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IMPROVED BECKER'S FRICTION VACUUM GAUGE

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The possibility to optimize the Becker's design of the friction vacuum gauge "REVA" has been investigated. The basic part of the gauge "REVA" is a metal ribbon stretched across magnetic field as a string ("string" gauge). The vibration of the ribbon is excited by an alternating current. The amplitude of the vibration is determined from the induced voltage and stabilized by varying the supply current according to the damping produced by gas molecules. This principle is analogical to that of the usual Pirani gauge control. The magnetic induction in the area of the string is for the sensitivity of the string gauge as important as the temperature of the heated filament is important for the sensitivity of the Pirani gauge. The shape of the magnetic field has been optimized according to the computation, using a finite element method. In order to achieve sufficient mechanical accuracy necessary for the optimal properties, a bifilar arrangement was chosen.

1. *Introduction*

Although the gas pressure is used as the basic quantity for measurement of vacuum, the forces exerted by the gas are so weak that their measurement is difficult already in the range of medium vacuum. Some alternative ways are used, e.g. measurements of a flow rate of some physical quantity transferred by gas molecules.

In fact, the volume concentration of particles is measured and it is usually converted into pressure units, assuming equilibrium gas state with known temperature.

The most widespread gauges of this type are those based on heat transfer measurement, e.g. the Pirani gauge. Its range is from 10^2–10^3 to 10^{-1} Pa. The gauge is of simple design, the output signal is directly electric and the necessary circuit is also comparatively simple. The whole apparatus is inexpensive and reliable. But it has also several disadvantages. From the fundamental point of view, an element of different temperature is introduced into the gauge and the equilibrium is inevitably disturbed; the conversion to the pressure units becomes more or less formal. In practical measurements, errors occur, especially when vapours near condensation are present.

The gauges based on momentum-transfer measurement, usually called gas friction gauges, can be used for this pressure range, too. The designs are not too tricky, all parts of these gauges have the same temperature and the readings for various gases depend only on $\sqrt{M}$. But the ways of reading the gauge signals (usually changes of amplitude or frequency of movement of some object within a certain interval) and converting them into electric signals for displays or process-control are more difficult than with the heat-transfer gauges. Up to now, the most successful design of gas friction gauge is VISCOVAC - the spinning rotor gauge. It is a precise gauge useful for calibration, but rather expensive for routine measurements.

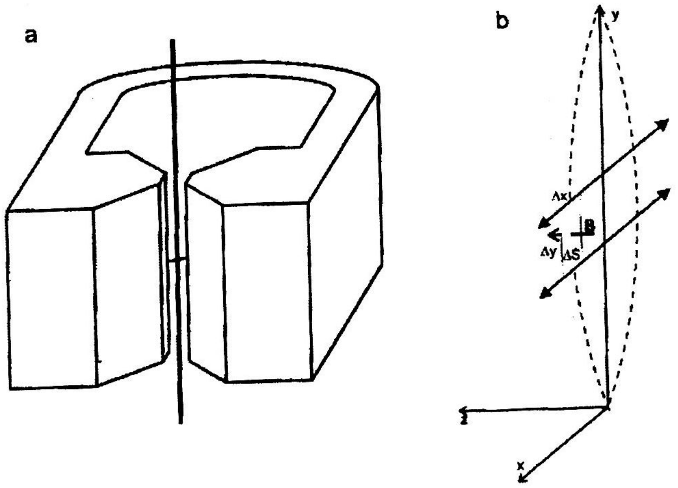

Fig. 1. a) Basic arrangement of the Becker's gauge and b) symbols of the quantities used in formulas.

In 1959 Becker [1] designed the friction manometer REVA with an interesting way of converting the output signal into the electric one. An object in vacuum is set into vibration by means of alternating current. The amplitude of the vibrations is picked up electrically and stabilised at a constant value by changing the exciting current. As the damping produced by gas molecules is (in a certain pressure range) proportional to the pressure, the power necessary for the amplitude stabilization is the measure of the pressure. Becker used a vibrating string, i.e. narow metal ribbon stretched across a magnetic field (schematically shown in Fig. 1a).

Arrangement similar to the original Becker's one was chosen in our laboratory to test it as a gauge for water vapour measurements. The main aim of our work was to improve the sensitivity of the Becker's gauge and to develop a design usable as a manometer suitable not only for tests but also for everyday measurements.

2. Theory

In order to understand what the sensitivity of the Becker's gauge depends on, let us compare it with the Pirani gauge. The sensitivity of the Pirani gauge is greater when the difference between the temperature of the heated element and the temperature of the walls is larger, at a certain value of the supplied power, because larger is also the heat transferred by gas. The heat transfer caused by gas molecules would diminish this temperature difference if it were not stabilized by the electronic control. The sensitivity of the Becker's gauge is the greater when the voltage induced in the ribbon at a certain value of the supplied power is larger. The momentum transfer carried by gas molecules would diminish this voltage if it were not stabilized by the electronic control. The ribbon of the string manometer represents a one-turn coil moving in the magnetic field. The induced voltage u_j equals the time derivative of the magnetic flux Φ. In a small part of the string Δy (see Fig. 1b) the induced voltage is

$$u_i = \frac{\mathrm{d}\Phi}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\int\limits_{\Delta S} B\mathrm{d}S = \Delta y \frac{\mathrm{d}}{\mathrm{d}t}\int\limits_{x}^{x+\Delta x} B\mathrm{d}x = \Delta y \frac{\mathrm{d}}{\mathrm{d}x}\int B\mathrm{d}x \frac{\mathrm{d}x}{\mathrm{d}t} = \Delta y B \frac{\mathrm{d}x}{\mathrm{d}t}. \quad (1)$$

Let us suppose that the whole string is in constant field B. Then, if the current through the string is $I\cos(\Omega t)$, the exciting force F per unit length does not depend on y along the string. The damping of each small part of the string is proportional to its speed with the coefficient of proportionality $2b$. Then the equation for the string vibration is

$$-\frac{\partial^2 x}{\partial t^2} + c^2 \frac{\partial^2 x}{\partial y^2} - 2b\frac{\partial x}{\partial t} + \frac{l}{\rho}F(t) = 0,$$

where c is the speed of elastic waves and ρ is the mass per unit length of the string. A solution of this equation is a standing wave

$$x(y,t) = A\cos(\Omega t + \varphi)\cdot \sin(\pi y/l). \quad (2)$$

where A is the amplitude, l is the length of the string and φ is the phase shift between the exciting current and the string vibrations. Analogically to the linear harmonic oscillator, the amplitude A can be considered proportional to the term

$$A \approx \frac{BIl}{\sqrt{(\omega^2 - \Omega^2) + 4b^2\Omega^2}} \tag{3}$$

where ω is the natural frequency of the string and I the amplitude of exciting current. From equation (1), the induced voltage is proportional to

$$u_i \approx B\frac{\mathrm{d}x}{\mathrm{d}t}. \tag{4}$$

From equation (2)

$$\frac{\mathrm{d}x}{\mathrm{d}t} \approx A\Omega. \tag{5}$$

Thus

$$u_i \approx B\Omega\frac{BIl}{\sqrt{(\omega^2 - \Omega^2) + 4b^2\Omega^2}}. \tag{6}$$

Frequency of the exciting current is assumed equal to the natural frequency of the string ($\Omega = \omega$)

$$u_i \approx \frac{B^2Il}{2b}. \tag{7}$$

The most efficient way to increase the sensitivity is to raise the field B as much as possible.

3. *Optimization of the magnetic field in the gauge*

Most of the magnetic flux should be concentrated in a narrow area along the string. The width of this is only several tenths of milimeter. Magnetic field near the median plane (see Fig. 2) can be considered translationally symmetric. For the reasons of symmetry, the field B in the median plane cannot have a component perpendicular to this plane. The vector potential there must be perpendicular to the plane. With these assumptions it is possible to compute the field by means of a two dimensional finite element method. The method described in Ref. 3, adapted for translationally symmetric problem was used. The shape of the magnetic field in the median plane was calculated for various widths of the gap, the angles and widths of the ridges of the pole pieces. An example of the results is shown in Fig. 3.

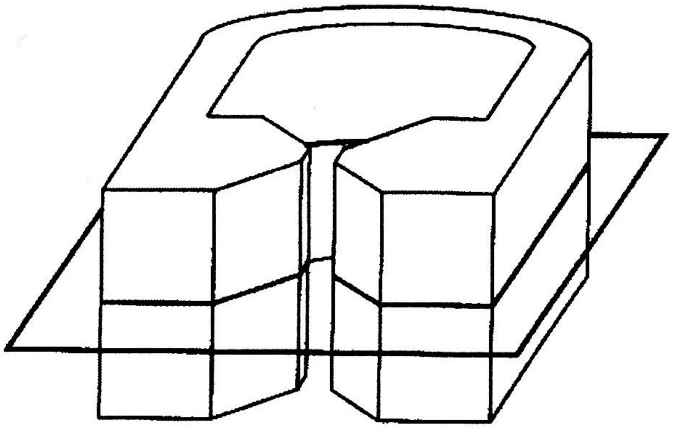

Fig. 2. The median plane of the magnet.

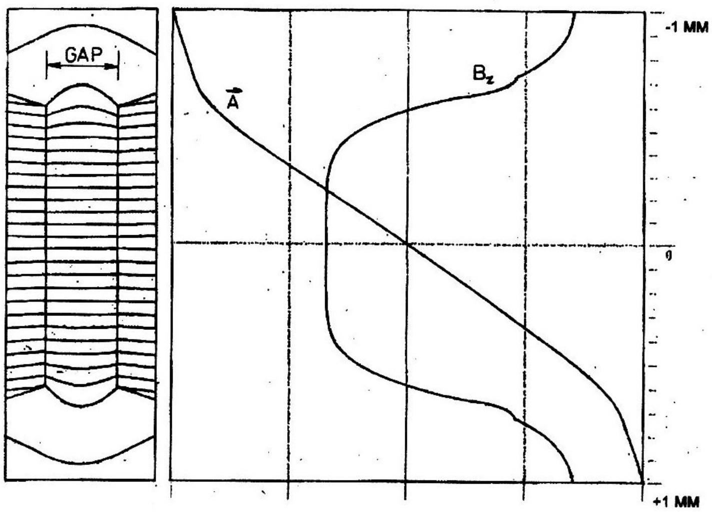

Fig. 3. An example of the results of computations: lines of induction in the gap of the magnet and the corresponding curves of the vector potential and the magnetic induction.

Some important conclusions for the design of the Becker's gauge can be drawn from the results of the computation:

1) The ratio between the width of the gap between the pole pieces and the width of the pole piece ridges is of crucial importance for the maximal field B and

its uniformity within the gap. The angles of the pole piece ridges slightly influence the uniformity.

2) The gap should be as narrow as possible so that (even when using only permanent magnets for exciting the field) it is easy to achieve an induction within the gap greater than 2 T.

The shape of the pole pieces was optimized according to the results of the computations in order to reach the maximal value of the field B in the space around the string. The most suitable materials for the pole pieces are alloys of iron and cobalt or pure iron.

4. The design of the gauge

Because the gauge should be used for routine measurements, the gauge should be small. The magnetic field is excited by means of permanent magnets of ALNICO type. The maximal field B which can be reached within the gap of the magnetic

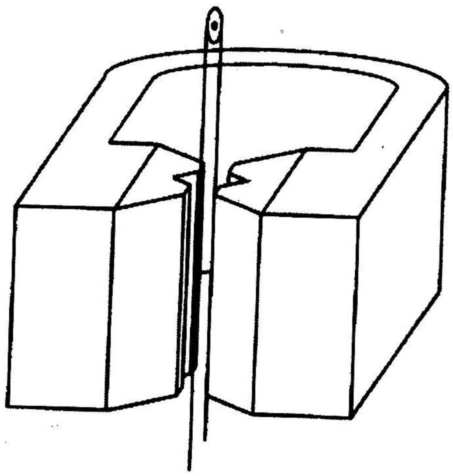

Fig. 4. The bifilar arrangement of the string gauge schematically.

circuit is limited by the saturation of the material of pole pieces. The alloy PERMENDUR (50 % Fe 49 % Co) was used; its B_s is approximately 2.35 T. The gap between the pole pieces was adjusted so that a slight oversaturation occurred at the ridges of the pole pieces. That should improve the uniformity of the field in the gap even if the tops of the pole pieces are not perfectly smooth. The gap should be as wide as possible in order to enable free movement of the string which is made of a ribbon as wide as possible. Pole pieces with two ridges and a pair of strings bring a considerable advantage at positioning over the original arrangement used by Becker. The string is turned round a small roller so that each part of the string passes between one pair of the pole-piece-ridges (schematically shown in Fig. 4). This arrangement has one additional advantage in a lower sensitivity to external vibrations, because these vibrations cause the movement of both parts of the string in the same direction while the electric current through the string causes the movements of each string in the opposite directions.

5. *Conclusions*

A gauge according to the above mentioned considerations concerning magnetic field and geometry was designed in our lab. There are some other parameters which can be varied to find optimal properties. They are:

1) The material of the string
2) The thickness and width of the string
3) The tension of the string.

The optimization of these parameters should be done experimentally. Thorough tests of the properties of the improved Becker's gauge are necessary before its practical use.

References

1) W. Becker, Vacuum **11** (1961) 195;
2) Z. Herynek, Diploma work (KEVF MFF Charles University Prague, 1991);
3) W. Kamminga, J. Phys. D: Appl. Phys. **8** (1975) 841.

POBOLJŠANA BECKEROVA VAKUUMSKA MJERKA

Vibracije trake razapete u magnetskom polju uzbude se izmjeničnom strujom. Amplituda vibracija se određuje i stabilizira pomoću induciranog napona. Veće gušenje uzrokovano trenjem molekula pri višem tlaku zahtijeva jaču uzbudu i to služi za određivanje tlaka. Radi poboljšanja mehaničke izvedbe i smanjenja osjetljivosti na vanjsko magnetsko polje, odabran je bifilarni sustav.