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CONTRIBUTIONS TO THE DEVELOPMENT OF FREELY-SUSPENDED TOP PAN BALANCES*

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ABSTRACT

The design of a freely-suspended top pan balance is described. It should enable thermogravimetric investigations to be made at very high atmospheric pressures.

INTRODUCTION

Interest in the development of top pan balances has increased because of the more practicable handling of a balance with a pan above the balance beam and the possibility of automatic weighing in an assembly-line process. With regard to thermogravimetry the influence of convection caused by the temperature gradient and other disadvantageous temperature effects on the balance could be diminished by using the top pan balance construction principle. A quite similar tendency is to be observed in the development of balances with a freely-suspended pan. Interest in the application of active and passive magnetic bearings has increased due to the development of magnetic material with high energy-content in the last few years. As a coupling between a balance beam and a pan, active magnetic suspensions have been used for many years. They were proposed by Gast[1] in 1960 and are manufactured by Sartorius Werke, Göttingen, Germany. The freely-suspended pan is completely separated from the recording balance so that one has the possibility to expose the sample to an environment such as pressure, temperature and the chemical nature of the atmosphere without any harmful influence on the weighing mechanism. In the Sartorius Model 4201 the pan is freely-suspended beneath the balance beam of an electromechanical balance by magnetic forces. The position of the pan is controlled automatically. The maximum load is 0.3 N, the limit of sensitivity is ± 0.1 μN.

Due to the reasons mentioned above, in 1969 Gast[2] proposed a magnetic coupling for a top pan balance which was developed later[3, 4]. The magnetic coupling described in the following is based on this development, an essential difference, however, is the arrangement of the sensors and the controlling elements.

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1 AN ACTIVE MAGNETIC COUPLING FOR GRAVIMETRIC MEASUREMENTS IN VACUUM

1.1 Description of the coupling

The coupling consists of two axially-magnetized permanent magnetic rings, repelling mutually (Fig. 1). The lower one (A) can be applied to the pan of an electronic top pan balance—e.g., the load cell described in chapter 2—while the upper one (B), which carries the pan (E), can be enclosed in a specially shaped non-magnetic container (F). Thus the freely-suspended pan and the upper magnet are completely separated from the recording balance. The device, however, is statically unstable because the center of gravity lies very high and horizontal magnetic forces try to push the upper magnet out of its set position just above the lower magnet. The horizontal forces vary linearly with horizontal displacements up to displacements of ± 3 mm (Fig. 2) and they are a function of the distance between both magnets, that is the weight on top of the pan.

Due to the statical instability—the transfer function of the controlled system is approximately double integrating—the upper magnet has to be stabilized by automatic control in two horizontal axes.

This is accomplished by two U-shaped electromagnets (D)—one in each axis—mounted on a baseplate inside the two annular magnets, which rest on the pan of the electronic balance or else on the baseplate drawn in Fig. 1. According to the direction of the displacement of the upper magnet the electromagnets have to push or to pull the permanent magnet. On the same axes of the electromagnets, there are U-shaped sensors (C), which observe the horizontal position of the freely-suspended pan.

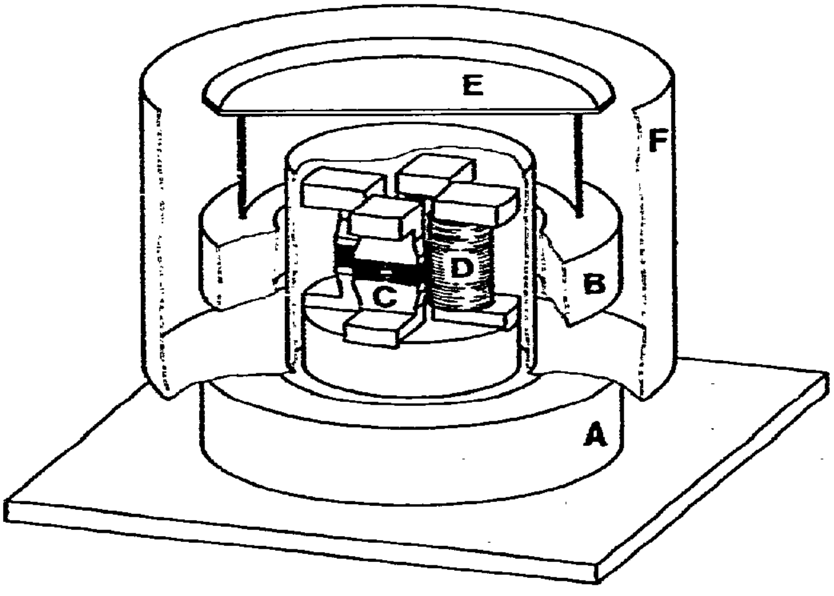
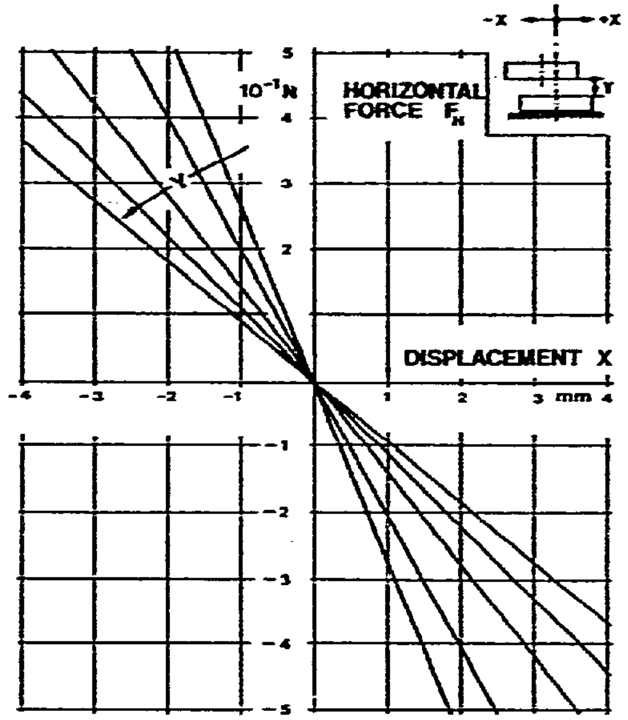


Fig. 1. An active magnetic coupling. A, B = magnetic ring; C = sensor; D = electromagnet; E = pan; F = non-magnetic container.



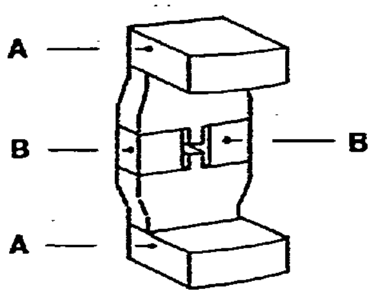


Fig. 2. Horizontal force F_H as a function of the displacement x and the distance y between the magnetic rings.

Fig. 3. Sensor for the position of the freely-suspended magnetic ring. A = pole-piece; B = permanent magnet.

Each sensor (Fig. 3) comprises a galvano-magnetic resistor in the gap between two pole-pieces (A). The free legs of the sensor are directed towards the magnetic ring. The working point of the resistor has been shifted into the quasi-linear part of its characteristic by a constant magnetic field, produced by two small permanent magnets (B) parallel to the gap. The magnets are made of magnetic iron oxide.

1.2 Description of the control circuit

The galvano-magnetic resistors are influenced by the magnetic field Ø of the freely-suspended magnet as indicated in Fig. 4.

A variation of the resistance due to horizontal displacements of the suspended magnet caused by horizontal forces F_H is transformed into a voltage-variation by a d.c.-fed Wheatstone half-bridge. The characteristic of the measuring transducer is linear in the working scope resulting in a proportional action. The output $\bar{U}_1$ of the transducer is taken for the actual value of the control circuit. It is equivalent to the actual horizontal position of the upper magnet and is compared with the set value w given by a high precision voltage source. The error signal due to a displacement is led to the input of a controller with proportional-plus-integral-plus-derivative action which compensates the displacement by means of the force produced by the electro-

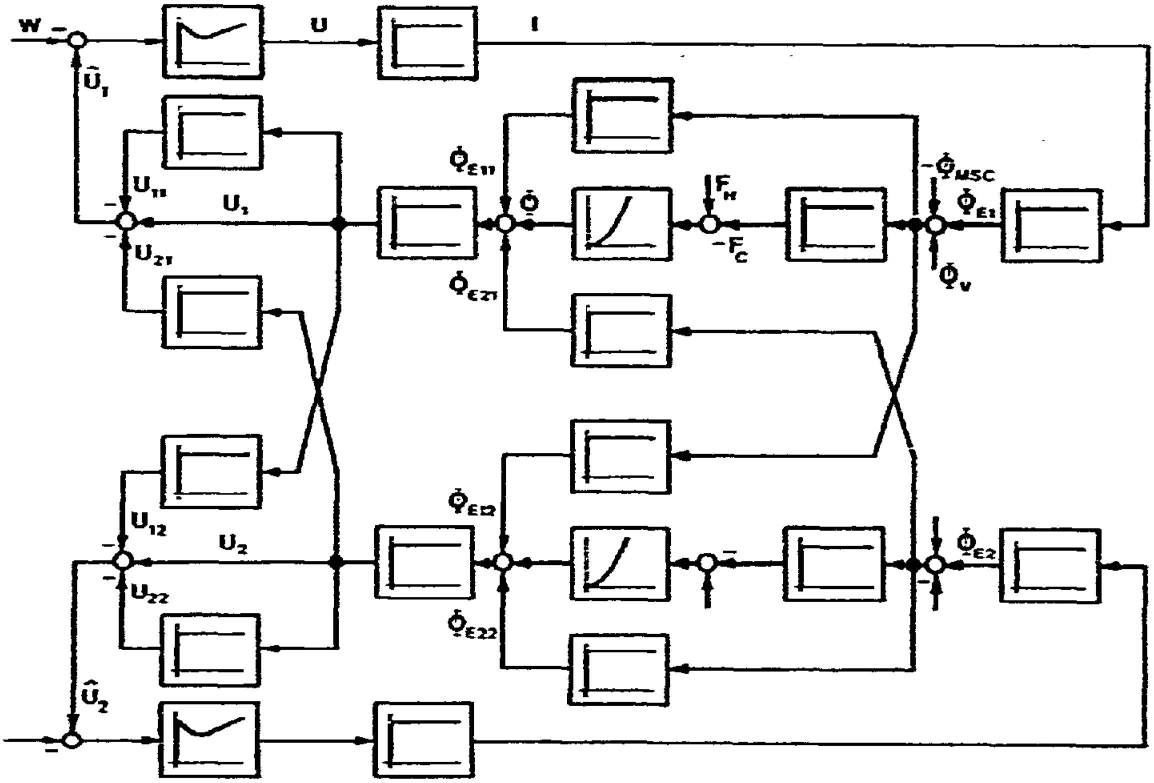


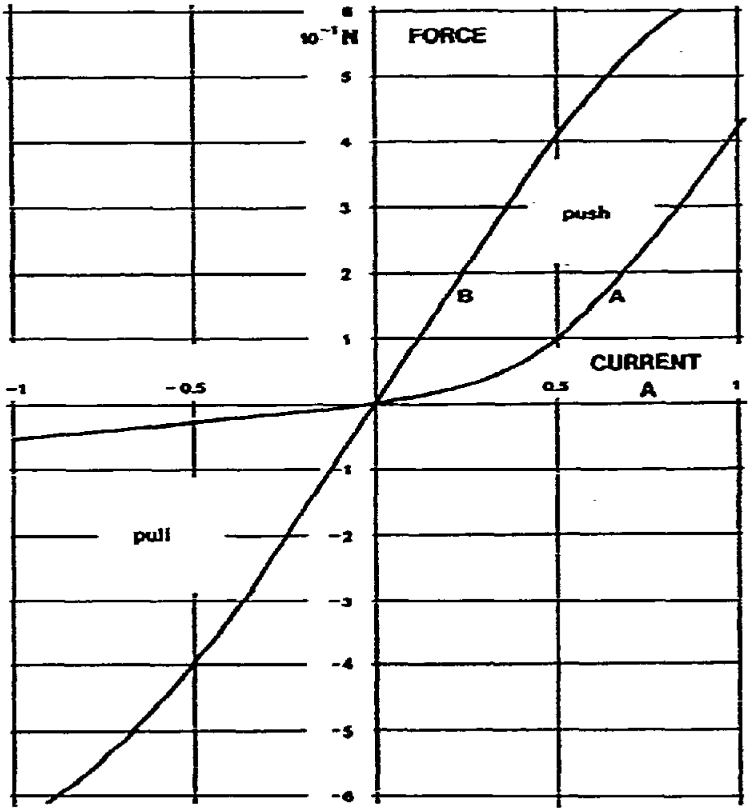
Fig. 4. Control circuit of the magnetic coupling. F = force; Ø = magnetic flux; i = current; u = voltage; w = set value.

magnet because of the magnetic field $\varnothing_{E1}$. The controller is followed by a power amplifier. Because of current feedback the power amplifier has proportional action.

There are two points, however, which have to be regarded in connection with the controlling element. Unfortunately each electromagnet influences both sensors by its stray field—$\varnothing_{E11}$ and $\varnothing_{E12}$ because of electromagnet 1—resulting in an error signal, and is influenced itself by the constant magnetic field $\varnothing_v$ of the permanent magnetic rings. The control circuits are magnetically coupled consequently. The characteristic of the electromagnet is shown in Fig. 5. It is non-linear because of iron saturation in the pulling part of the characteristic. By a magnetic by-pass $\varnothing_{MSC}$ (Fig. 6) between the two legs of the electromagnet (A) parallel to the coil, consisting of a samarium–cobalt-permanent magnet (B) and a ferromagnetic spacer (C), the working scope of the controlling element is shifted into the linear part of the characteristic (Fig. 5); the characteristic is balanced. This way, the characteristics of the error signals due to the stray field of the electromagnets are also balanced (Fig. 7). Therefore, the error signals can be eliminated by linear electric correcting networks U_{11} and U_{21} with proportional action as indicated in Fig. 4, resulting in decoupled control circuits.

1.3 Experimental result and characteristic data

A vertical displacement of the upper magnet will occur by loading or unloading



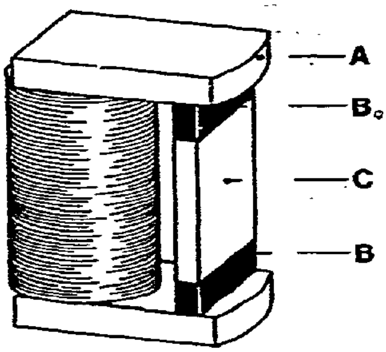


Fig. 5. Characteristic of the electromagnet. A = without correction; B = with correcting permanent magnet and ferromagnetic spacer.

Fig. 6. Electromagnet as controlling element in the magnetic coupling. A = electromagnet; B = permanent magnet; C = ferromagnetic spacer.

the pan. The horizontal forces, which try to push the suspended permanent magnet out of its set position are a function of the distance between both annular magnets (Fig. 2). This means, they are a function of the load. Therefore the power amplifier must have a sufficient reserve source of power in order to keep up the horizontal stability. Due to the vertical displacement, the working point of the sensors is influenced, resulting in a subsequent horizontal displacement of the upper magnet. To eliminate this error, the set value has to be varied due to the load.

Experiments, however, have shown, that there is no disadvantageous influence on the stability of the controlled system up to a load of 1 N, the set value being constant.

As the distance between both magnets is a function of the load, forces caused by the load could be measured by measuring the distance. Temperature, however, influences the magnetic field and causes an error in the force measurement. Therefore, the magnetic bearing is used as a coupling between a balance and the freely-suspended pan. This way, the temperature effects have no influence on the transmission of forces.

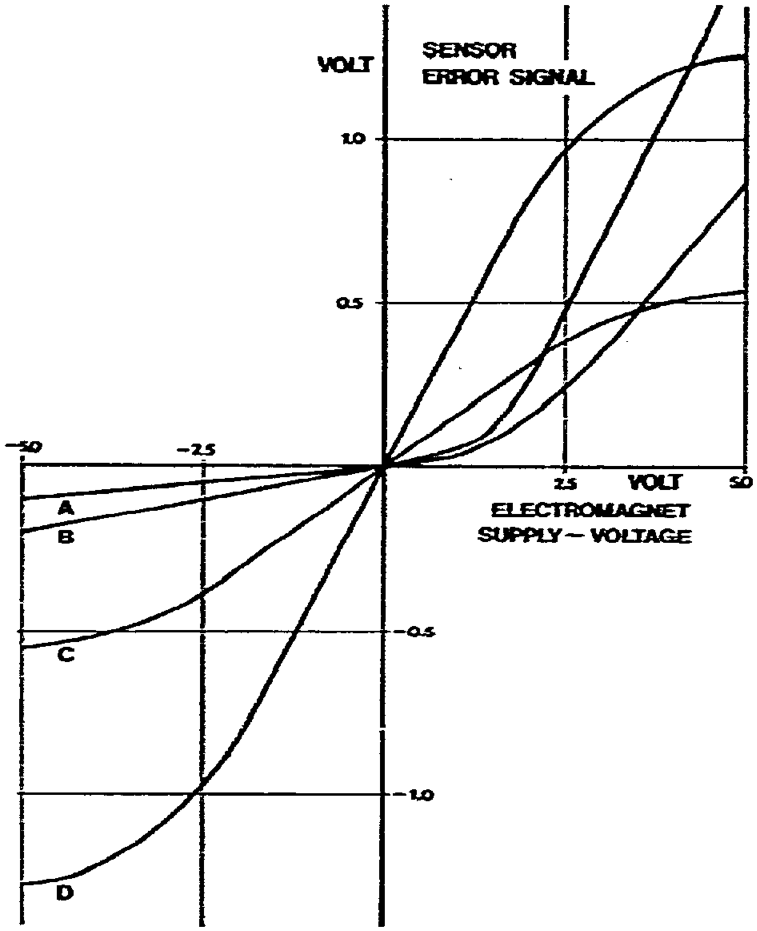
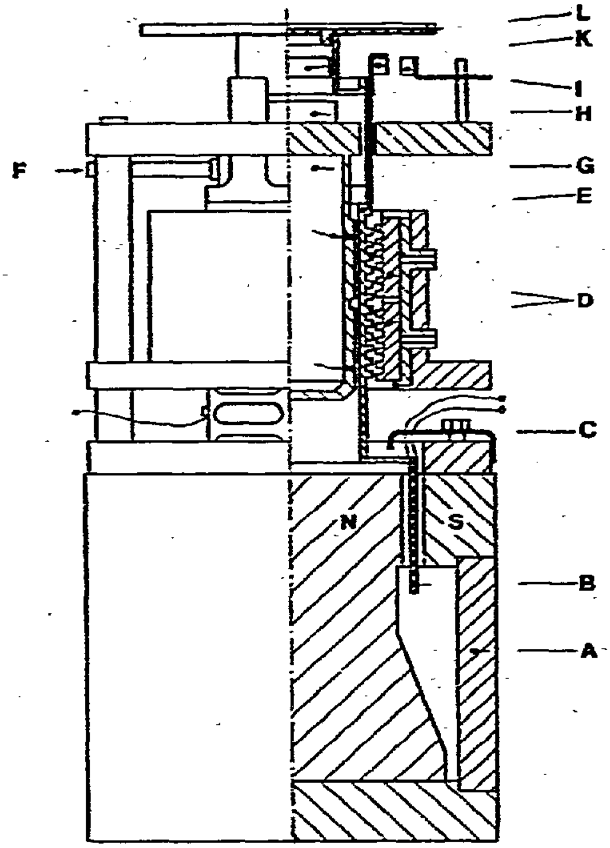


Fig. 7. Error signal of the sensor because of the stray field of the electromagnets. A = error signal because of the stray field of the opposite electromagnet; the characteristic of the electromagnet corresponds to line A in Fig. 5. B = error signal because of the stray field of the cross electromagnet; the characteristic of the electromagnet corresponds to line A in Fig. 5. C = error signal because of the stray field of the opposite electromagnet; the characteristic of the electromagnet corresponds to line B in Fig. 5. D = error signal because of the stray field of the cross electromagnet; the characteristic of the electromagnet corresponds to line B in Fig. 5.

To avoid instability of the control circuits for the upper magnet, the position of the carrying magnet must be stable in radial direction. That is, the balance beam and the balance pan does not have bearing clearance.

A balance with no bearing clearance is shown in Fig. 9 and will be described in the following chapter. The suspension was mounted on top of the pan of this load cell. Forces up to 1 N could be transmitted without contact between the cell and the suspended pan, the smallest distance between the ring-shaped magnets being 10 mm. The rings consist of magnetic iron oxide. The diameter is 78 mm, the caliber is 45 mm and the height is 14 mm.



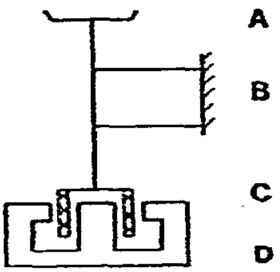


Fig. 8. Schematic diagram of a load cell. A = pan; B = parallel spring plates; C = coil; D = pot-shaped magnet.

Fig. 9. A load cell with air-suspension. A = pot-shaped magnet; B = coil; C = buffer; D, E = differential capacitor; F = air intake; G = container; H, I, K = permanent magnet; L = pan.

2 A SELF-COMPENSATING LOAD CELL

A load cell is a balance without a balance beam. The principle is shown in Fig. 8. In the moving part, the cell consists of the balance pan (A), carried by a vertically arranged rod connecting two parallel spring plates (B) and the coil (C), which plunges into the strong radial field of the pot-shaped magnet (D). The weight of the moving part is in balance with the force caused by the coil if it is not tared via the spring plates or by another arbitrary force.

The position of the rod is usually sampled by means of opto-electronics. If the equilibrium is disturbed, the opto-electronic sensor acts on an amplifier, which generates a voltage or a current signal. This enters the coil and causes a compensating force. The output signal of the amplifier corresponds to the weight of the mass on the balance pan. Due to the disadvantages of suspensions with parallel spring plates or parallel spring joints, such as hysteresis and effects by temperature and aging, an air-suspended load cell was developed^5. Experience with this load cell encouraged the authors to improve construction and electronics with the model shown in Fig. 9.

2.1 Description of the air-suspended load cell

The load cell consists of the following components: balance pan, differential capacitor, moving coil magnet and compensator. An essential construction element of the balance is the air-suspension, which is also part of the sensor for the vertical position of the pan. The compressed air flows from a small pump via the air intake (F) into a cylindrical container (G). From there, it passes several nozzles and streams against the inner wall of the grounded inner electrode (E) of the differential capacitor (D, E). Six nozzles with a diameter of 300 μm are equally spaced over the contour on both top and bottom of the container, respectively. The air leaves the load cell at both sides of the suspension.

As the stability of the air suspension is more important than the carrying capacity, the nozzles have no pockets downstream. To avoid torques, which try to get the airborne part of the load cell into rotation, the aerostatic bearing has to be done very accurately with regard to parallelism, roundness, concentricity and surface finish. But asymmetry is not completely avoidable. Therefore, a small permanent magnet (I) is attached to the airborne part beneath the pan (L), repelling a second one at the same level, thus preventing rotation. Another small axially magnetized permanent magnet (K) is fixed above the inner electrode directly under the pan. The compensating coil (B), however, is connected to the bottom of the inner electrode. A second axially magnetized permanent magnet (H) is mounted on top of the air container just beneath the magnet mentioned before. The magnets, repelling one another, act as an axial bearing. That is, the lower magnet carries the weight of the contactless part of the load cell consisting of the pan, the upper magnet, the inner electrode and the coil which plunges into the pot-shaped magnet (A). The distance between the two permanent magnets is chosen in such a way that the magnetostatic force is in balance with the dead weight, resulting in a currentless coil.

The differential capacitor transforms the vertical displacement of the pan, caused by loading or unloading, into a proportional electrical signal. For the impro-

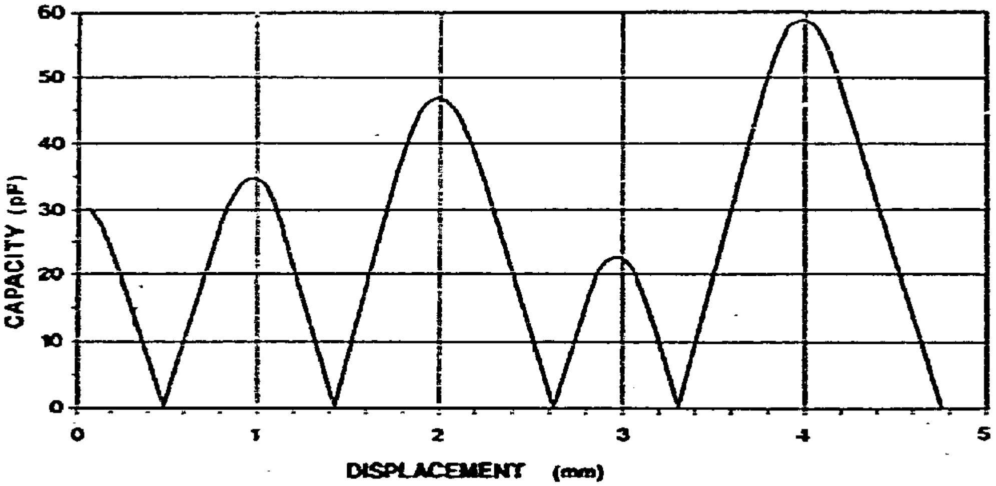


Fig. 10. Characteristic of the differential capacitor of the load cell with air-suspension.

vement of the sensitivity of the sensing capacitor, the surface of the electrodes is serrated. The characteristic of the differential capacitor is shown in Fig. 10. It is altogether non-linear. A linear part of this curve was chosen as a working scope limited on the one side by the mechanical buffer (C) and on the other side by the inner pole of the pot-shaped magnet. The sensitivity of the variable differential capacitor is 100 pF mm^{-1} at the working point.

2.2 *Description of the control circuit*

In the manner of notation of automatic control theory, the contactless part of the load cell, consisting of the pan (L), the upper magnet (K), the moving electrode (E) of the differential capacitor, the collar of the air-suspension, respectively, and the coil (B) have to be regarded as the controlled system, shown in Fig. 11 as block diagram. If the magnets (H, K) were not installed and the air-damping could be omitted, the characteristic of the transfer function would be double integrating. That is, the controlled system is unstable, the closed loop cannot be stabilized by a controller without derivative action. In addition to this, the controller must have integral action to compensate completely a displacement caused by the weight on top of the pan, resulting in a strong proportionality between the compensating force via the electrodynamic system and the unknown weight.

By addition of both permanent magnets (H, K) the characteristic of the controlled system changes. The unstable system becomes statically stable and gets dynamic stability through the air damping. The dynamic stability, however, is not sufficient. To improve the dynamic stability, the controller must have derivative action.

2.3 *Description of the electronic circuit*

The capacitor is part of a crystal-controlled carrier frequency bridge shown in

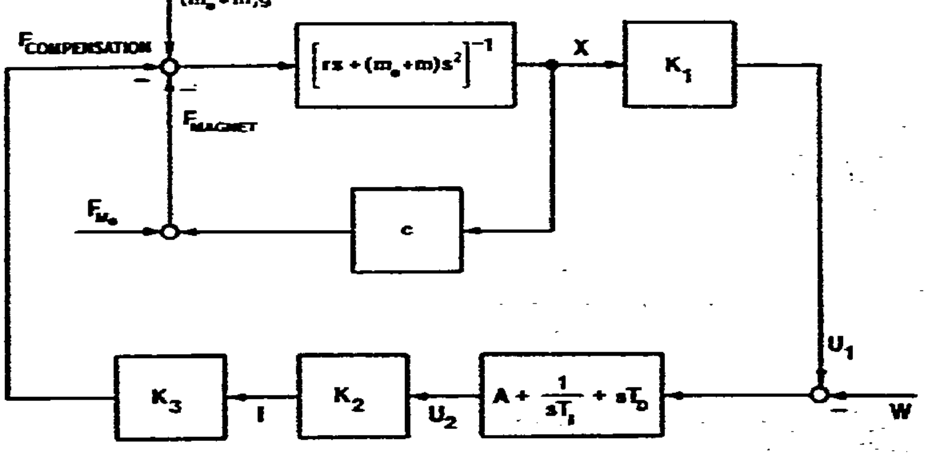


Fig. 11. Control circuit of the load cell with air-suspension. A = amplification; c, K = constant; F = force; i = current; m = mass; r = damping; s = komplex parameter; T = time constant; u = voltage; w = set value; x = displacement.

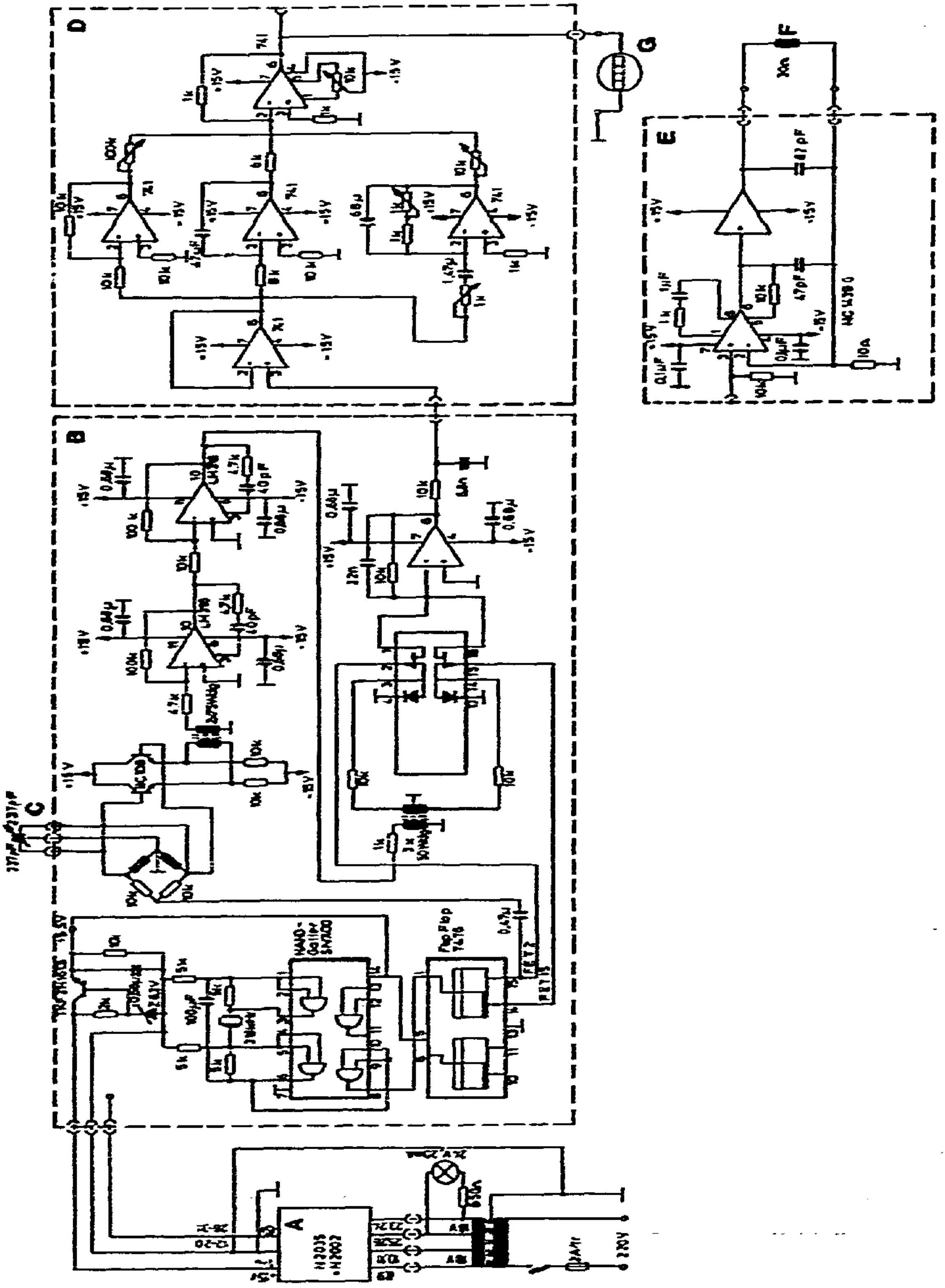


Fig. 12. Circuit diagram of the load cell with air-suspension. A = power supply; B = measuring transducer; C = differential capacitor; D = controller; E = power amplifier; F = coil.

Fig. 12. The frequency of the quartz-stabilized oscillation is 622 kHz. This is the first harmonic of the quartz crystal. The oscillator has also to provide a square wave for the demodulator. By use of a flip-flop in the oscillation circuit instead of resistors, temperature effects on the symmetry of the square wave caused by drift can be avoided. The flip-flop changes its state only by positive voltage variations thus bisecting the frequency. The impulse time is exactly one half period. At the output of the flip-flop a square-wave signal between 0 and 5 V with a frequency of 311 kHz is generated, which controls the phase-selective rectifier and feeds the alternating bridge via a capacitor balancing the voltage relative to ground.

The bridge, consisting of two parallel-resonant circuits with series resistances, one in each arm, is tuned to the frequency of the oscillator. In case of load variations, the inner electrode of the capacitor will deviate, thus generating a voltage in the diagonal of the bridge which is dephased to the input voltage. Via two emitter-followers acting as impedance transformers, the bridge signal gets to a transformer, separating alternating from d.c. voltage and fixing the signal to ground. It is then amplified by means of two frequency-compensated amplifiers and demodulated by the phase-selective rectifier via another transformer. The output voltage of the rectifier passes an integrator and a low-pass filter which suppresses frequencies above 10 kHz. The sensitivity of the whole signal modulator is 3.4 mV μm^{-1} in the linear part of the characteristic.

The filtered signal is led to the input of a controller with proportional-plus-integral-plus-derivative action which compensates the displacement caused by the unknown weight via a power amplifier by means of the electrodynamic system.

Usually the potential difference at a precision resistance parallel or in series to the compensating coil is chosen as equivalent to the weight. In the case at hand, the controller output voltage corresponds linearly to the mass on the balance pan because of current feed back of the power amplifier.

2.4 *Experimental result and characteristic data*

The sensitivity of the load cell is 10 mV g^{-1}, the maximum load 1000 g, the limit of sensitivity better than 10 mg. The building-up time corresponding to the load is 0.1 sec maximum. The air-suspension requires 0.15 $m^3 h^{-1}$ and a pressure of 1.5×10^5 N m^{-2}. There is no zero error within the effective range.

The load cell described is a balance without any bearing clearance. It is a contribution to the development of top pan balances. The pan however is not completely freely-suspended because there are three connections from the coil to the controller output and from ground to the inner electrode and the coil, respectively. These connections could influence the weighing result eventually. Therefore, a load cell with freely-suspended pan would be advantageous.

3 A LOAD CELL WITH FREELY-SUSPENDED PAN

A load cell with magnetostatic bearings and a freely-suspended pan is shown in

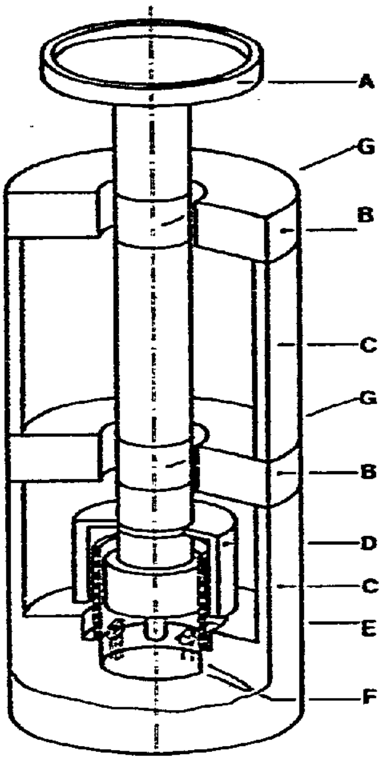


Fig. 13. A load cell with freely-suspended pan. A = pan; B, G = permanent magnet; C = case; D = pot-shaped magnet; E = coil; F = opto-electronic sensor.

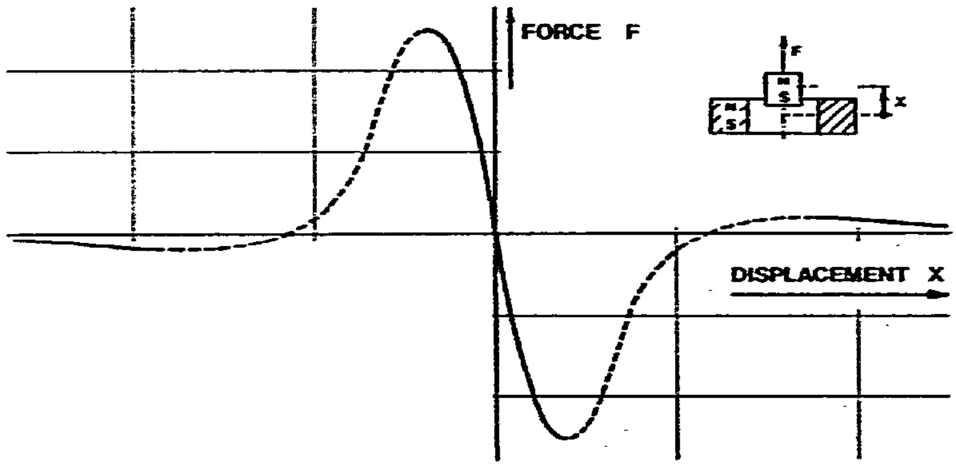


Fig. 14. Characteristic of a magnetic bearing.

Fig. 13. The pan (A), two magnets (G) and the pot-shaped magnet (D) are the essential elements of the moving part of the cell. They are not connected with any of the stationary parts of the load cell that are the two annular magnets (B), the case (C), the coil (E) and the opto-electronic sensor, which is placed within the coil. The

sensing element is a foto-transistor which reacts on a light-emitting diode. The beam of the light is influenced by a metallic nose fixed in the middle of the inner pole of the pot-shaped magnet. The axially magnetized magnets (B, G) act as radial bearing, thus providing for radial stability of the freely-suspended part of the load cell. By skillful use of ferrofluid to support the pot-shaped magnet, the lower magnetic bearing could be removed, the pan being still freely-suspended. The characteristic of the magnetic bearing is shown in Fig. 14. The linear part of the characteristic nearby the zero-point is chosen as working scope. The magnets consist of samarium–cobalt. Axial stability is obtained by automatic control of the vertical position of the pan. The sensor acts on a controller, which generates a current signal. This enters the coil and causes a stabilizing force. The transfer function of the controlling element (D, E) is linear. Therefore, the current corresponds linearly to the weight on top of the pan. At the time the load cell is tested. Results will be published in a later paper.

Both construction principles reported—parallel spring joint suspended load cell with electrodynamic system and magnetic coupling—are applied to the freely-suspended top pan balance described in the following chapter.

4 A LOAD CELL FOR HIGH PRESSURE INVESTIGATIONS

The load cell is developed for thermogravimetric investigations under very high pressure. The principle is shown in Fig. 15. The pan is mounted on a vertically arranged pipe (K) which leads through three axially magnetized annular samarium–cobalt magnets. The pipe ends in a specially shaped short circuit ring. The vertical motion of this ring influences the inductive reactance of a coil (D) which transmits a signal to a controller via a carrier frequency bridge and a phase-selective rectifier. The controller output affects an electromagnet (F) which acts on the middle annular magnet on the pipe thus stabilizing the vertical position of the pan. Horizontal stability is obtained by combining two annular axially magnetized permanent magnets (E, G) with the magnets on top and bottom of the pipe. They act as magnetostatic bearings. The freely-suspended part of the load cell is completely separated from the remaining by a quartz container (I).

The electromagnet is attached to the wall of a cylindrical container which is held by a fork-shaped parallel spring joint (L) fixed by straps to the outer case (H). Fastened to the bottom of this container is a cylindrical skeleton which carries the moving coil (B). The coil plunges into the pot-shaped magnet (A). The skeleton acts as a short-circuit ring which influences the inductivity of a differential transformer (C).

Forces are transmitted from the suspended top pan via the permanent magnets to the electromagnet and vice versa. The latter which is part of the moving electrodynamic system will deviate because of these transmitted forces. The vertical position of the electromagnet, however, must be stable because otherwise stability of the pan-controlling circuit cannot be obtained. Therefore, another regulator controls the vertical position of the electromagnet automatically by means of the differential transformer. Displacements are compensated by the moving coil. The output signal of

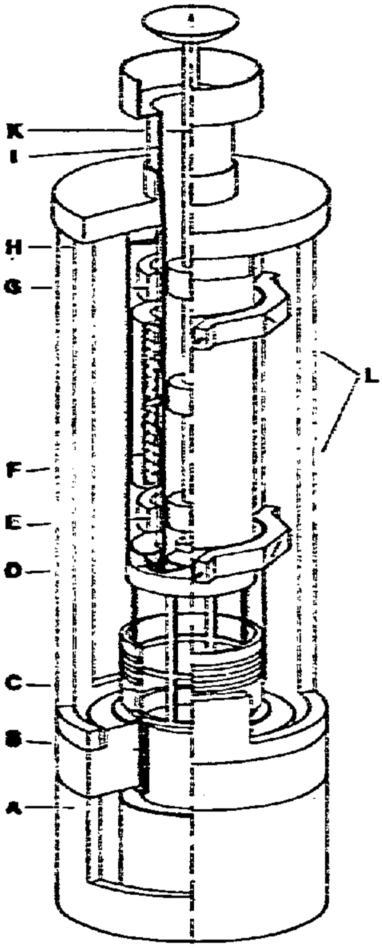


Fig. 15. A load cell for thermogravimetric investigations under high pressure (schematic diagram). A = pot-shaped magnet; B, D = coil; C = differential transformer; E, G = permanent magnet; F = electromagnet; H = case; I = container; K = pipe; L = parallel spring joint.

this controller corresponds linearly to the sample on top of the pan whereas there is a non-linear relation between the sample and the output voltage of the controller mentioned before because of the non-linear behavior of the magnetic suspension. On the rear of the joint, there is a device—not drawn in Fig. 15—to allocate weight pieces taring the weight of the moving electrodynamic part of the load cell. As a result, the plunging coil is currentless when the pan is unloaded. To avoid the risk of a dynamic unstable load cell because of both force-coupled control circuits, they must have a different behavior in time. This is accomplished by adequate choice of the time constants of the controllers.

The load cell is filled with silicone oil except the gas-filled quartz container and is itself placed in a silicone-oil-filled tank. The gas volume which is under very high pressure is in contact with the oil via a diaphragm which acts as a pressure compensator when the pressure changes in the quartz container.

The pan of the load cell is enclosed in a small oven, not drawn in Fig. 15.

In connection with very high pressure, the buoyancy which acts on the mass influences the weighing result. This error is eliminated by a special computer-aided and computer-controlled measuring process. The microcomputer encludes a microprocessor type 8080. First results have been reported by Mirahmadi[6].

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