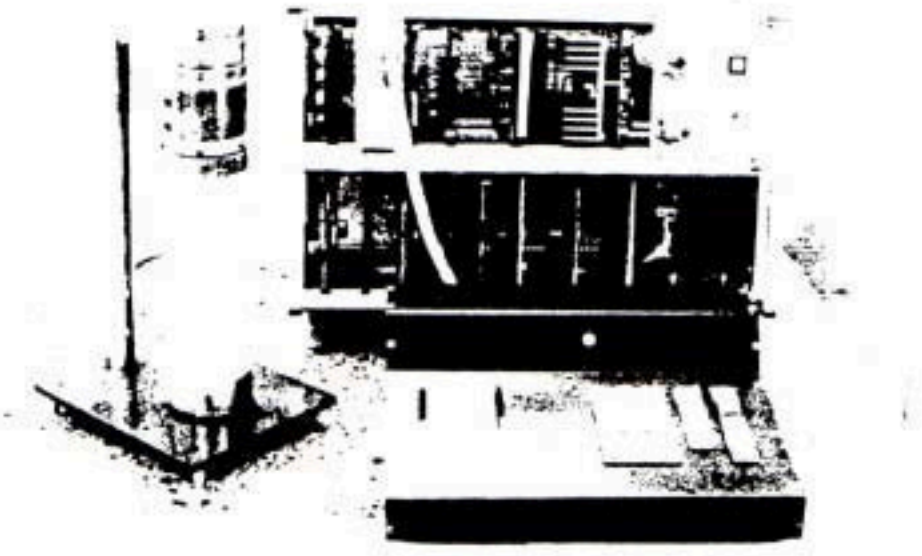

Fig.26 Very High Pressure Balance with
Electronic Circuit and Microcomputer

Starting from the fact, that precision mass determination is always connected with sensitive and reliable displacement detection, some examples for the use of displacement sensors in balances have been presented. The amazing useful sensitivity attained with modern balances is partially due to the development of new sensors. While normal balances may or may not utilize the principle ofautomatic compensation which always implies feedback control, the closed loop is indispensible for weighing in the freely suspended state.

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