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GENERAL CLASSIFICATION OF THE ELECTRICAL METHODS FOR MEASURING MECHANICAL QUANTITIES

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Abstract: The main purpose of the paper is to outline the essential properties, principal classes and most widely used principles / methods / approaches typical for the modern instrumentation in the area of electrical measurement of force and related quantities (such as torque, pressure, strain, vibration). For beginning, the concepts of *sensor* and *transducer* are clarified, emphasizing that the sensor is the element being influenced by the measurand, while the transducer is usually a more complex device performing the input-output conversion. A general classification of the *electrical methods* for measuring mechanical quantities is proposed, comprising 12 basic plus two additional classes. Another classification is given for twelve types of *elastic elements* of force transducers. Finally, a few typical examples are chosen to illustrate the domains of the TC3 (Force, Mass and Torque), TC5 (Hardness) and TC22 (Vibration), jointly organizing this IMEKO conference in Cape Town, Republic of South Africa.

Keywords: electrical methods, measurement principles, sensors and transducers, elastic elements, mechanical quantities

1. INTRODUCTION

In accordance with the international terminology of metrology, *sensor* is the item that measurand directly influences, while *transducer* is the device that enables the correspondence (conversion) between input and output quantities, in compliance with a specific law.

The measurement engineers prefer to classify transducers according to some variable parameters (resistance, inductance, capacitance), and then to add transducers generating voltage, charge or current, and other sensing devices not included in the preceding groups [1].

2. GENERAL CLASSIFICATION CRITERIA

Based on several classifications existing in the technical literature (among them [2]), a most general systematization of the electrical methods for measuring mechanical quantities is proposed by the author [3], introducing 12 classes: resistive, inductive, capacitive, piezoelectric, electro-magnetic, electrodynamic, magnetoelastic, galvano-magnetic (Hall effect), vibrating wire, resonant, acoustic, and gyroscopic.

As a special category, optical methods may be added, which represent some subtle combinations of fine mechanics and advanced electronics.

Apart from the above mentioned measuring principles, there exist others that would be difficult to classify in these categories, like those used in solid-state electronic devices (e.g. tunneling current) or CNTs (carbon nanotubes), that could equally be considered as piezoresistive, piezo-electric or resonators. We prefer to treat them as complex methods.

These 14 classes of transducers together with their working principles are shown in Table 1.

With regard to the measurement range, piezoelectric, magnetoelastic and resistive transducers are able to measure forces higher than 100 MN, while capacitive, galvanomagnetic, as well as MEMS (micro-electro-mechanical systems) resonator transducers attain forces down to very low values, i.e. piconewton level.

The most widespread force transducers use resistive strain gauges. They may be associated with elastic elements (EE) of various shapes; an extended classification of them is presented by the author in [4]: stretched / compressed column, stretched / compressed tube, *cantilever* (bending beam, see Fig. 3), bending and/or torsion shaft, middle bent bar with fixed ends, shear beam, bending ring, yoke / frame, diaphragm, axial-stressed torus, axisymmetrical and voluminous EE.

The description of these elastic elements will be further detailed (dimensions, mechanical and electrical sensitivities, and force range) in the oral presentation.

Table 1. Types of transducers for measuring force and related mechanical quantities

No	Types	Operating principles (*in italics are those illustrated by slides during the oral presentation*)
1	Resistive	*Strain gauge*, pretensioned wire, potentiometer, piezoresistive film, conductive polymer
2	Inductive	LVDT (linear variable differential transformer), reluctive, mutual inductance, *eddy current*
3	Capacitive	*Differential overlapping*, variable angle, air gap or thickness of dielectric pad
4	Piezoelectric	*Quartz crystal*, organic polymer (PVDF), solid state sensor and actuator
5	Electromagnetic	*Magnetoresistive*, magnetic flux quantum, magnetic higher-order harmonic fields
6	Electrodynamic	*Electromagnetic force compensation* (EMFC), tester with moving coils
7	Magnetoelastic	*Magnetostrictive strip* or amorphous wire, various shapes of magnetoelastic elements
8	Galvanomagnetic	*Hall devices* (e.g. transverse voltage strain gauges based on the Hall effect)
9	Vibrating wire	*Piano wire electromagnetically plucked* measuring force and other related quantities
10	Resonant	Various shapes of quartz or silicon, *metallic resonator*, double-ended tuning fork (DETF)
11	Acoustic	*Surface acoustic wave* (SAW) *devices* with interdigital transducers (IDTs)
12	Gyroscopic	*Classical*, inertial, vibratory (resonator), with SAW, based on Coriolis force or optical
13	Optical	*Fiber Bragg gratings*, interferometers (e.g. Fabry-Perot), atomic force microscopy (AFM)
14	Complex	*CNT*, solid state devices, electromagnetic (Lorentz force) acoustic transducer (EMAT)

3. UNIVERSAL SIGNAL CONDITIONER

All these types of transducers may be connected to a universal signal conditioner [5].

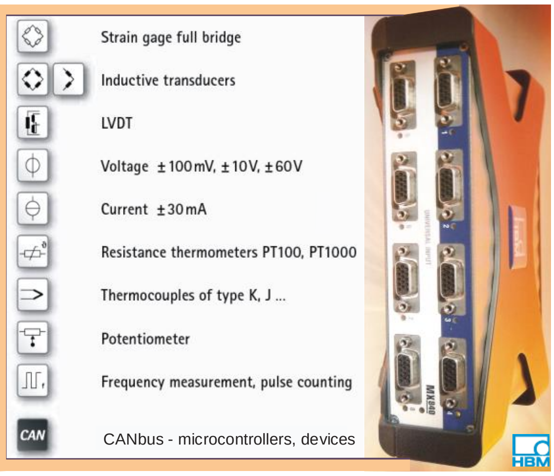

Fig. 1. HBM Universal Signal Conditioner

Pictograms in the left side of the Figure 1 illustrate the wide possibilities of use:

– Strain gauge full bridge is suitable for the resistive, magnetoresistive and CNT ones.
– Reactance bridge can be used in association with differential capacitive transducers.
– LVDT is compatible with a wide category of inductive transducers.
– Piezoelectric, magnetoelastic and galvano-magnetic transducers have a voltage output and their input supply is also a voltage.
– Electrodynamic (force balance) transducers are fed with current.
– The “Frequency Measurement” mode may be used in conjunction with “intrinsically digital” transducers (resonators, vibrating wires and gyroscopes) and equally with any other transducers by adding an analog-to-digital converter (which improves their resolution / sensitivity / accuracy).
– The “Pulse counting” input is intended for acoustic and optical transducers.

4. APPLICATIONS

TC-3: The PTB electromagnetically compensated balance (ECB) includes some interesting combinations of a variety of measurement principles (resistive – strain gauges, capacitive, piezoelectric, electromagnetic) and computerized signal processing [6].

The balance set-up is shown in Figure 2. Sartorius WZ 215-cw (210 g) or WZ 1203 (1200 g) are used as force transducer. The piezoactuator is a 100 µm PIFOC® with a capacitive transducer and a PI controller. A U1A strain gauged transducer and a precision DMP40 amplifier (HBM) are used for testing purposes.

The spring constant of the rack (including the traverse, the stage and the basis, clamps the ECB, the force transducer under test and the force generator together) is 1 MN/m, i.e. applying a load of 1 N produces a 1 µm bending.

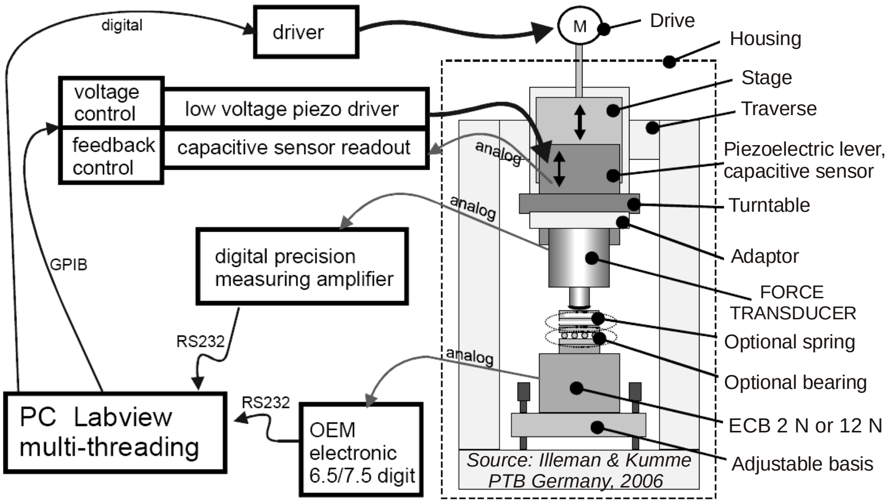

Fig. 2. The PTB electromagnetically compensated balance used as a force standard machine

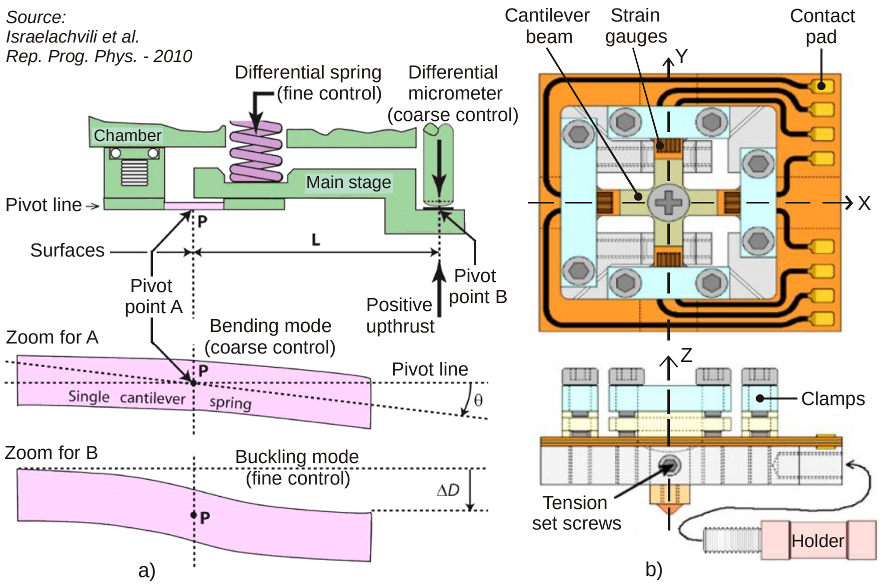

Fig. 3. The evolution from single- (a) to four-cantilever (b) elastic elements in surface force measurements

This equipment can be used as a **force standard machine** (FSM) with a range of a few newtons and a feed-back stabilized resolution of micronewtons. The traceability to the force definition is ensured by the subsequent calibration of this balance using newton-equivalent dead-weights.

TC-5: Measurement of force is essential in applications concerning **hardness** determination as well. A suggestive example is the surface forces apparatus (SFA), whose evolution and recent advances have been presented in [7]. The basic unit for normal and adhesion force measurements, SFA 2000 has one central single-cantilever spring used for generating both coarse and fine motions over a total range of seven orders of magnitude below millimeters. Due to this bistable device, two kinds of pivoting motions are possible (Fig. 3,a):

- The *bending mode*, when a *normal force* is applied by the coarse control micrometer, the pivot point A being just at the center P of the cantilever;
- The *buckling mode*, when the force is applied by the fine control on a helical spring, due to the resulting *side effect* of the spring the pivoting being at point B and the cantilever in the *buckling mode* (a rare case when buckling is a useful / stable situation!).

A **multi-component force transducer** as well as the increasing of strain gauge sensitivity for each measured component could be obtained by multiplying the number of cantilever beams. A significant improvement in the SFA area has been brought by the miniature 3D attachment (Fig. 3,b). The probe is held in the center of a four-cantilever foil, that is like a cross spring made of a single 25 µm thick titanium foil. Deflections of the probe in the X, Y and Z directions are detected by eight strain gauges, bonded on both sides of each cantilever. The sensitivity of the four-cantilever spring can be readily varied by *in situ* adjustment of the tensions on the foils. This sensing device could be scaled from macro- (tribometer, **indenter**) to medium- (SFA) or nano-scale (AFM – atomic force microscopy).

TC-22: A Quartz Crystal Microbalance (QCM) is based upon a piezoelectric crystal and its **vibration** in thickness shear mode. It works on the principle of measuring a small change in resonant frequency of an oscillating piezoelectric crystal due to change in mass on the sensor surface [8]. The resonant frequency of a quartz crystal is a linear function of the mass of material deposited on the crystal surface. Due to their small dimensions and high stiffness, piezoelectric transducers are ideal for **dynamic force measurements**.

5. CONCLUSIONS

As a conclusion, most *transducers* are based on a common principle: the applied load modifies certain properties (electric, magnetic, acoustical or optical) of a sensor, which, in turn, are converted to an adequate (usually electric) output signal. The included sensors are called, in the majority of cases, *strain gauges* [9].

We have attempted to point out first of all two basic matters concerning the electrical methods for force or other mechanical quantities measurement:

- systematization of the measuring principles;
- classification of the elastic elements used in parametrical transducers (R, L or C).

Our endeavour has not a purely "academic" significance; we believe that its results could be of a real scientific, educational and practical importance. In this paper three complex applications were presented, illustrating the wide possibilities of the transducers for electrical measurement of mechanical quantities.

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