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# A Versatile Automatic Weight Changer For Mass Comparators

Kyi Kyi Swe
Department of Mechanical Engineering,
Technological University
Thanlyin, Myanmar

Kyaw Myat Moe
Department of Mechanical Engineering,
Yangon Technological University, Myanmar

Zar Chi Thaung
Department of Mechanical Engineering,
Technological University
Thanlyin, Myanmar

**Abstract**: This paper describes an automatic weight changer for changing weights on the pan of a mass comparator. The weight changer is easy to use, and is designed to be readily fitted to most common types of top-loading mass comparators and balances of maximum capacity 20 g to 200 g. The versatility of the weight changer is demonstrated by its use in improving the efficiency of routine mass calibration and by its use to compare weights in an evacuated chamber. In each instance the repeatability achieved is 20% or less of the resolution of the balance. The weight changer currently allows up to five weights (or groups of weights) to be automatically compared, but is easily modified to allow comparison of more weights.

**Keywords**:

## 1. INTRODUCTION

The requirement for National Metrology Institutes to carry out routine calibration of high accuracy weights has meant that there has been continuing interest in improving the efficiency of such calibrations. Over the past century, research has been carried out on suitable design schemes for calibrating sets of weights, and the favoured schemes are those in which each weight is involved in more than one comparison, both alone and as part of a group of weights 1,2. In addition, the choice of a method of mass comparison is not trivial. Repeated loadings of weights are required to reduce or establish the uncertainty in the result, or to allow compensation or correction for any drift in the comparator zero 3. Research into methods of mass comparison has shown that the best performance is obtained when 3 to 5 weights (or groups of weights) are involved in a cyclic comparison sequence 3.

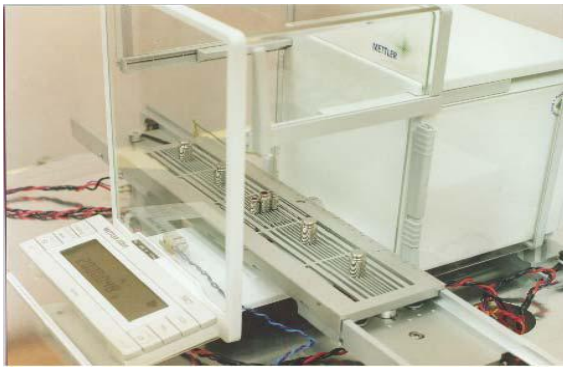

Figure 1. The automatic weight changer fitted to a mass comparator of 200 g capacity

Recent developments in mass comparator technology have also contributed much to the improvement in efficiency of mass calibrations. Top-performance commercially-available mass comparators have weight changers that operate under computer control to automatically load weights on and off the weighing pan.

Comparator readings are also sent to the computer, so that mass comparisons may be carried out under full computer control. This makes such comparators ideally suited to comparison methods that require repeated interchange of weights. These comparators provide consistent loading of weights, and eliminate tedious, time-consuming manual loading by an operator. In addition, these comparators allow mass comparisons to be carried out without operator disturbances and at times when environmental influences (such as vibration from traffic) are least.

However, these top performance comparators are intended for the highest accuracy comparisons and aspects of their operation make them unsuitable for the routine calibration of weights. Firstly, considerable care is required in loading weights onto the changer. These comparators have self-centering pans, and weights must be accurately centered in each changer position to reduce the amount of movement of the pan on loading and to avoid collision between the pan and the changer. In some cases the pan consists of a thin strip of metal and careful loading is required to prevent weights from falling over. Secondly, the design of the changer and pan on these comparators severely limits the combinations of weights that may be used in a group, so that most common weighing design schemes cannot be implemented. Some comparators require special disk weights to allow combinations of weights to be used, but in such cases the possible combinations of weights (other than disk weights) are even more limited. These comparators have rotating weight changers which restrict the number of weights that can be compared at one time to four (in some cases two). Thirdly, these highest accuracy comparators require long waiting times (~ 1 minute) to reach stability each time the pan is loaded.

Here we describe a weight changer that has all the advantages of automatic operation and that is ideally suited for routine high accuracy calibration. One feature of the design of the changer is that it may be fitted to most types of top-loading mass comparators (of similar capacity) with minimal effort. (We use the word comparator to also mean a balance that is used for mass comparison). A second feature of the weight changer is that it can be used to implement most design schemes as there are practically no restrictions on the combinations of weights that may be loaded onto it. Weights (or groups of weights) may be loaded onto the changer with no more effort than is normally required to ensure weights are sufficiently centred to avoid significant pan position (eccentricity) error. A third feature is that the speed of the weight changer may be varied to suit the type of weighing. We give examples of the versatility and performance of the weight changer through its use in routine mass calibration and in comparing weights inside an evacuated chamber.

## 2. DESCRIPTION

Figure 1 shows the automatic weight changer fitted to a comparator of 200 g capacity. The changer consists of a weight carrier with linear movement that fits over the pan of the comparator. The carrier is moved vertically (to load and unload the weights) or horizontally (to change weights). In the configuration shown, the carrier has positions for 5 weights (or groups of weights), but is easily modified to allow comparisons of up to 10 or 15 weights (or groups of weights). As the doors of the comparator weighing chamber must be left open, the carrier and comparator are enclosed in a draught shield during use (not shown in Figure 1).

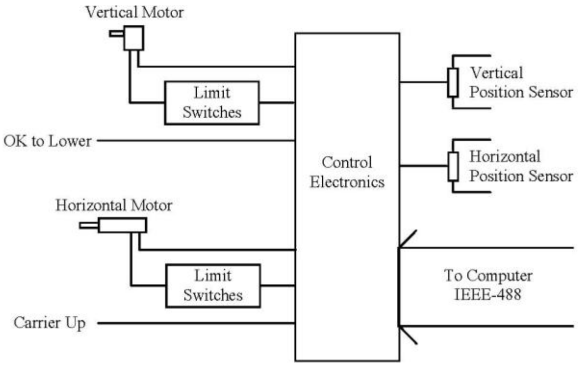


Figure 2. Schematic diagram of the weight changer control electronics

The only modification required of the comparator is that the weighing pan be replaced by a custom-made pan consisting of "fins", for supporting the weights, that fit into slits in the weight carrier. The tops of the fins can be seen in Figure 1 protruding through the slits in the carrier, as the carrier is being lowered and the fins are just starting to pick up the three weights. With this design, we believe the changer may be easily adapted to common types of top loading comparators of 20 g to 200 g capacity. We are currently able to use the weight changer with a 200 g capacity Mettler AT201 balance and a 50 g capacity Sartorius C50 comparator, both of which are used routinely to calibrate weights from 5 g up to 200 g, and a Mettler AE 200 balance which is used for vacuum weighing applications.

The current weight carrier has slits 3 mm apart in the centre and is designed for weights with diameters from 6 mm to over 60 mm. It will carry standard weights as small as 1 or 2 g. The largest load that the carrier will support is currently limited by the vertical drive motor to a total capacity of about 1 kg.

The weight changer and comparator are mounted on a 700 mm diameter 25 mm thick aluminium base, supported by three adjustable feet at 120° spacing and of sufficient height to allow space for the drive motors which are attached underneath the base. Toothed belts couple the drive motors to the horizontal and vertical movements and ensure repeatable positioning. On top of the base are three adjustable V-groove slots (in a Yconfiguration) which allow secure and accurate positioning of the comparator. To assemble the system, the comparator is first placed in position on the base, and the carrier is then placed over the weighing pan and secured to the base. The base shown in Figure 1 is also the bottom of a chamber that encloses the comparator for mass comparisons in vacuum. This base has vacuum feed throughs for electrical connections and the motor drive shafts. When using the automatic weighing system in ambient air, the only requirement is for a base of sufficient rigidity to allow suitable performance of the comparator.

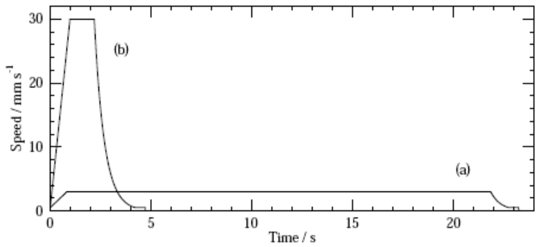


Figure 3. Typical speed profiles for the horizontal movement of the weight carrier. (a) profile with a maximum speed of 3 mm s$^{-1}$, (b) profile with a maximum speed of 30 mm s$^{-1}$

The design of the control electronics (Figure 2) is a major factor in the versatility of the weight changer. Two programmable speed dc motors are used to move the weight carrier horizontally and vertically, so that the computer has full control over the speed and positioning of the weight carrier. Weights can be moved by the carrier at horizontal speeds from 0.25 to 50 mm s$^{-1}$, and at vertical speeds from 0.01 to 1.20 mm s$^{-1}$. Position sensors (potentiometers) on the vertical and horizontal movements provide position information for the computer. In addition, two sensors are used to prevent undesirable movement. One sensor checks that the carrier is up before horizontal movement can commence, and the other checks that the carrier is in one of the five positions suitable for lowering. The horizontal and vertical movements have limit switches at their allowable extremes and each motor has an over-torque cut-out.

Communication with the controlling computer is provided through an IEEE-488 interface with listen and talk capabilities.

Limited local operation from the front panel of the controller is also available, including two speed horizontal and one speed vertical movement. The control electronics are custombuilt but could be assembled using commercially available motor controllers.

Computer software routines for positioning and moving the carrier (vertically or horizontally) may be incorporated into any computer program written for a specific application of the weight changer. Figure 3 shows typical programmed speed profiles for moving the carrier horizontally from one weighing position to the next adjacent position (a distance of 66 mm). Figure 3 (a) is a profile used for routine weighings in air, in which weights are moved slowly (maximum speed 3 mm s$^{-1}$) to minimise air currents. The profile of Figure 3 (b) gives faster movement (maximum speed 30 mm s$^{-1}$) and is used for weighings in vacuum (see later). The feature of each profile is the exponential slowing down to a set minimum speed as the target position is approached, in order to allow reproducible positioning of the carrier to well within 0.5 mm. Software routines are also used during initial setting up of the changer to establish potentiometer readings corresponding to the weighing positions and to the carrier-up and carrier-down positions.

During the initial setting up of the changer it is necessary to ensure that the top of the carrier is parallel to the top of weighing pan, to prevent the weights from ‘walking’ during mass comparisons. The tendency for the weights to walk increases with the number of repeat loadings in the given application, and also apparently with the diameter of the weights and the height of the centre of mass of the weights. The best alignment is achieved by observing the projection onto a screen of a laser beam reflected vertically from a mirror placed on the weighing pan. The carrier-pan alignment is adjusted to minimise the movement of the projection as the mirror is just lifted off the pan by the weight changer. With the carrier aligned by this method, trials using 46 mm diameter 85 g weights showed that after 80 repeat loadings of the weights, the weights had only moved by about 0.5 mm.

For routine calibration work using standard weights, alignment by levelling both the weighing pan and the carrier using a bubble level is sufficient. With the system aligned by this method the alignment error was less than 0.003 radians. Trials with 200 g weights showed that after 80 consecutive loadings of each weight, the weights had moved by 4 mm or less. The amount of movement was progressively less for smaller weights of the same diameter. For routine comparisons typically carried out in our laboratory, this rate of movement does not cause significant pan position error.

Table 1. Results of comparisons of reference standards using the weight changer with a Mettler AT201 balance.

| Nominal mass / g | Measured difference - calibration difference $\Delta m_m$-$\Delta m_c$ / µg | Std. uncertainty of measured difference / µg | | Std. uncertainty of calibration difference / µg | | $t$ | |
|---|---|---|---|---|---|---|---|
| 100 | 1.88 | 1.00 | $v = 8$ | 1.40 | $v = 23$ | 1.09 | $v_{eff} = 30$ |
| 100 | 2.58 | 1.62 | $v = 9$ | 1.40 | $v = 23$ | 1.21 | $v_{eff} = 22$ |
| 50 | -0.67 | 1.15 | $v = 8$ | 1.00 | $v = 22$ | 0.44 | $v_{eff} = 20$ |
| 50 | 3.02 | 1.34 | $v = 9$ | 1.00 | $v = 22$ | 1.80 | $v_{eff} = 19$ |
| 30 | 1.00 | 1.42 | $v = 9$ | 0.88 | $v = 22$ | 0.60 | $v_{eff} = 16$ |
| 20 | -2.13 | 1.77 | $v = 8$ | 0.57 | $v = 22$ | 1.14 | $v_{eff} = 9$ |
| 20 | -0.66 | 1.23 | $v = 9$ | 0.57 | $v = 22$ | 0.48 | $v_{eff} = 13$ |
| 10 | 0.29 | 0.59 | $v = 8$ | 0.73 | $v = 22$ | 0.31 | $v_{eff} = 27$ |
| 10 | -5.23 | 0.97 | $v = 9$ | 0.73 | $v = 22$ | 4.32 | $v_{eff} = 19$ |
| 10 | 3.05 | 1.68 | $v = 8$ | 0.73 | $v = 22$ | 1.66 | $v_{eff} = 11$ |
| 5 | 1.72 | 1.42 | $v = 9$ | 0.96 | $v = 22$ | 1.01 | $v_{eff} = 17$ |

# 3. APPLICATIONS

Routine Calibration of Weights

The weight changer is currently being used with a 200 g capacity Mettler AT201 balance (resolution = 10 µg) for routine calibration of weights ranging in nominal mass from 200 g to 5 g, to accuracies of 5 parts in $10^7$ (with a lower limit of 10 µg). In OIML terms [4], such accuracies are suitable for the calibration of Class $E_2$ weights. Ongoing assessment of the performance of the comparator and changer is being carried out in conjunction with its use, and involves the inclusion of two calibrated reference standards in positions on the carrier during each weighing. These reference standards have been recently calibrated using a more accurate comparator. The measured difference $\Delta m_m$ in the mass of these two standards is compared with the difference $\Delta m_c$ obtained from their calibration. A typical weighing at (for example) 20 g, and which utilises all five positions on the carrier, consists of comparisons in the following cyclic sequence: 20, 20s, 20´s, 20´, (10+10s), where’s denotes a reference standard. In this case a weighing consists of 3 cyclic repeats of the sequence to give 15 readings in total. The mass differences are calculated by a least squares method assuming linear drift in the comparator zero [3]. For the purposes of assessing the performance of the comparator and changer, a weighing is repeated 9 or 10 times, taking a total time of 2.5 to 3 hours.

Table 1 shows the results obtained for all comparisons of the reference standards during a two month trial of the comparator and weight changer. The quantity listed in the second column of Table 1 is the difference between the measured difference $\Delta m_m$ in mass of the two reference standards (the mean of the results of the 9 or 10 repeat weightings), and the “calibration difference” $\Delta m_c$. This quantity gives an indication of the performance of the comparator and weight changer combination. Corresponding standard uncertainties and degrees of freedom $\upsilon$ are tabulated in the third and fourth columns of Table 1.

The most striking feature of these results is that the standard deviations in measured mass differences are all below 18 % of the resolution of the comparator. We cannot achieve this level of performance by manually loading the comparator. For a mass comparison where the uncertainty is due only to the resolution r of the comparator, the standard uncertainty $r_5$ in a measured mass difference is $r\sqrt{2}/\sqrt{12}$, that is, 41% of the resolution. Clearly, there is sufficient variability in the comparator readings so that using the weight changer reduces the limitations of the comparator resolution.

Assuming that the tabulated uncertainties are dominated by Type A [5] components, we may use the t-test [6] fo significance in the tabulated differences. Calculated t values and effective degrees of freedom $\upsilon_{eff}$ (see Table 1) indicate

that, with only one exception (that for which t = 4.32), the differences are not significant at a 95 % level of confidence.

## 3.1 Weighing In Vacuum

The weight changer was originally designed for weighing the floating elements of gas pressure balances in vacuum [7]. It is the mass in vacuum of these floating elements that determines the pressure generated by an absolute mode pressure balance. Conventional weightings in air and in water could not be used to accurately determine the true masses of the floating elements because of their complex structure and internal cavities.

The balance used for these weighings in vacuum is a special version of the 200 g capacity Mettler AE 200 that has the weighing cell and display module in two separate units, allowing the display module to be outside the vacuum chamber. This Mettler AE-SE 200 has a resolution of 100 µg. Prior to the weighings, the pan and carrier were aligned using a laser, as described earlier, because the base of the floating elements is about 46 mm in diameter, so they are prone to ‘walking’ with repeated loading and unloading.

A typical weighing in vacuum uses all five carrier positions with two reference standards S1, S2 and three floating elements FE1, FE2, FE3 loaded three times in the sequence S1, FE1, S2, FE2, FE3. The floating element masses are either 85 g or 170 g. Each three cycle weighting is performed within 10 minutes to allow changes in mass after evacuation to be monitored. This short weighing time is achieved by changing the masses at a maximum horizontal speed of 30 mm $s^{-1}$ (see Figure 3 (b)).

As with the application to routine weight calibration, the accuracies achieved in the automatic weightings in vacuum are well within the resolution of the balance. The performance was checked by comparing the difference between the calibrated mass values for two 85 g reference standards with the difference measured in a typical vacuum weighing. The average measured difference between the two 85 g standards obtained from six weightings in vacuum was 714 µg with a standard uncertainty of 20 µg, compared with their calibration difference of 707 µg. The measured difference minus the calibration difference is only 7 µg and the 20 µg standard uncertainty is just 20 % of the resolution. In this case, the drift in the balance zero of 8 µg per reading (on average) contributed to reducing the standard uncertainty to below the 41 µg resolution limit.

## 4. CONCLUSION

We have described an automatic weight changer that may be readily fitted to common types of top-loading mass comparators and balances, and we have given examples of its use in routine calibration of weights and in a vacuum weighing application. We have demonstrated the effectiveness of the weight changer through its versatility, and through its ability to allow optimal mass comparator performance to be achieved, all of which make it well suited for use in a mass standards laboratory of a National Metrology Institute.

## 5. ACKNOWLEDGMENT

The preferred spelling of the word “acknowledgment” in American English is without an “e” after the “g.” Use the singular heading even if you have many acknowledgments. Avoid expressions such as “One of us (S.B.A.) would like to thank ... .” Instead, write “F. A. Author thanks ... .” Sponsor and financial support acknowledgments are placed in the unnumbered footnote on the first page.

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