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HIGH-SPEED WEIGHING*

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Abstract

Weighing is a relatively slow process and often requires a considerable time within investigation procedures or production processes. Measures for the speeding-up of weighing are discussed, two cases being considered:

1. If slow reactions are observed, the equilibrium value can be extrapolated from the mass change curve.

2. If the reaction is faster than the balance response, the damping device can be manipulated and/or the equilibrium value can be calculated from the oscillating balance readings.

Keywords: balance, check-weigher, mass determination

Introduction

In the present hasty times, weighing seems to be a far too slow measuring technique. Even as long ago as in Old Egypt, however, the person carrying out the weighing tried to shorten the procedure by arresting the movements of the balance, as shown in Fig. 1. In consequence of the dimensions of the balance and the resulting natural oscillation time, modern balances need a period of the order of a second or more to attain the rest position. This may be sufficient for weighing in commerce. The rapid observation of fast events require a fast balance, which may be limited in range. In the following, we discuss possibilitie› to shorten the weighing time of high-resolution balances for industrial control processes by accelerating the indication. In the observation of slow processes, the weighing time can be curtailed by optimizing the measuring procedure and by extrapolating the mass curve.

Influence of damping

Sensitive balances are usually equipped with a damping device [1] which can be manipulated to some degree. We shall discuss the extent to which such manipulation can influence the time of measurement.

* Dedicated to Bert Neeb on his 65th birthday

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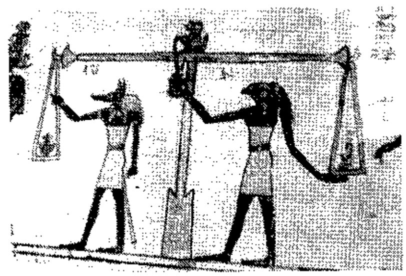

Fig. 1 Weighing scene in the Book of the Dead. Anubis holds one of the suspension cords of the pan. Horus stops the movement of the other pan and touches the dangling plummet*, which is a part of the indicator system. Papyrus Ker'Asher, late first century B.C., Thebes, Egypt. British Museum, London
* This detail was misunderstood by the painter

Let us consider a balance with given values of the moment of inertia J and of the restoring (torsion) constant C. We shall show what happens as concerns the time t_m necessary for a measurement when the damping constant K is varied from zero to a very large value When K equals zero, the balance exhibits free oscillations with frequency $\omega_o=\sqrt{C/J}$. From two subsequent reversal points of the signal of the oscillating balance, the unknown torque can be calculated and so we find for the time of measurement:

undamped balance:

$$K=0:\ t_m=\pi/\omega_o=\pi\sqrt{J/C} \tag{1}$$

If we increase K, we have to take at least three reversal points to deal with the declining amplitude:

lightly damped balance:

$$0<K<2\sqrt{JC}:\ t_m=\frac{2\pi}{\omega_o}=\frac{2\pi}{\sqrt{C/J-K^2/4CJ^2}}=\frac{2\pi\sqrt{J/C}}{\sqrt{1-K^2/4CJ}} \tag{2}$$

For K not too near $2\sqrt{JC}$, we see that the measurement time is twice that for the undamped balance. When K for an oscillating balance approaches a value of $2\sqrt{JC}$, the time of measurement increases quickly. When K equals the critical value of $2\sqrt{JC}$, the balance is critically damped and reversal points do not occur. The time of measurement is then defined as the time necessary for the balance to reach equilibrium to a satisfactory degree. The word satisfactory introduces some subjectivity, but the following value is usually considered acceptable:

critically damped balance:

$$K=2\sqrt{JC}:\ \ t_m=2\pi\sqrt{J/C} \tag{3}$$

For higher values of K, we again encounter some subjectivity, but the following is generally accepted:

heavily damped balance:

$$K > 2\sqrt{JC}: \quad t_m = 4K/C \tag{4}$$

When the velocity of the balance is not under control at the beginning of a measurement, an extra uncertainty of some 30% of the value given in Fig. 2 has to be taken into account.

From the values along the ordinate in Fig. 2, we see that, for fast weighing, balances with a high value of C are to be preferred. However, the value of C is inversely proportional to the sensitivity of the balance. This means that the speed and sensitivity of weighing are contradictory aims.

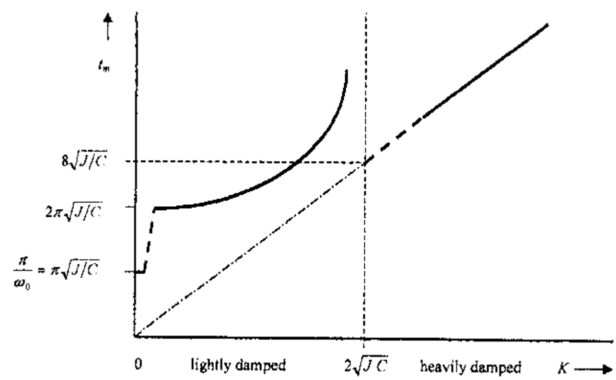

Fig. 2 Influence of damping on measuring time

During recent decades, however, this contradiction lost much of its importance because optical and electronic displacement sensors allow increase of the sensitivity practically *ad libitum*. Accordingly, in many modern weighing procedures, high values of C can be used to speed up the performance. Another solution to minimize the measuring time is dealt with elsewhere in this volume [9].

Fast observation of slow processes

In thermogravimetry [2], a mass loss is usually observed at constant pressure as a function of time, during continuous temperature increase. In the investigation of gas adsorption, mass change at constant temperature is measured as a function of pressure. In both cases, a very slow or a stepwise operation may reveal the fine structure of the resulting graphs [3]. Since the measuring time for such investigations is governed by the reaction, an optimally damped balance may be used.

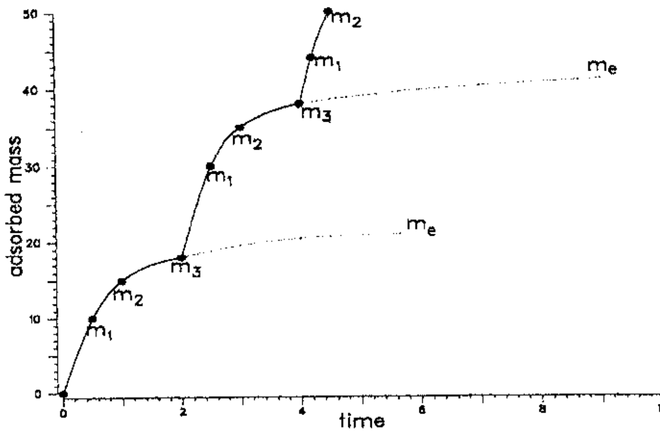

Fig. 3 Estimates of equilibrium values m_e from three consecutive mass indications m_1, m_2 and m_3, in the gravimetric measurement of adsorption isotherms according to Jäntti *et al.*

At the 9th Conference on Vacuum Microbalance Techniques in Berlin, Jäntti *et al.* [4] proposed the extrapolation of equilibrium for stepwise measurements. By measuring three consecutive values of the mass indication, m_1, m_2 and m_3, at equal time intervals (Fig. 3), they calculated the equilibrium value m_e, presuming that the adsorption process has an exponential character:

$$m_e = \frac{m_2^2 - m_1 m_3}{2m_2 - m_1 - m_3} \tag{5}$$

Jäntti reported a time saving of up to 70%.

Fast weighing

A balance with a beam, cantilever, magnetic suspension, flexural body, spring, etc. is usually a movable system. As a result of disturbing influences or because of the loading procedure, the system may start to oscillate. On account of friction in the bearings or in the surrounding material, the system comes to rest after an extended period of time and assumes a new equilibrium position. If the mass changes to be observed are faster than the response time of the balance, quasi-static measurement of the equilibrium value by means of a conventional balance in the gravitational field is wearisome.

Rapidly oscillating systems (quartz resonators, oscillating bands) give a fast response, but they need a strong connection of the sample to the sensor. Impulse balances may provide a faster indication and are sufficient for rough mass tests. In coin-acceptor units of slot machines, for instance, a spring-mounted lever measures the impulse of a coin accelerated in an inclined channel. Likewise, attempts have been made to check the mass of drug tablets by measuring the maxi-

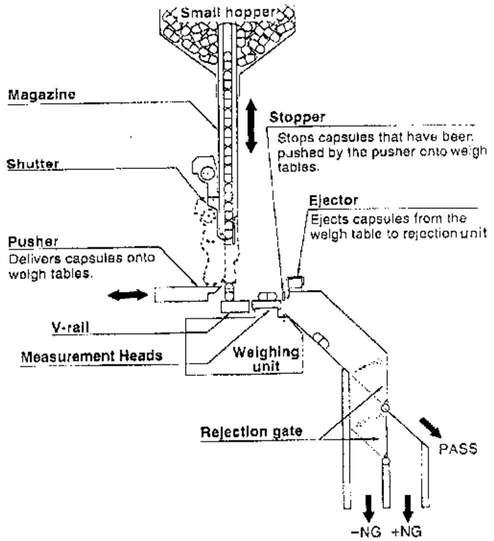

Fig. 4 Scheme of a capsule check-weigher (Anritsu Corporation)

mum amplitude when they are dropped from a defined height. The method turned out to be rather unreliable. The mass of tablets is today checked by means of electronic balances with a limited measuring range. This balance controls gates to channels which sort out the samples according to mass (Fig. 4). A passage rate of 2 tablets per second can be achieved [5]. It is obvious that, in such an apparatus, not only the response time of the balance, but also the time needed for the settling of the sample determines the total weighing time.

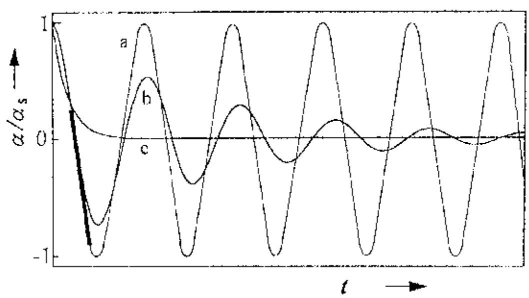

Fig. 5 Oscillation of a balance α – deflection, α_s – maximum deflection, t – time, a – undamped balance, b – damped balance, c – aperiodic limit. The bold line denotes the evaluated part

Prior to the use of effective damping devices, consecutive amplitudes of the needle, α_1, α_2, and α_3, were observed in sensitive analytical weighing. The equilibrium deflection α_e was calculated (Fig. 5) by using [6]

$$\alpha_e = \frac{\alpha_2^2 - \alpha_1\alpha_3}{2\alpha_2 - \alpha_1 - \alpha_3} \quad (6)$$

or approximately

$$\alpha_e \approx \frac{\alpha_1 + 2\alpha_2 + \alpha_3}{4} \quad (7)$$

The method is still applied in the examination of standard weights with comparators, which are usually not equipped with damping devices.

It can be seen in Figs 2 and 5 that, after initially disturbing effects, the undamped signal is always faster than any damped one. The initial part of the harmonic oscillation already includes all information on the equilibrium value [7]. The equation of motion of a beam balance is

$$J\ddot{\alpha} + k_d\ddot{\alpha} + k_t\alpha = T + T_c \quad (8)$$

where J is the moment of inertia, α is the angular deflection of the beam or the variation in length of a spring, $\dot{\alpha}$ and $\ddot{\alpha}$ are the velocity and the acceleration, respectively, k_d is the damping constant and k_t is a constant restoring force, while T denotes the torque to be determined and T_c a compensating torque, e.g. a counterweight or a Lorentz force. At the 21st Conference on Vacuum Microbalance Techniques in Dijon, Massen *et al.* proposed measurement of the parameters and calculation of the torque by means of a computer. Progress is reported in this volume [8].

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