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NEW DEVELOPMENT IN MICROWEIGHT DETERMINATION BY FREE MAGNETIC SUSPENSION

TH. GAST

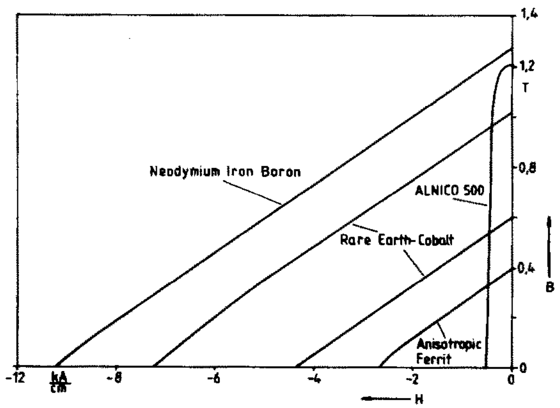
Institut für Meß- und Regelungstechnik der Technischen Universität Berlin,
Budapester Str. 46-50, D 1000 Berlin 30

ABSTRACT

Improvements in the field of weighing with free magnetic suspension are reported. They concern the ratio of load capacity to deadload of a magnetic coupling, the accuracy of eddy current sensors, the elimination of undesired feedback from the control current of the magnetic coupling to a microbalance, adaptive control for the magnetic suspension and direct magnetic weighing without an additional balance.

INTRODUCTION

By previous reports in conferences on vacuum microbalance techniques it has been shown, that balances with free magnetic suspension of the sample can be realized as micro-semimicro - and macro-balances. Progress in the field of such instruments was enabled by new magnetic materials, advanced sensor technique, recent methods of automatic control and variations in the concepts of magnetic suspension. Some examples are presented in this paper.



Magnetization Curves of Various Permanent Magnet Materials

Fig. 1.

IMPROVEMENTS

New magnetic materials

With magnets of rare earth-cobalt and neodymium iron boron /1/, the maximum energy product has been increased sixfold and tenfold compared with ALNICO. Fig. 1 shows typical magnetization curves of the materials in question. The impact of this progress on the design of suspension systems can clearly be seen by comparing the following figures.

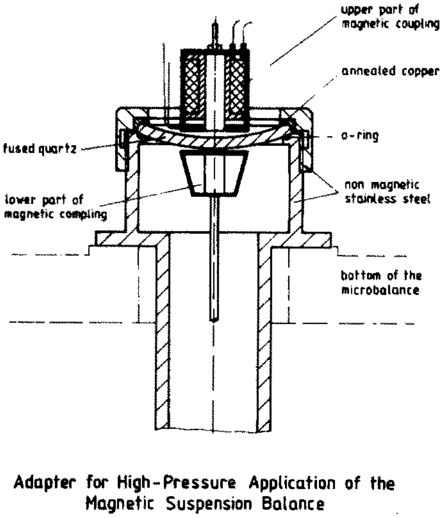


Fig. 2

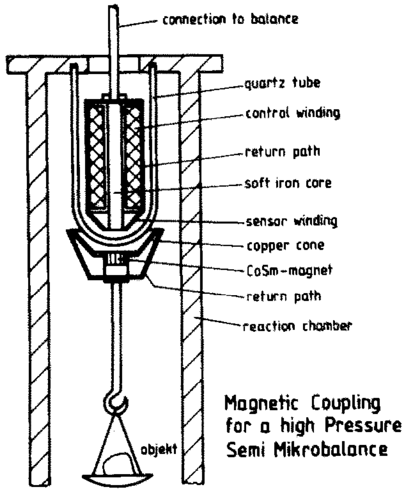


Fig. 3

While figure 2 is a section of the coupling with two ALNICO magnets contained in the suspension balance manufactured by Sartorius, figure 3 shows a new coupling, especially designed for a high pressure suspension balance. The second coupling consists of an electromagnet as the upper part and one small rare earth-cobalt magnet in its lower part. Equal load capacity provided, the weight of the new type is considerably smaller than that of the older one. The high coercive force of the magnet prevents loss of attraction by separation of the coupling. In both examples of couplings, the partition wall between reaction chamber and balance withstands pressures up to 150 bar. The configuration of the second example allows to use a rather thinwalled cupola. Core and return path of the electromagnet and the return path of the permanent magnet consist of cobalt iron-alloy with high saturation magnetization. Material and shape tend to diminish magnetic leakage /2/.

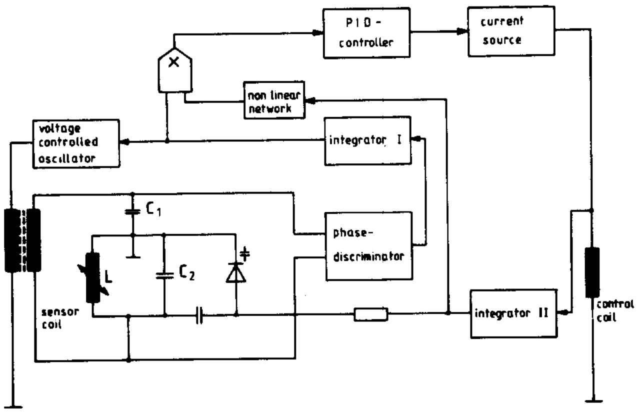
Sensor technique

The eddy current sensor as used in the suspension balance has proved useful. As it is seen in fig. 3, a conical shape of the sensor coil and a conical counterpart of copper can be applied for better adaption to the spherical partition wall.

The sensor coil had been previously inserted as inductivity into the tank circuit of an oscillator, whose frequency served as measure for the distance between coil and conducting counterpart.

The signal of the oscillator was demodulated by a frequency discriminator, while the setpoint for the distance could be chosen by variation of the capacity in the tank circuit. The demodulated signal was fed to the controller whose output current flew through the control winding of the coupling.

A modernised circuit is shown in figure 4.



Block Diagram of the Suspension Coupling with Adaptive Loop Gain Control

Fig. 4

Together with the capacitor C_2, the sensor coil L constitutes an oscillatory circuit which is fed by means of a transformer and a capacitor C_1 from the output of a voltage controlled oscillator /3/. The phases of the partial voltages across L and C_1 are compared by a phase discriminator.

If the frequencies of the VCO and the natural frequency f_n of the oscillatory circuit L C_2 are different, a voltage arises at the output of the subsequent integrator I which brings the frequency of the VCO to unison with f_n. Because of the linear relationship between the frequency of the oscillator signal and the control voltage of the VCO, this voltage is a measure of distance between the sensor coil and its conducting counterpart. It is led to the input of a PID-controller with succeeding current source which supplies the exciting current for the electromagnet.

It is an advantage of this circuit, that the VCO is tuned to the undamped natural frequency of the circuit consisting of L and C_2. The sensor is therefore only slightly temperature dependent. A second advantage is offered by the very low noise of the demodulation, which allows high amplification in the control circuit.

The voltage at the control winding is fed into the integrator II and from there through a resistor to a varactor connected in parallel to the oscillatory circuit formed by L and C_2. The capacity of this diode determines the set point of the distance between sensor coil and counterpart. Consequently, the distance varies until the mean value of the controlling current is zero. The generation of heat in the control winding is thereby minimized.

I will come back to this measure later on.

It could be necessary, to provide a partition wall of nonmagnetic metal in order to withstand very high pressures.

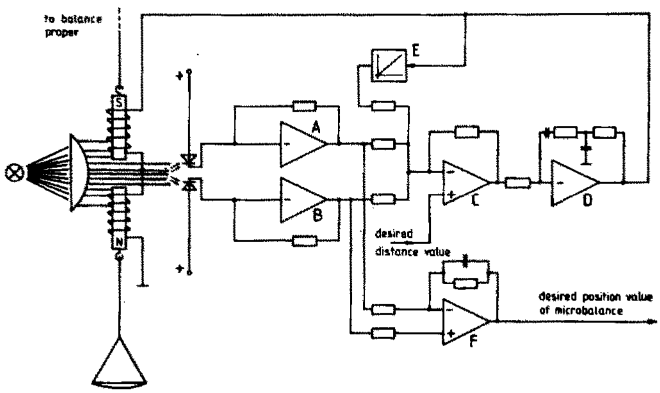
In this case, the position of the lower part of the coupling can be measured absolutely by an optical sensor or an eddy current sensor placed in the reaction vessel / 4 /.

In the course of the last years a number of optoelectronic sensors became available, which allow to measure accurately the distance of the upper and lower parts of the coupling or the absolute position of the lower part.

Without going into details, I would like to mention in this context especially the glass fiber sensors, which allow the transmission of signals through very narrow bore holes. This may be important for high pressure applications /5/.

As an example for the improvement of an optoelectronic sensor by additional circuitry,the magnetic suspension according to fig. 5 is chosen /3/. It serves as coupling between a balance pan and a microbalance. Two bar magnets are attracting one another. The distance between the adjacent poles is stabilized by means of a stationary coil and a sensor arrangement which controls its exciting current.

Collimated light from a LED passes through the pole gap of the magnets onto two photodiodes. The sum of the received light fluxes is formed by the amplifiers A, B and C. It depends linearly on the distance of the poles and is compared with a setpoint by the amplifier C. A controller D follows which stabilizes the pole distance by a current through the stationary coil. In order to obtain the set distance, the controlling current will probably differ from zero. If we assume, that the set point of pole distance corresponds to a roughly symmetrical position of the magnets with regard to the coil, the feed-back of the control winding onto the balance will be small, but usually not zero. The feedback can be reduced, if the control current is brought to zero by an additional control loop.



Distance, Current and Symmetry Control of the Magnetic Coupling for Microbalances

Fig. 5

The loop comprises the integrator E, with the voltage drop across the controlling coil as input signal. The output signal of E is added to the distance signal at the input of C.

Thus, the distance of the poles is adapted to the load, as it is reduced with increasing weight and vice versa, until the controlling current more or less disappears.

Unfortunately, the benefit of this action is partially lost because symmetry cannot be maintained in the magnetic system. This is unavoidable because the upper magnet is rigidly kept in position by the microbalance while the distance of the magnet poles changes. There are three ways of correction. The first consists in inserting a helical spring in the suspension of the upper magnet, preferably of nonlinear characteristic matched to the law of attraction between the magnets. The second way is shown in fig. 5. The difference of photocurrents is formed by the delayed amplifier F and applied to change the desired position value of the microbalance. Possible changes in zero point and sensitivity of the balance could easily be corrected. The third mode of correction provides vertical displacement of the photodiodes together with the coil and the light source by means of a miniature electromotor driven by the output of F.

Control technique

The stable magnetic suspension can be principally realized with a PID-Controller. If high quality of control is essential, e.g., in an environment with strong vibrations, adaptive control may be useful, especially with large variations of load. The additional loop for current control has been already mentioned. It causes a superproportional enhance of open loop gain, if load increases. Thus, the natural frequency of the system changes. In order to keep the dynamic properties of the coupling constant, an adaptive control path can be established. As a measure of load, the controlling voltage of the varactor can be used. According to fig.4 it is led over a nonlinear network to one input of a multiplicator which determines the loop gain of the control circuit.

There is at present no demand for digital signal processing in the control circuit of the suspension balance.

Nevertheless, it should be mentioned, that signal processors are available which can be useful for this purpose. The application of such a signal processor in a model suspension has recently been described / 6 /.

Input and output of the processor are analogue, thus it can e.g., be inserted in the signal path between an optoelectronic sensor and a current source, just as the controller D in fig.5 .

Concepts of direct weighing in free magnetic suspension

In equilibrium, the weight of a magnetically suspended part is equal to the force F of attraction between the poles of the upper and lower part of the system. The force is given by the equation

$$F = \frac{1}{2} \mu_0 H^2 A = \frac{1}{2\mu_0} B^2 A = \frac{1}{2\mu_0} \phi^2 A$$

The weight of an object is therefore retraceable to a difference in attraction forces. Consequently it is possible to renounce a separate balance and to determine the unknown mass of the object from a magnetic variable of the suspension directly.

The first variable considered is the current through the coil of the electromagnet which keeps a low retentivity armature in free magnetic suspension. This has, indeed been attempted long ago / 7 /. The force of attraction for a given current depends in a rather complicated manner on shape and size of the ferromagnetic parts and on their magnetical state. It is also temperature dependent and affected with hysteresis. Though it seems feasible to realize suspension balances in this way, especially with the aid of a computer, other possibilities will be regarded in the following.

Weighing could for example be led back to the measurement of magnetic flux with the aid of an auxiliary winding around the central pole of a coaxial upper magnet. But this would only be applicable for rapid changes of weight because of the inevitable drift in the result of the necessary integration.

Another possible method consists in pulse width modulation of the exciting current by a control loop which keeps a constant distance between the adjacent poles of upper and lower part of the coupling. Though the ratio of time intervals could be measured very accurately, the problem of providing reliable upper and lower levels of flux seems to be difficult.

Measurement of the magnetic field strength in the air gap should be one reasonable way to determine the force between the poles of upper and lower parts of the system. Hall probes and magnetoresistors fail to possess the resolution necessary for weighing purposes. Concerning the Faraday effect, multiple reflection in a parallel plate would be necessary, to obtain an average value of field strength by magnetic rotation, but the method seems not hopeless. Magnetic rotation by thin layers of ferromagnetic materials, for example garnets should also be considered / 8 /. Measurement of the field strength by nuclear magnetic resonance would be sufficiently accurate, but too expensive for this application.

A possible solution for the task of direct weighing with magnetic suspension is based on the cascade control for the exciting current of the electromagnet in figures 4 and 5 Because the current is zero in equilibrium, the law of attraction between the unexcited upper magnet and the permanent magnetic system underneath determines the distance for a given weight.

The characteristic is shown in fig.6 IV. It is curved in such a manner, that the reciprocal value of distance increases out of proportion to weight.

If the distance is measured with the already mentioned eddy current sensor, the resulting frequency f increases subproportional with the reciprocal distance /9/. This function is drawn in fig. 6 III.

In this way, the function f (m) is to a certain extent linearized, which can be seen in fig.6 I. The weight, as displayed by a computer, is accurate to 10^{-4}. It is hoped to improve the accuracy in the course of further development .

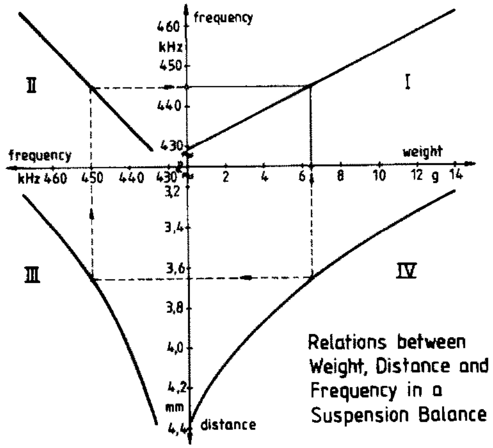


Fig. 6

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