

# ELECTRONIC CONTROL OF PRECISION MASS BALANCE

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*Abstract: Electronic balance control of a high precision two-pan flexure-strip mass comparator for double weighing at the UK National Physical Laboratory has been implemented. Critical damping of the freely oscillating loaded beam has been achieved. With a 10 mg differential in 1 kg mass comparisons, steady-state compensation was held for 10 minutes alternatively on either pan, with a stability in mass reading of (standard deviation) 3 parts in  $10^{-10}$  of a kilogram. Noise attenuation resulted in signal-to-noise ratio of 80 dB on a recovered mass difference signal magnitude of 6 volts dc equating to 1  $\mu$ g in 1 kilogram. The design enables a two-pan balance to be used in single and double weighing mode. The paper briefly outlines previous work on high-precision mass comparators, then outlines the basic system features of the NPL high precision mass comparator and describes the design and performance of the automatic balance control. The work undertaken confirms that the flexure strip balance, with correctly designed and constructed electronic control, forms a superior instrument for accurate measurement of mass (< 1  $\mu$ g in 1 kg).*

*Keywords: mass balance, beam balance control*

## 1 INTRODUCTION

Two-pan swinging arm mass-comparators are routinely used for comparing of kilogram masses from the highest accuracy down to the scales of household and light commercial use. The highest accuracy required is when the transfer of mass standard from the International Prototype<sup>®</sup> and its many copies, to the best quality stainless steel mass in the traceability chains of respective national laboratories. The uncertainty of mass determination is, at this level, required to be 1  $\mu$ g in 1 kilogram or better.

A significant development of balance technology was the negative feedback force compensated beam by way of electromagnetic and permanent magnet field interactions on the balance body and pan suspension respectively [1]. The electrical current needed to drive an asymmetrically loaded beam back to a null horizontal position was the measure of mass difference between a standard mass and a measurand mass. This design was adapted to an existing balance and resulted in improved accuracy of mass comparison and greater convenience in operation. Following this pioneering work at the UK National Physical Laboratory (NPL) a further balance was designed specifically as a force compensated balance, particularly for the realisation of the SI watt [2][3].

Adapting force-compensating feedback technology to the concept of beryllium copper flexure strips as pivots to replace traditional knives and planes, resulted in a further significant development of high accuracy balance engineering. The result was the first of a new generation of flexure strip balances, where initial trials at BIPM showed accuracies of 0.5  $\mu$ g in 1 kilogram [4]. This development used smaller electromagnets than those used at NPL and were mounted, in series, either end of the beam (one pair of each polarity). The null position was detected by two optical transducers, also mounted on the ends of the beam, from which a signal was taken to drive the analogue feedback controller. Continued development results in accuracies of mass comparisons becoming significantly improved by up to a factor of 10, 50 ng in 1 kilogram [5].

A similar balance using flexure strips as pivots, and a force compensation nulling system was designed and built at NPL. Nevertheless, accurate control of the mechanical system was unrepeatable and at times was unstable. The control system to be described in this paper is the result of work done which removed this problem [6]. A degree of retro-engineering to the mass balance was undertaken.

## 2 FEEDBACK LOOP

A block diagram of the system is shown in Figure 1 with specified elements: phase sensitive detector (PSD) proportional differential-integral three-term controller (PDI), detector overshoot control (DOC), data recovery system (DRS).

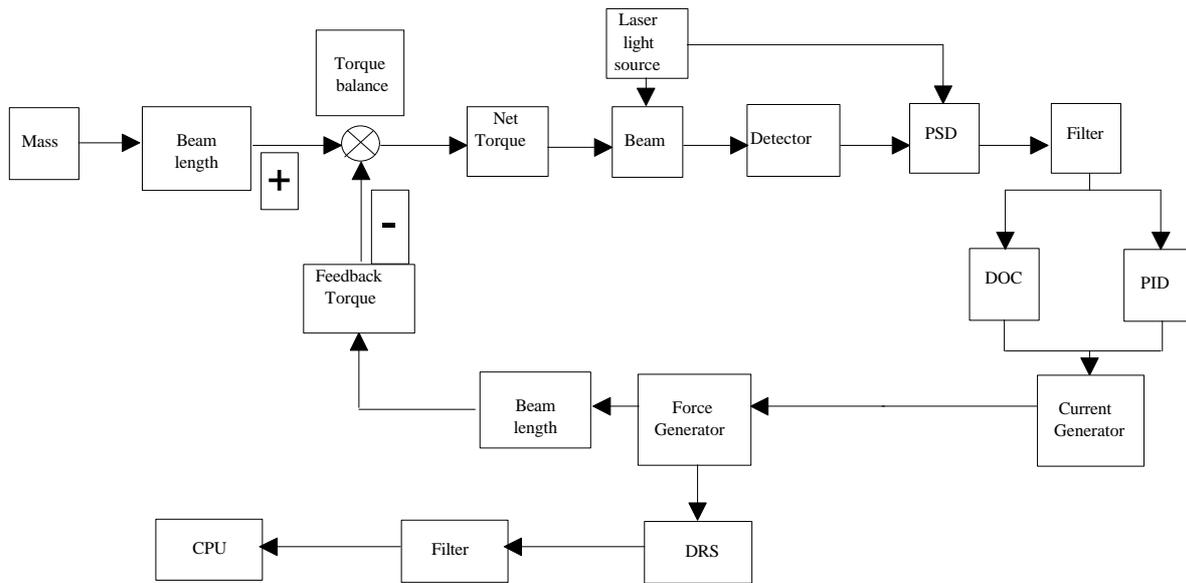


Figure 1. Beam balance system block diagram.

The input is the mass difference and the output is the corresponding current needed to drive the mechanical assembly to its null horizontal position.

The balance beam is a second-order system with mechanical inertia  $0.029 \text{ kgm}^2$ , damping due to flexure strip and air resistances  $0.066 \times 10^{-3} \text{ Nms rad}^{-1}$  and flexure stiffness  $0.052 \text{ Nm rad}^{-1}$ , and was thus calculated to have a transfer function

$$G(s) = \frac{19}{(29s^2 + 0.066s + 52)10^{-3}} \quad (1)$$

The period of the undamped natural frequency of oscillation of the beam is approximately 6 seconds. The optical angular displacement transducer comprises a laser diode whose output is square-wave modulated at 2 kHz and a twin-cell photoelectric detector. The transducer can resolve angular displacements of 70 nrad (caused by balance mass differences of 10  $\mu\text{g}$ ) and span the angular range 70  $\mu\text{rad}$  (caused by balance mass differences of 10mg). A Butterworth second-order filter with an angular frequency break-point at 70 rad/s has been used to smooth modulation spikes of 5 mV peak to peak at the output of the PSD; the maximum recovered signal at this point has a value of 6 V.

The PDI three-term controller has differential time constant of 0.1 second and integral time constant 20 seconds, and the mass balance is critically damped.

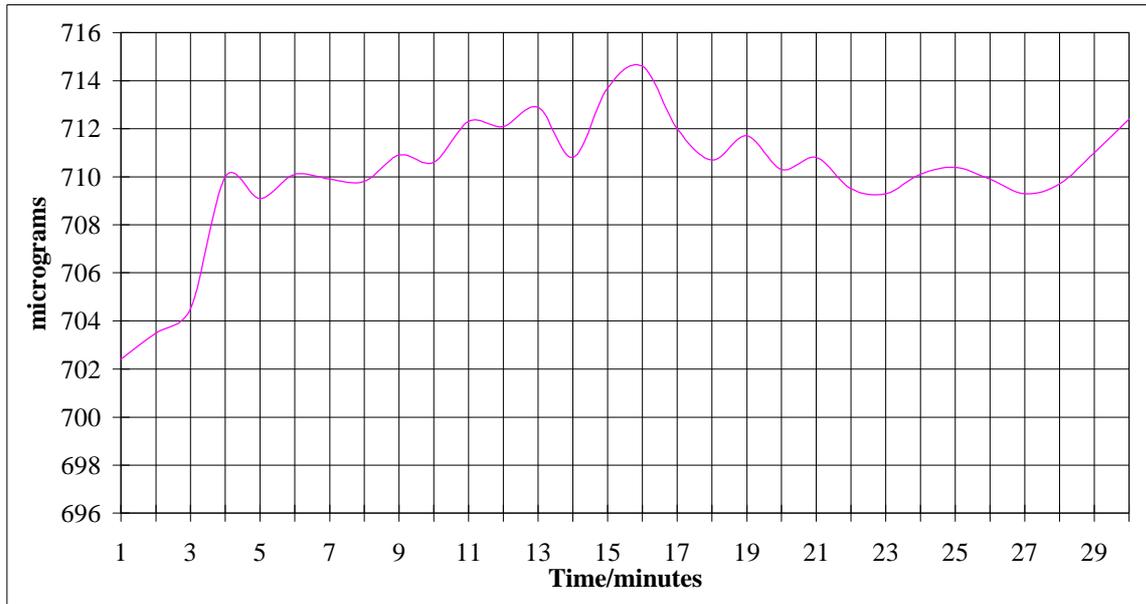
The electromagnetic coils interact with SmCu permanent magnets. The DOC network simulates the detector cell width so as to allow the feedback to remain in the correct polarity if the light spot should overshoot one of the optoelectronic detectors. In practice the network has not been activated due to the effectiveness of the three-term controller.

Great care has been taken to remove 50 Hz mains pickup by proper screening, grounding connections and positioning of equipment. The final output was filtered via a second-order Butterworth filter cascaded with a fifth-order switched capacitor active filter both having cut-off frequencies of 10 Hz.

### 3 OPERATION AND RESULTS

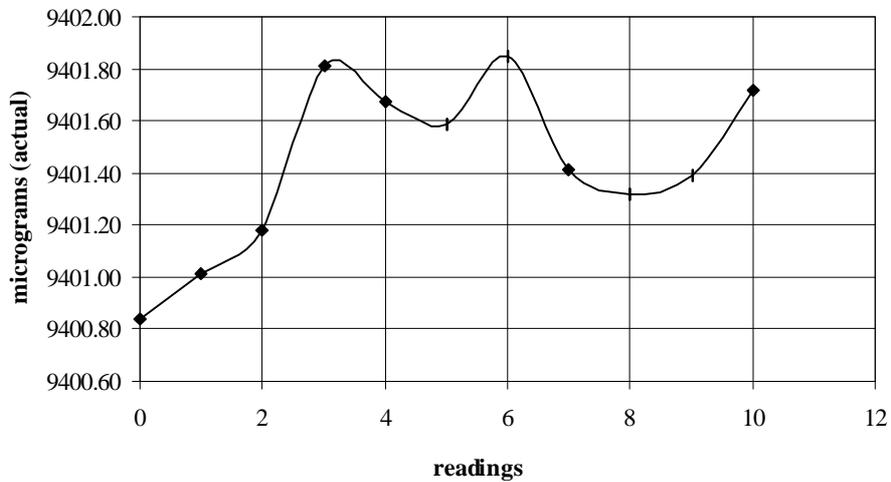
For full differential load of 10 mg the output signal was 5.682 V with an associated noise of approximately 0.7 mVrms. This equates to a resolution in mass of 1.2  $\mu\text{g}$ .

The stability of repeatability of measurement over a reasonably long time of 70 minutes was monitored with an unloaded balance except for an off-set of 712  $\mu\text{g}$ . In practice such periods of time would not be used for mass comparisons due to changing ambient conditions. Figure 2 shows a typical result for this test. Steady-state was reached after completion of controller actions, and following switch-on the steady-state was reached in about 4 minutes.



**Figure 2.** Steady-state trial results with 712 µg off-set.

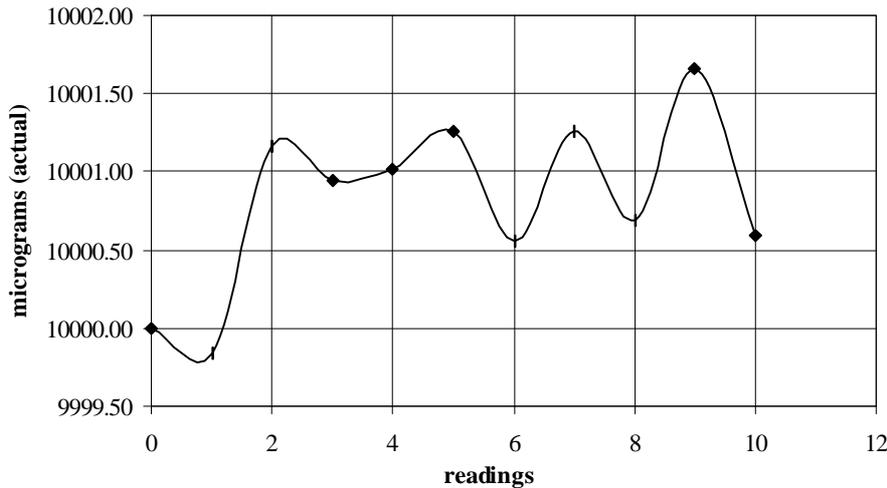
The results of a 10 mg off-set in 1 kg mass comparisons applied to either pan alternatively for 10 minutes are shown in Figures 3 and 4.



**Figure 3.** Steady-state results for maximum range off-set on pan 1.

The results of Figures 3 and 4 show a stability that equates to an uncertainty in mass measurement of a standard deviation of 3 parts in  $10^{10}$  of a kilogram.

The work reported confirms the high accuracy in mass balance comparisons possible with the high precision flexure-strip mass balance. With the possible further reduction in instrument noise levels sub-microgram uncertainties are possible.



**Figure 4.** Steady-state results for maximum range off-set on pan 2.

## ACKNOWLEDGEMENTS

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