Journal of Thermal Analysis and Calorimetry, Vol. 71 (2003) 19–23

SURVEY ON MASS DETERMINATION SYSTEMS
Part I. Fundamentals and history

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Abstract

The influence of mass and force on the frequency of vibrating bodies today is widely applied. In Part I of the survey the historical roots are reviewed and the physical principles of the several arrangements modes of operation explained.

Keywords: balance, history, oscillator, pendulum, quartz balance, vacuum

Historical remarks

After the 'Review on modern vacuum microbalances' [1] which covered electromagnetic beam, spring and suspension balances we continue in this paper with oscillating systems. Mass and force determination based on mechanical oscillators is a pretty new measuring techniques though the influence of tension on a string was known since lutes, harps and fiddles existed. Already 200 years ago elastic waves were studied experimentally and theoretically [2]. However, in the 19th century mechanical beam balances achieved the extraordinary relative sensitivity (sensitivity/maximum load) of 10^{-9}. So there was no motive to concern with other principles for mass determination apart from the very simple spring balance.

The effect of added mass on crystal frequency has been known since the early days of radio when frequency adjustment was accomplished by a pencil mark on the controlling quartz crystal. Sauerbrey was the first to investigate theoretically and experimentally the quartz crystal's suitability for determining mass [3, 4]. Probably independent, Warner and Stockbridge developed a quartz crystal balance based on long years research on application of quartz crystals [5]. In the same year Wade and Slutsky reported on adsorption measurements of water vapour and hexane at a vibrating quartz crystal [6]. A period of lively activity and enthusiastic research and devel-

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1418–2874/2003/ $ 20.00

Akadémiai Kiadó, Budapest
Kluwer Academic Publishers, Dordrecht

opment was initiated, in the course of which the quartz crystal microbalance (QCM) underwent considerable improvements and became very widely used. Already 1971 King Jr. had been asked to present a survey [7] and in 1984 the applications were reviewed in a book [8].

Besides cheaper materials were applied in the form of strings, ribbons and thin-walled hollow bodies. The suitability of a horizontally arranged rotary pendulum for adsorption measurements was investigated. The application potential of oscillators for mass determination is still not exhausted. The following review is based on the chapter ‘Vacuum Weighing’ [9] in Kochsiek/Gläser’s ‘Comprehensive Mass Metrology’ and supplemented by recent developments.

The principle

Determination of mass by means of mechanical oscillators is based on inertia. The coupling of an additional mass changes the resonance frequency, and this can be registered quickly and with high precision. The connection between frequency and mass may be calculated by means of an analytical equation which expresses the basic physical law. As a rule, it is preferable to calibrate the system, whereby due to the relatively small changes, an empirical linear interrelationship between the changes in mass and frequency can be assumed. For a thickness shear quartz oscillator the interrelationship between the mass m_s deposited on the quartz crystal with a mass m_q and the change in frequency Δf, these causes can be expressed in simplified form by the equation:

$$\frac{m_s}{m_q} = \frac{-\Delta f}{f_q} \tag{1}$$

where f_q is the frequency of the unloaded crystal. This relationship given by Sauerbrey is applicable to mass loads that constitute layers that are thin in comparison with the thickness of the crystal. For thick layers, different geometry’s of the oscillating body, other materials etc. modified equations had been derived.

Piezoelectric, electrodynamic, electrostatic and magnetostrictive transformers can be used to excite the oscillation, displacement, velocity and acceleration sensors used for detection. Sensors with binary output signals are also suitable. To generate self-starting autonomous oscillations, the sensor is coupled back to the exciter, a phase-locked reaction coupling being frequently used.

The sensitivity of the mass determination is restricted by the interval during which the resonance frequency is subject to stochastic fluctuations. Mechanical oscillators react sensitively to ambient parasitic indications such as temperature, pressure, humidity and interfering fields. Systematic deviations related to these are either compensated or corrected. Ageing can also be a source of error.

Modes of operation

An elastic body can be stimulated to oscillations of different shape and mode as indicated in Figs 1–3. In general mass and force sensors produce continuum oscillations – though their modelling often may be simplified – also discrete spring-mass-oscillators are applied.

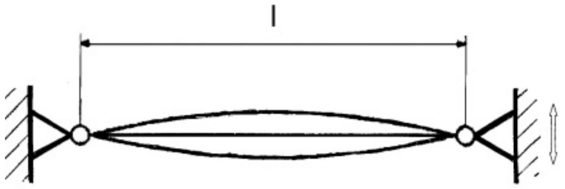

Fig. 1 Transversally oscillating belt

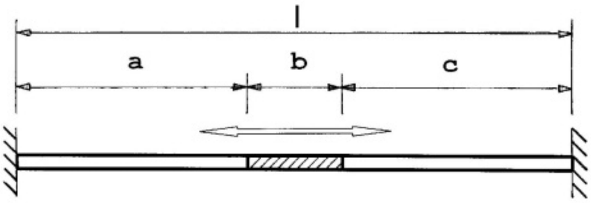

Fig. 2 Longitudinally vibrating ribbon

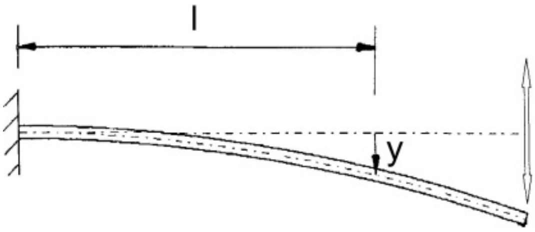

Fig. 3 Flexural resonator

The shape and mode of motion of the crystal are of crucial importance for its function. A mode of function extremely well suited to mass determination is the thickness shear mode of a thin lamina, the upper and lower surfaces of which have an antiparallel movement and remain undistorted (Fig. 4). Certain orientations of the surface to the crystal's axis (AT cuts, BT cuts) result in these modes of motion and enable the temperature coefficients of the resonance frequency to be optimised.

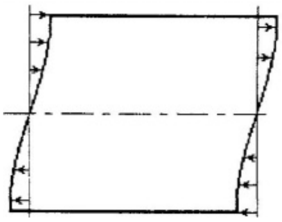

Fig. 4 Thickness shear vibration of a quartz crystal (SC-cut)

Vibrating particle

In the Millikan experiment charged particles are suspended in a constant electric field to determine the relation e/m of charge to mass of a suspended particle [10].

Straubel improved this method by superposition of an alternating field (Fig. 5).

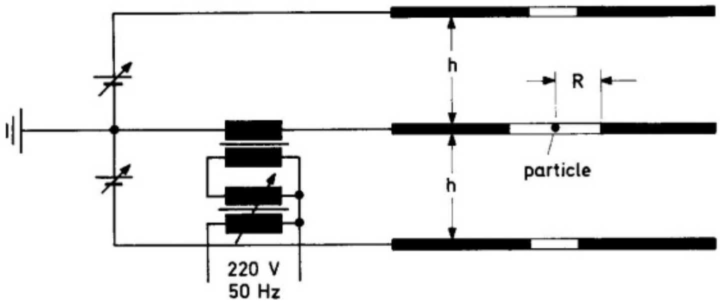

Fig. 5 Determination of e/m of particles suspended in an alternating electric field according to Straubel

An electrically charged particle with mass in the nano- and picogram range is suspended electrostatically in the inhomogeneous alternating field of a three-plate capacitor. The alternating field keeps the particle in a stable position in the bore hole of the intermediate electrode; a constant field between the outer electrodes may be applied to counterbalance the mass of the particle. Relative mass changes due to sorption or vaporisation are determined from the onset of oscillations caused when the stabilising a.c. voltages is raised. In this way changes of less than 1 pg can be observed. If the charge, which exhibits always discrete values is determined by an independent method, the absolute mass can be determined [11].

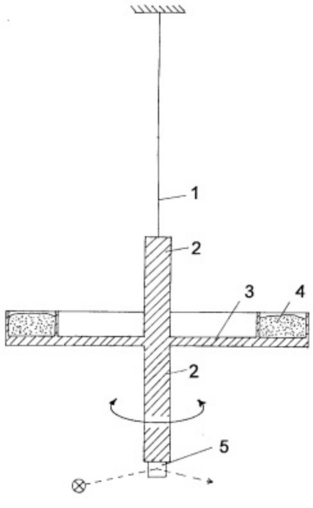

Fig. 6 Diagram of a rotary pendulum for adsorption measurements on a powder sample. 1 – torsion wire, 2 – stabiliser, 3 – disc, 4 – grove with sample, 5 – mirror to reflect a laser beam

Pendulum

A very troublesome effect in traditional weighing under gravity with changing gas pressure, for example in adsorption measurements, is buoyancy. In particular the density of the sample is frequently unknown, or it changes during the measurement as a result of temperature effects or reactions with the environment. Buoyancy can be avoided if the mass is determined by means of an inertia measurement. Keller used the slow oscillations of a horizontally arranged rotary pendulum to measure adsorption of gases at dispersed solids (Fig. 6) [12].

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