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A new magnetic suspension coupling for microbalances

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Abstract

Balances utilizing the principle of free magnetic suspension can be very useful for thermogravimetric experiments, especially if extreme conditions such as high pressure or corrosive gases are to be applied to the sample. Magnetic coupling systems with automatically controlled attraction can be used for direct conversion of weight into an electrical signal or for the separation of object and balance.

The magnetic suspension balance is described and a new versatile magnetic coupling system with an extremely low dead weight is presented. Intended for use in industrial and scienific research institutions, the coupling provides microgram resolution and may be combined with unmodified commercial micro- or semimicrobalances.

INTRODUCTION

Thermogravimetric experiments are important in the scientific investigation and quality control of many materials. By measuring the weight of a specimen exposed to a certain atmosphere at a given pressure and temperature, several physical or chemical properties, e.g. surface density, porosity or chemical resistivity, can be examined with high accuracy at comparatively low expenditure. Thermogravimetric systems generally consistent of an electromagnetically compensated beam balance, a furnace and equipment to adjust the atmospheric pressure inside the reaction vessel.

The accuracy of measurement is restricted by undesired interactions between the balance and the experimental atmosphere. Errors due to sorption effects and buoyancy, which depend on a large number of mostly unknown parameters, including surface density, temperature and the

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volume of the recipient, concentration of adsorbate in the atmosphere, saturation of the surface, etc., sometimes make the high resolution of modern beam balances useless to the respective investigation. However, an ultra-high vacuum may be contaminated by desorption of matter from parts of the balance. Finally, harsh reaction atmospheres may corrode or even destroy the balance; moreover, the corrosivity of some gases is enhanced by increased pressure.

The range of ordinary thermogravimetric systems is therefore restricted to moderate conditions, such as inert atmospheres and pressures up to 100 bar at best. The development of thermobalances in which the weighing system was separated from the object by using a magnetic bearing was considered a most important step. The load, which is kept floating by controlled magnetic attraction, is coupled to the beam without any mechanical guidance and thus can be placed inside a hermetically sealed reaction vessel. The conditions that may be applied to the sample depend merely on the sturdiness and chemical resistivity of the autoclave. A diagram of the magnetic suspension balance is shown in Fig. 1.

An armature, which supports the balance pan, is kept in a floating state by the attracting force of an electromagnet. The latter is placed in the load

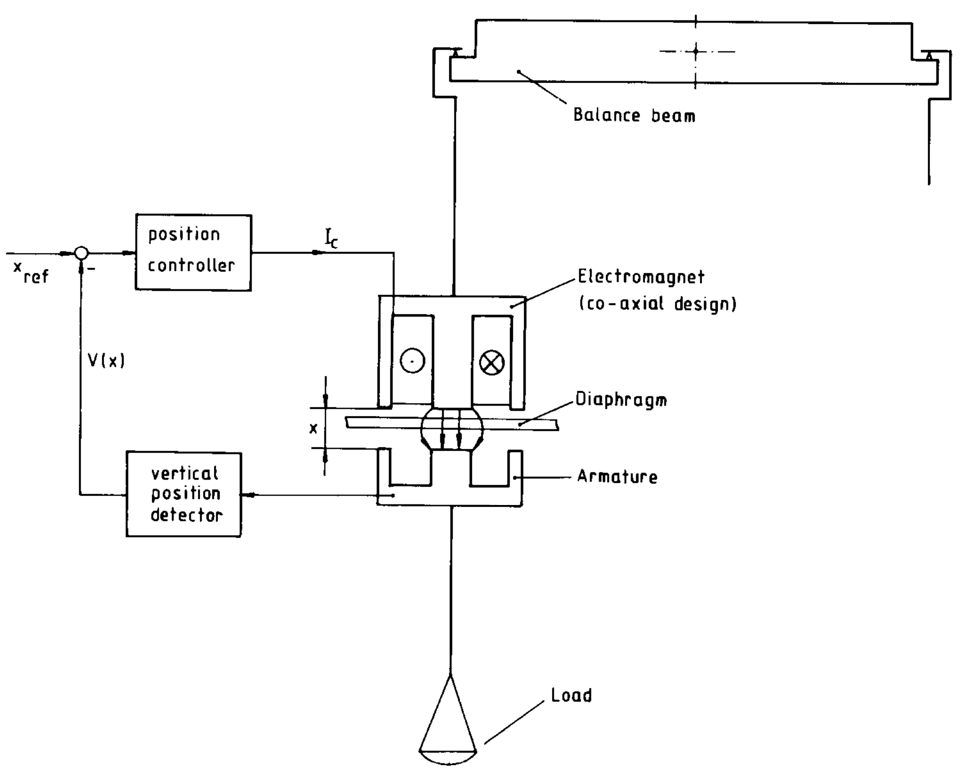

Fig. 1. Diagram of the suspension balance.

suspension of a beam balance. Floating is maintained by a position-control circuit which keeps the armature at a given distance from the pole face of the electromagnet.

The first commercial suspension balances provided a useful resolution of 10 μg at a load capacitance of 30 g. Gravimetric sorption analysis, however, often requires micro- or even ultramicrogram resolution, and the maximum pressure of 40 bar is exceeded by ordinary weighing cells which are enclosed in a pressurized casing. In addition, these early devices were complicated to operate. Although there is no doubt that an enlarged operating range would be extremely useful to meet the various requirements of thermogravimetry, further industrial development has not taken place for nearly 30 years. Commercial suspension balances still provide insufficient versatility and reliability at a comparatively high price, and thus little use has been made of them until now.

Progress in sensor technology, analog signal processing and magnetic materials allows both improved accuracy and a considerably increased maximum pressure.

SUSPENSION SYSTEMS FOR WEIGHING PURPOSES

According to Earnshaw's theorem, which was demonstrated by Braunbeck [1], free suspension of a diamagnetic body is possibly in non-uniform magnetic fields. Suspension of ferromagnetic bodies, however, requires artificial stabilization by mechanical guidance or a control circuit, because at least one degree of freedom must be restricted. Unfortunately, diamagnetic materials (except superconducters) show a permeability close to unity, and a bearing force sufficient for weighing purposes cannot be attained with them at a reasonable cost.

The first suspension systems with active position control of the floating body were realized by Holmes [2] and Beams [3]. In 1947, Clark [4] designed a simple magnetic suspension balance for direct conversion of weight into an electrical signal. An electromagnet attracts an armature of mild steel in a vertical path of deflection, which supports the load. The position is detected by a light barrier and thus the deviation controls the excitation current through the force coil. This current corresponds to the suspended mass and can be measured. Gast [5] separated the functions of weighing and coupling of the object to the balance by free magnetic suspension, thus utilizing the high resolution of electromagnetically compensated beam balances.

Coupling the object to the balance via magnetic suspension

Figure 2 shows the cross-section of the coupling in a modern version of Gast's design [6]. An electromagnetic in co-axial form attracts a permanent

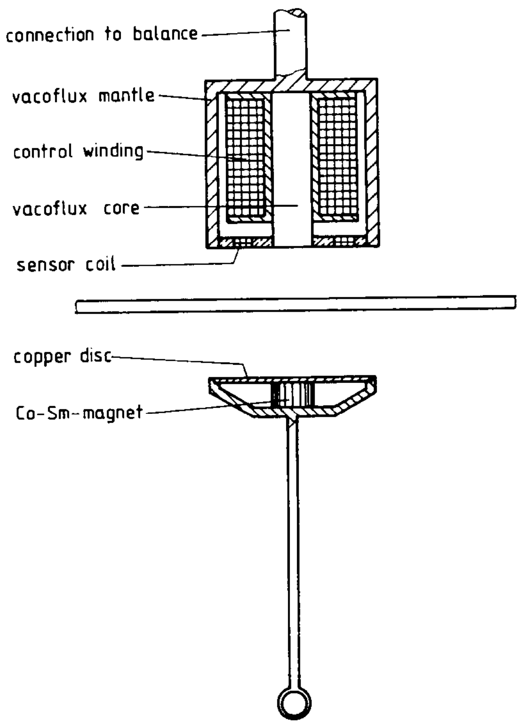

Fig. 2. Magnetic coupling for semimicrobalances.

magnet made of cobalt–samarium. Both electromagnet and armature are provided with a co-axial Vacoflux mantle, which increases the efficiency of the force coil and also reduces the stray flux considerably. Distance between the parts of the coupling is detected by an eddy current sensor. The latter consists of a flat sensor coil, which is placed at the front side of the regulating unit, and a copper disc at the upper end of the armature. The inductance of the coil, which is part of a resonant circuit, is measured with the aid of a phaselock-loop.

Using an electromagnet in combination with a permanent magnet allows for minimum power dissipation in the winding, if the attracting force between magnet and core is kept equal to the force of weight. This is possible by adequate control of the pole distance. In order to maintain this state of equilibrium, a superimposed current control circuit is established. If a current flows through the force coil, the corresponding voltage drop causes an integral controller to send a rising or falling voltage x_{ref} (Fig. 1) to the summing point of the position-control circuit. Consequently, the position of the armature will adjust to a distance where the force required to keep the balance pan suspended is generated solely by the magnet, and the mean value of the control current vanishes. Only transient components are required to keep the system in stable equilibrium. To avoid interactions of the two circuits, an integration time must be selected that is large relative to the time constants of the position-control circuit.

Beamless suspension balances

As mentioned above, the first application of free magnetic suspension for direct conversion of weight into an electrical signal was made by Clark. Meanwhile, beamless suspension balances have been developed to a high degree of perfection. A sensitivity of 10 μg at a load capacitance of about 50 g and a useful resolution of 1×10^{-5} have been attained by a sophisticated version of the coupling shown in Fig. 2, which acts as a direct weighing system with a frequency-variant output [7].

The force of weight is converted into deflection by the current-control circuit, which drives the armature into the equilibrium position. The corresponding pole distance is detected by a high-resolution eddy current sensor with an extremely low temperature coefficient, using a precision phaselock-loop.

According to the non-linear distance–force characteristic, the sensitivity depends on the working point of the system and varies with the applied load. The deflection corresponding to a given change of mass increases with the distance between the pole faces. The eddy current sensor provides a characteristic in the opposite sense, with increased sensitivity at small distances. With a special design of both sensor and regulating unit, these effects adequately compensate each other and the balance ultimately shows a linear characteristic.

Direct weighing systems, however, cannot be expected to replace beam balances combined with magnetic couplings in the short term, because the bearing force largely depends on the temperature coefficient of the applied magnetic materials, so that sensitivity and useful resolution are restricted to the semimicrogram range; therefore, they will not be considered in detail.

MAGNETIC COUPLING FOR MICROBALANCES

With coupling systems, which are based on the principle shown in Fig. 2, the accuracy of measurement as well as the range of application are restricted by several disadvantages. Firstly, the load capacitance of microbalances is exceeded by a high dead weight, resulting from the control winding and the co-axial mantle. Secondly, the employed inductive sensor requires a dielectric or poorly conducting non-metallic ‘window’ in the separating wall. Ceramic materials, however, are brittle and are not suitable for conditions of high internal pressure. Thirdly, the coupling provides both a large surface area and volume, which may cause considerable errors due to buoyancy and sorption effects.

The new design presented below provides distance control by utilizing the stray field of the unshielded force-generating magnets. To minimize errors due to external fields, the bearing force is limited to the load capacitance of microbalances.

General description

The new coupling system is shown in Fig. 3. It consists of four bar-shaped and axially polarized permanent magnets and a concentric coil to control the virtual mutual attraction by superimposing a magnetic field. Thus, the dead weight is reduced, because the coil is rigidly mounted on the casing. Two pairs of magnets are used to prevent the floating part of the suspension from twisting around its axis. In this application, the current-control circuit, which was intended to prevent convection by minimizing the power dissipation in the winding (see above), is also necessary for accurate transmission of the desired force of weight. Considering the forces exerted on the upper and lower magnets, any difference is registered by the balance and thus causes an error in measurement. This error, which depends on the degree of symmetry in the system, is eliminated with the mean value of the current.

The position of the magnets is detected externally by a magnetostatic sensor, consisting of two Hall probes. This allows an all-metal enclosure to

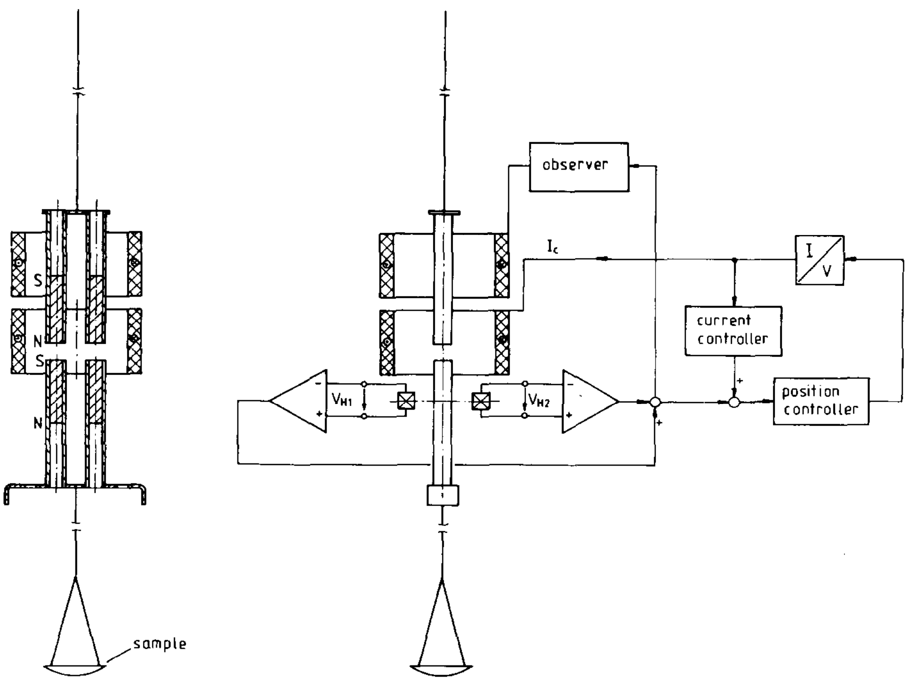

Fig. 3. Magnetic coupling with extremely low dead weight.

be used. Interference between the control balance and suspension circuits is inhibited by an auxiliary circuit, which consists of a state observer and an additional winding that act on the bearing magnets alone.

Using pairs of slender rare-earth magnets, a load capacitance of 4 g has been attained at a tare of only 1.5 g. Because of its small diameter, an enclosure can be made that withstands an internal pressure of several thousand bars without obstructing the external distance control.

Electrodynamic force unit

An attempt to replace the electromagnet in the balance suspension by an external stator coil was first made by Gast and later considered by Wagner and Kleinrahm [8], but their system showed inferior dynamic behaviour compared to the original coupling. The reasons for this were not investigated precisely as the new design was not pursued because of its unsatisfactory nature. In this section we show that the disturbing effects are caused by undesired components of the restoring force, which can be minimized by proper design of the regulating unit.

Consider a field coil of cylindrical bore and rectangular cross-section, acting on a slender bar magnet as shown in Fig. 4. Let h be the length and d_i the inner diameter of the coil. In the case of homogeneous magnetization, the pole strength of the magnet may be represented by surface charges, which are spread uniformly across the pole faces with a density ω. Provided that the magnetization is independent of external fields, the force F_i exerted

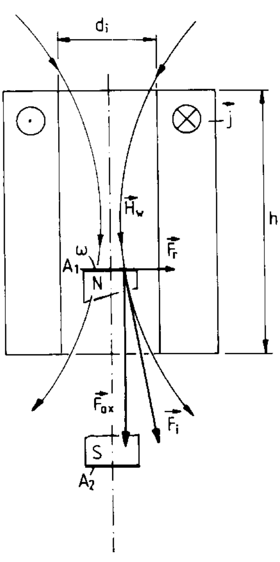

Fig. 4. Axial and radial forces exerted on a bar magnet by the field of a concentric coil (effects on the outer pole face neglected).

on the magnet is

$$F_i = \omega\left\{\int_{(A_1)} H_{w1}\,dA - \int_{(A_2)} H_{w2}\,dA\right\} \tag{1}$$

where $A_{1,2}$ are the pole face areas and $H_{w1,2}$ the field strengths of the winding at A_1 and A_2. Equation (1) provides linear magnetic behaviour and refers to magnetic materials with high coercitive force, such as CoSe or NeBFe. The force on a slender AlNiCo magnet, however, may be expressed in the same way if its demagnetization factor is negligible.

To calculate the force between magnet and coil according to eqn. (1), we first have to investigate the field inside the bore. With H_w directed parallel to the axis of rotation, the field strength of a long thin coil with one layer of windings approximately corresponds to the number of ampere turns NI

$$H_w = NI/h \tag{2}$$

In fact, the flux lines bend towards the axis as outlined in Fig. 4, and H_w shows a radial component at all points, except on the axis itself and in the equatorial plane of the coil (this can be demonstrated, for instance, by computer-aided field calculation). Consequently, there are both axial and radial components of force. If the axes of magnet and coil coincide, the radial components cancel. Any deviation, however, generates a lateral force, unless the pole face is in the equatorial plane. Considering these features, one has to expect disturbing lateral forces as a secondary effect of the regulation process. Indeed, the system may be destabilized by this, especially if high compensating currents are needed to maintain the floating state.

Optimization of the system is straightforward and provides a slender design of both magnet and coil, because the radial component of H_w inside the bore decreases with a decrease in the ratio of inner diameter d_i to length h of the winding. Figure 5 shows the lateral force exerted on a single point-pole related to the deviation from the axis (a) at a given altitude, if the ratio d_i/h is varied from 0.5 to 2. For numerical calculation, the coil was approximated by a thin cylindrical sheet with a current layer distributed homogeneously across the surface. The results are referred to the maximum value, which is obtained for $x_0 = d_i$ and $d_i/l = 0.5$. It is evident that by proper choice of the length h, the disturbing force can be reduced to an insignificant order of magnitude.

Circuitry

Position detector

Utilizing the field of the suspended magnet, magnetostatic or electrodynamic methods can be applied to generate a reliable position signal. Gast and Luce [7] have shown that stable magnetic suspension at an extremely low expenditure is possible with the control winding acting as a velocity sensor.

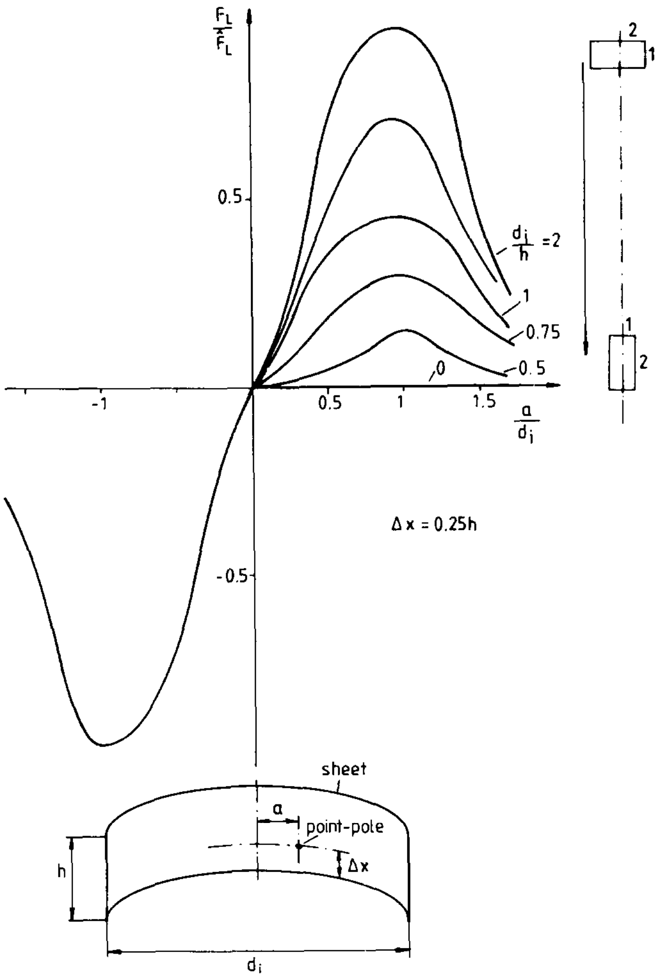

Fig. 5. Approximation of the regulating unit by a thin sheet and a point pole enables analytical calculation of the lateral force. The force on a dipole of given length is obtained as the difference between the respective characteristics.

The electromotive force, which corresponds to the velocity of the magnet relative to the winding, is separated from the superimposed control voltage and a signal representing the position of the magnet is derived by subsequent integration.

Direct measurement of the flux density by a magnetostatic sensor, however, is less disturbed by interference from the compensating current. To understand this, we first have to consider the field of the magnet, which was assumed above to be generated by oppositely charged pole face areas. The flux lines, which emerge from the pole faces, bend into elliptic curves as shown in Fig. 6. The radial component B_r is detected by a Hall probe which is placed in the equatorial plane of the magnet.

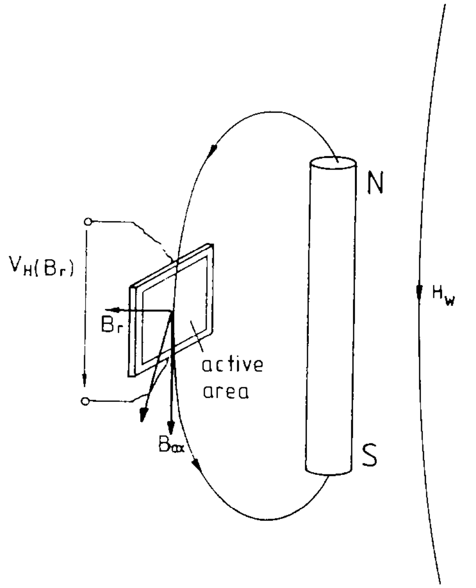

Fig. 6. Magnetostatic position detector.

Magnetostatic sensors generate an output voltage, which corresponds to the normal component of the flux density at the position of the active area. The tangential component, however, is not registered. Thus, with the field of the coil perpendicular to B_r, the arrangement shown in the figure provides a position signal that is independent of the compensating current. Unfortunately, the flux density changes as well with the altitude of the magnets relative to the probe, as with the respective horizontal distance. This means that in the floating state, swinging of the suspension will cause simultaneous vertical displacements. To avoid this, two Hall probes are employed and a signal representing the vertical position alone is formed by addition of the single voltages.

Control techniques

In principle, stable magnetic suspension is possible with a PD-controller [9]. According to the distance–force characteristic, the working point of a coupling system depends on both the quasi-elastic magnetic spring constant and the suspended mass, which are assigned to each other by the current-control circuit. An increase in weight causes a superproportional enhancement of the magnetic spring tension and thus reduces the time constants of the open loop. If there is large variation in load, adaptive control may be necessary in order to keep the dynamic properties of the control circuit sufficiently constant. This is possible by incrementing the open loop gain with the increased mass, as can be shown by graphical representation of the root locus [10]. Adaptive control, however, provides continuing evaluation of the system parameters. Chen [11] has shown, that on-line identification is possible at an acceptable expenditure by cross-correlating the excitation current with the position signal, using interfering underground vibrations as a natural identifying signal. Static observation of either signal by a discriminator enables a stepwise adaption, which is suitable for more indifferent control circuits with a slightly bent distance–force characteristic.

Due to their symmetrical design, beam balances provide a high discrimination of interfering underground vibrations. This may be considerably reduced by a magnetic suspension, because the floating part is encoupled to the beam via a quasi-elastic link, while the counterweight is suspended by a solid connection (or rigidly mounted to the beam if the balance is asymmetrical). Consequently, vertical acclerations of the casing will generate disturbing torques, which are registered by the balance. It is possible to compensate these torques in several ways, but in this report we will concentrate on methods using an auxiliary branch between the balance and suspension control circuits.

The first method was reported by Chen in 1978. Starting from the idea that the coupling can be used as an accelerometer, the excitation current is fed to the controller of the balance via a special filter. This filter generates an auxiliary signal, which inhibits controller action as a response to the restoring force. Thus, the actuating current of the balance is independent of the force transients exerted by the coupling, and, because there is no counteracting force, the beam is deflected by these transients. Unfortunately, the time constants of the filter largely depend on the working point of the coupling and must be adapted to the suspended mass in small steps. The reasons for this will not be discussed in detail here.

In contrast, the second method provides reduced compliance of the beam by compensating the disturbing force with the aid of an auxiliary actuator (see Fig. 3). To explain this, we consider the coupling as a mass-spring oscillator of second order, the spring constant resulting from the error of the control circuit. To determine the interacting force, we compare this model to a continuous suspension. It is evident that if the balance is subjected to a vertical acceleration, the motion is not followed by the armature immediately. This means that the suspended part of the coupling is accelerated relative to the casing, and consequently there must be some accelerating force that is different from a continuous suspension. This force component is registered by the balance and thus may be considered as an interfering variable.

Restoration of the undesired force is straightforward. With the position sensor rigidly mounted to the casing, the relative motion of the armature is measured directly. From this the accelerating force can be derived by subsequent differentiation. Using a high-pass filter of second order

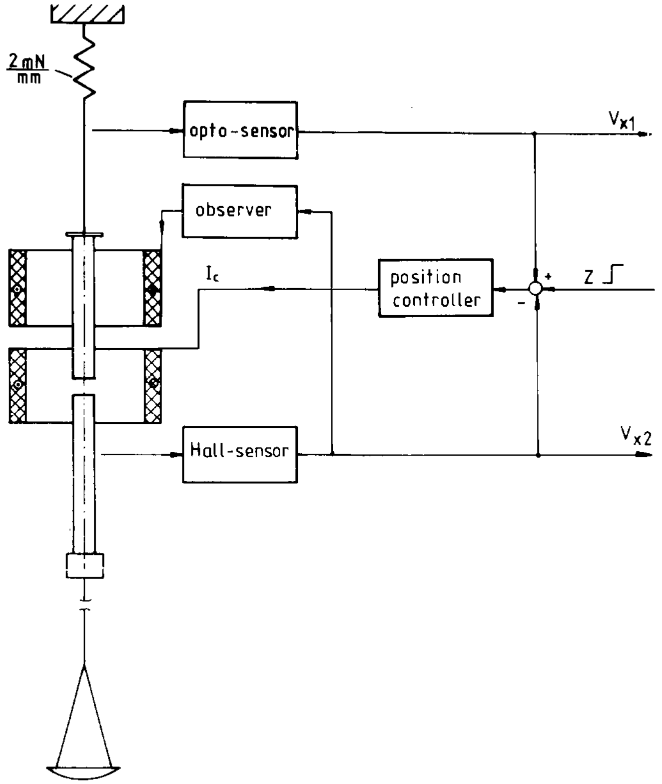

Fig. 7. Compensation of accelerating force transients by an auxiliary branch. The counteracting force is restored by subsequent differentiation, using two high-pass filters of first order in series. The cut-off frequency of the filters was selected to be 15 Hz.

provides minimum expenditure, but observation of the state variables according to Luenberger is preferable in respect to the signal–noise ratio. In any case, there will be an inevitable dynamical error due to the cut-off frequency of the observing network. This can be seen from the transient responses shown in Fig. 6 [8].

Figure 7 shows the test arrangement for the compensating branch. The compliance of the balance beam was simulated by a spring. An opto-electronic sensor observes the position of the bearing magnets, while the armature is caused to change its position rapidly by transients of a disturbance variable *Z*. If the accelerating force exerted on both the armature and the bearing magnets is entirely compensated, the latter must keep their position in spite of the highly compliant spring. The transient responses of the upper and lower part are shown in Fig. 8. Due to the error of observation, the bearing magnet is deflected for a very short span Δx during the first 30 ms. The accelerating force, however, is calculated to be reduced by 95%.

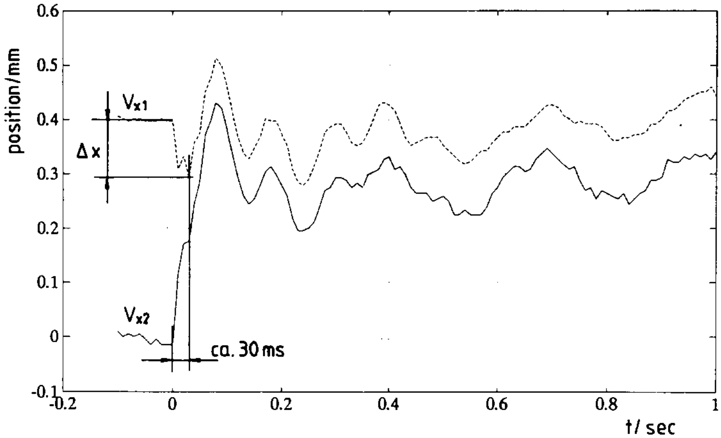

Fig. 8. Transient responses of the suspended and bearing magnets.

A detailed explanation of the methods described in this section is presently being published [12].

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