Air-damped Balances

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Introduction.—During the last few years balances have been constructed, by various makers, enabling the process of accurate weighing to be carried out more rapidly and with greater ease than was formerly possible. The improvement is achieved by attaching to the beam of the balance a damping mechanism consisting of light metal pistons which move in fixed metal cylinders. There is a "clearance" space of about 1 mm. between the pistons and the cylinders, and the damping is due to the motion of the air produced by the motion of the pistons. Owing to the viscosity of the air, the oscillation of the balance beam is rapidly reduced; the damping may even be made so great that the balance beam moves gradually to its new equilibrium position without executing any oscillations.

As a consequence of the rapidity with which the beam becomes steady in its final position, it is no longer necessary to estimate this position by reading three successive extreme positions of a pointer on a scale. Moreover, because the final position of the beam may be observed at leisure, it has been possible to incorporate another feature in the design. The tip of the pointer is replaced by a small transparent scale, or graticule, rigidly attached to the beam. A small electric lamp and an optical system project an enlarged image of this graticule on to a ground glass plate, across the centre of which is a fiducial line. If the sensitivity of the balance has a fixed value, independent of the load on the balance, the graticule may be so constructed that each scale division represents some simple sub-division of a gram. It is then unnecessary to use any riders or weights less than, say, 0·1 g., the smaller weights being read *directly* on the ground glass.

These balances, provided that they do not introduce or increase errors, have many advantages. More weighings can be done in a given time. The balances are pleasanter to use, and there is less liability to mistakes in counting and arithmetic. There is also the psychological effect that the ease in using the balances induces a desire to carry out a weighing whenever it may be at all useful. When rapid chemical or biological action is taking place, the time that could be devoted to a weighing might be so short as to preclude the use of any but an air-damped balance. The rapidity of the weighing with an air-damped balance may decrease some errors, such as any that are due to gradual changes in the temperature of the room. Finally, the shorter time required for a weighing enables repetitions to be made, to check and improve the accuracy of the measurements.

THE DAMPING SYSTEM.—When weighing to a high degree of accuracy, it is not advisable to use *liquid* to produce damping, for the somewhat erratic surface-tension forces would prevent the beam from reaching its true final position. No such error can occur when air-damping is used. In fact, air-damping seems to be the only satisfactory method, with the possible exception of electro-magnetic damping.

The balance should be constructed so that there is no possibility of the pistons rubbing against the cylinders. The pistons should be light in construction, and not too far from the central knife-edge, in order that the moment of inertia of the beam be not unduly increased. They must be rigid, for if they were bent at any time, the position of the centre of gravity of the beam would be changed, and the sensitivity of the balance would be altered. In some balances this last disadvantage is avoided by fixing the pistons to the stirrups from which the pans are suspended, instead of attaching them rigidly to the beam. Change of temperature should not displace the centre of gravity of the beam sideways. This possible error is most simply avoided by making the whole system symmetrical, a piston and cylinder being provided for each arm of the balance.

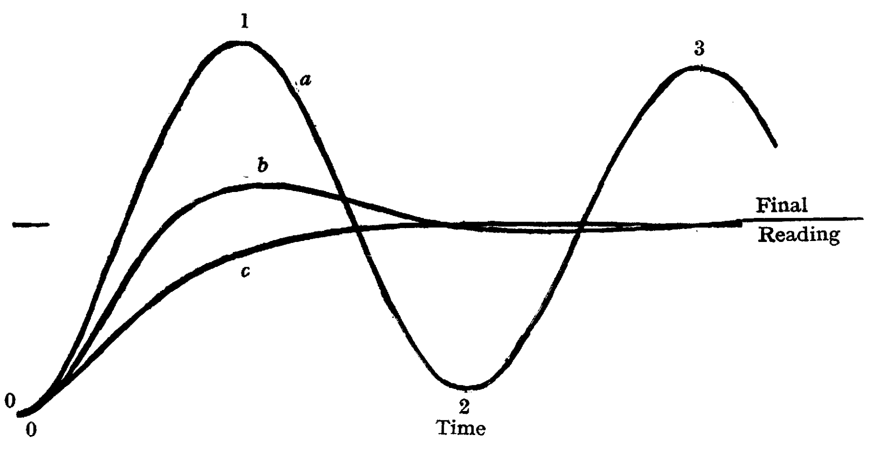

Fig. 1

The advantage of the damping can be seen by reference to Fig. 1. Curve (*a*) shows the slowly decaying oscillations of an ordinary balance. Curve (*c*) shows the gradual movement to the new position that takes place when the same balance is "critically damped." In this case no oscillations occur. When the damping is not quite so great, the motion is such as is indicated in curve (*b*), the oscillations rapidly decreasing in amplitude.

In using an ordinary balance and "weighing by swings," readings would be taken at points (1), (2) and (3) of curve (*a*). By the time reading (3) is taken, the pointer of a similar balance *that was "critically damped"* would have moved 99·8 per cent. of the way towards its final reading. With the ordinary balance, we have still to calculate the value of

$$\frac{\frac{(1) + (3)}{2} + (2)}{2}$$

and multiply it by the sensitivity. In the meantime the damped balance would have proceeded on the remaining 0·2 per cent. of its journey, and the fraction of 0·1 g. could be read direct on the ground glass scale. The definite advantage of the damping is at once evident.

The advantages of the air-damped balance have been slightly overstated above, the increase in moment of inertia due to the presence of the pistons having been neglected. On the other hand, in using an undamped balance it is unlikely that reading (1), curve (*a*), will be taken on the very first swing.

If the damping is greater than in the critical case [curve (*c*)], the beam will be slower in reaching its final position, which is a disadvantage. It is probably better to have slightly *less* than the critical amount of damping, because the small oscillations [curve (*b*)] enable the observer to judge how soon the final position may be considered attained. With critical damping, the observer is apt to keep wondering if the reading will eventually creep much further. If the damping is nearly critical for small loads, the balance will be somewhat under-damped when the load is larger. The damping pistons are sometimes provided with small holes partly covered by adjustable flaps, so that the amount of damping may be adjusted by moving the flaps to a suitable position.

Experiments with Air-damped Balances.—The results of experiments that I have carried out on five air-damped balances, made by four different makers, are described below. The experiments were designed to test the speed and accuracy of the balances. The results indicate how such balances may be expected to function under ordinary working conditions, and the experiments may be useful as a guide to anyone who wishes to test an air-damped balance.

Rapidity of Weighing.—After the weight had been adjusted to the nearest 0·1 g., the time required to release the beam, wait for a steady reading and record it to an accuracy of 0·0001 g. (or less) varied from 50 seconds to 20 seconds. The shortest time was found with a small balance designed for a maximum load of 20 g. In this balance, used at half its maximum load, a single swing (or half oscillation) occupied about 4 seconds, and each excursion of the beam was of about $\frac{1}{8}$ of the amplitude of the preceding excursion. This corresponds to a curve about mid-way between curves (*b*) and (*c*) in Fig. 1. If 4 seconds are taken in releasing the beam, the amplitude will decrease during the next 16 seconds to about $\frac{1}{8} \times \frac{1}{8} \times \frac{1}{8} \times \frac{1}{8}$ or 0·0003 of the original amplitude, and the beam can be considered at rest in its new position.

Constancy of Zero.—Good air-damped balances, in a room where the temperature does not change rapidly, seem to be subject to a change in zero corresponding to about 0·0001 g. in half-an-hour of weighing. For a badly-designed balance, or when the temperature changes are rapid, the zero may change by as much as 0·0001 g. in 10 minutes of weighing. Even under very adverse conditions, however, error can be avoided by taking a weighing with the object in the left-hand pan, a second weighing with the object in the right-hand pan, and averaging the two results. This takes little extra time, and the procedure is advisable where a high degree of accuracy is required.

Inequality of the Lengths of the Two Arms of the Balance.—In a good balance the lengths of the two arms should not differ by more than about 1 part in 100,000. To find the inequality in the arms, we find the zero and then weigh a body first in one pan and then in the other. Let the lengths of left and right arms be a and b; the true weight of the body be W; the apparent weights when the body is in the left- and right-hand pans, W_1 and W_2, respectively. Then, if a and b are nearly equal, we have, to a close approximation,

$$W = \frac{W_1 + W_2}{2}$$

and

$$\frac{a-b}{b} = \frac{W_1 - W_2}{2\,W_2}$$

For the balances that I tested the fractional error, $\frac{a-b}{b}$, had values of between 0·000,013 and 0·000,001. Hence, neglect of any correction would have caused the weighings to be in error by only about 0·001 per cent. or less. However, the method of double weighings, mentioned at the end of the section on "constancy of zero," will give a weight that is not only free from the effect of "zero error," but is also free from any error due to the arms of the balance being of slightly different lengths.

Accuracy of Weighing.—In order to test the accuracy of weighing, three weights of nominally 1 g. each were compared in pairs on five balances. In every experiment a reading was taken, and a second reading with the weights on the pans interchanged. The two results were then averaged, thus eliminating error in zero and effect due to inequality in the arms. No other corrections were applied. The results obtained were:

Weights.	Difference in weight, in grams, using balance number:—				
	I	II	III	IV	V
1*–1	0·000,83$_5$	0·000,86	0·000,85	0·000,8$_5$	0·000,83$_5$
1**–1	0·000,47	0·000,49$_5$	0·000,48	0·000,4$_5$	0·000,53$_5$
1*–1**	0·000,32	0·000,35	0·000,36	0·000,3$_5$	0·000,39$_5$

By comparison of these results it can be concluded that the maximum error of any one of the 15 experiments (each of which was the mean of two weighings) was about 0·000,05 g. The "probable error" of a single experiment was

$\pm 0{\cdot}000{,}016$ g. Hence the balances can be used to weigh 1 g. to an accuracy of about 1 part in 50,000.

A few similar experiments were carried out with 10-g. weights, and the probable error of a single experiment was found to be $\pm 0{\cdot}000{,}01_6$ g., corresponding with an uncertainty of 1 part in 500,000.

Testing the Graticule.—If the graticule and optical system are arranged so that the scale-readings represent simple fractions of a gram when the balance is used for small loads, it is to be expected that at greater loads the sensitivity of the balance will be slightly different, causing the scale-readings no longer to represent the fractions of a gram quite accurately.

It is found that, for a load of 50 g., the sensitivity of these balances may differ from the sensitivity at zero load by as little as 0·2 per cent. or by as much as 2 per cent. The scale will usually be employed to estimate about 0·05 g. of the total load. This 0·05 g. (or so) may therefore be in error by as much as 2 per cent., giving an error of 0·001 g. in 50 g. Complete data cannot be given, as the error will depend on the particular balance and will not be directly proportional to the load.

When weighing masses of as much as 50 g. to an accuracy of 0·001 g., it is certainly desirable to calibrate the graticule by means of a 0·05-g. weight at *each* load that is used. The need of this calibration seems to be the only real trouble in using these balances. It may, however, be noticed that a similar calibration is necessary when "weighing by swings" with an undamped balance, and the correction is much easier to determine when using an air-damped balance.

The divisions on the graticule should be almost uniformly spaced, a slight allowance being made because the difference between the loads on the two pans is proportional to the tangent of the angle of deflection. The scale may be tested by weighing (say) a 0·02-g. weight, weighing another that may be denoted 0·02*, and then weighing them together. Whenever I tried such an experiment, I found that the reading for (0·02 + 0·02*) agreed with the sum of the separate determinations within the experimental error, indicating that the graticules were satisfactorily graduated.

The optical system should be rigid, or "changes in zero" may occur.

Finally, it may be remarked that the balance room should be suitable, the weights should be standardised, and a buoyancy correction should be applied (which is often a correction of 1 part in 800 and may be even greater).

My thanks are due to Captain John Golding for suggesting this investigation and giving me facilities for using the air-damped balances at the National Institute for Research in Dairying, Shinfield, Berks.

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Discussion

Captain J. Golding said that their experience at the National Institute for Research in Dairying was in accord with Dr. Bond's conclusion. They had found that a balance air-damped at each end of the beam gave the most satisfactory results. This balance weighed up to 20 grams, and, for the routine determination of total solids in milk, aluminium capsules differing but little in weight were used, so that the balance weights seldom required adjusting. The graticule was graduated over its whole length in fifths of a milligram.

Mr. F. G. TATE said that in some of the work at the Government Laboratory they had to do a very large number of routine weighings, and as something in the nature of a damped balance was necessary, they had tried various types. The oil-damped balances were open to grave criticism. For example, the oil was inclined to creep, and the zero of the balance might be affected by the temperature and age of the oil and the condition of the rod supporting the piston. The air-damped balance with the piston under the pan was liable to get out of gear very easily.

Some time ago Captain Golding had brought to the notice of the Society a balance with damping at one end of the beam. Mr. Tate had criticised this and, at subsequent meetings at the Government Laboratory between himself and the balance makers, a scheme to have an air damper at each end of the beam had been evolved. This had been found to be very satisfactory, and on one such balance they were now doing about 200,000 weighings per annum. He agreed with Dr. Bond that the best scaling was from one end of the graticule to the other.

Mr. P. BILHAM remarked that he had had experience with eight of these balances over a period of six years. If he might advise prospective users, he would urge them to deal with those balances with dampers in an elevated position. As these balances were used by people in a hurry, sooner or later they would spill something, which would enter the dampers if they were beneath the pans and necessitate dismantling in order to clean the balance. He added that with these balances it was possible to weigh substances which were almost hydroscopic.

Dr. J. GRANT said that he had had an opportunity of comparing a chainomatic and an air-damped balance, and came to the conclusion that for speed of weighing the air-damped balance had the advantage, but that for accuracy, weight for weight, the chainomatic was more satisfactory. With the air-damped balance, it was found that, after being adjusted in the morning it was decidedly "out" by the evening. Finally, it was discovered that the light in the balance room was not hanging symmetrically between the pans and that the air between the damping-cylinders on one side was getting warmer than on the other. Therefore, it was necessary to see that any source of heat did not affect one side more than the other.

Dr. W. N. BOND, replying, said that he had not had any real working experience of chainomatic balances. If one were aiming at considerable accuracy, the air-damped balance did not seem to introduce any cause of error, whereas the chainomatic did. He felt that there was an advantage in having the graticule numbered from one end, whichever way one used it. It was easier than writing down plus and minus and then working it out, but he did not know anything about the actual accuracy.