

## Automated Mass Handling for High Performance Pressure Balances

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### Abstract

The piston gauge or pressure balance is essential to pressure metrology research and as a calibration tool. Over the years, its basic performance has been improved by several orders of magnitude. However, in most cases, the instrument's operation remains tedious and labor intensive.

A line of piston gauges introduced in the early 1990s integrates the electronics necessary to support the automation of piston gauge operation. These include monitoring of piston behavior and environmental conditions. Limited automated pressure control became available in the mid-1990s. Most recently, an automated mass handling accessory has been introduced, covering the full range of pressure in gauge and absolute modes. This makes fully automated operation over the complete pressure range possible.

Experience shows that the benefits of automated piston gauge operation are both practical and metrological. These range from obvious gains in productivity to other types of benefits such as reduced mass wear over time and making possible new test programs. The impact of automated piston gauge operation on transfer standard characterization and calibration is examined.

### 1. Introduction

Pressure balances are valued in pressure metrology for their fundamental operating principle, very high precision, relatively low influence of ambient conditions, very high stability over time and the ability of the floating piston to stabilize the set pressure. However, their use is generally tedious and labor intensive. In particular, the requirement to load a different combination of masses on the piston for each pressure to be set has both practical and metrological consequences.

An automated mass handling accessory has been introduced for an existing line of pressure balances [1]. The accessory can eliminate the need for manual mass handling in day to day operation and, combined with automated pressure control, allows fully automated pressure balance operation.

### 2. Design of the automated mass handling system

#### 2.1 Objectives

From the start, a main objective of the new mass handling system was to make automated mass handling a routine feature of high performance pressure balances, rather than an exclusive system for limited, special applications. These objectives were used to define the project:

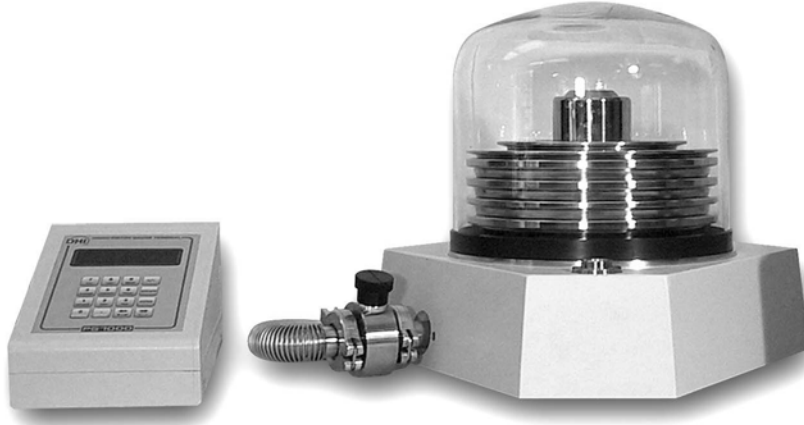
- Accessory to existing platform and piston-cylinder modules – To meet the practicality and costs objective, the automated mass handling system must be able to be used on existing pressure balance platforms with existing piston-cylinder modules, as is.
- Piston-cylinder accessibility – The piston-cylinder must remain easily accessible for range changing, piston-cylinder cleaning, etc.
- Minimum mass – Increasing the minimum mass load should be avoided so that the range of each piston-cylinder is not significantly reduced.
- Mass loading resolution – The resolution with which mass values can be loaded needs to be fine enough to provide an adequate number of pressure increments when the balance is used to calibrate devices with ranges lower than the full range of the piston.
- Mass wear – When loading and unloading masses there must be no friction between masses and/or between masses and the loading system. Friction would cause mass wear, defeating one of the main benefits of avoiding manual mass manipulation.
- Reliability – In particular if the mass handling system requires a mass set that cannot easily be used manually, the mass handling system must be highly reliable and not requiring frequent maintenance. There must also be no possibility of undetected incorrect mass loads.
- Operation with vacuum reference – to support absolute pressure operation, it is necessary to manipulate mass under vacuum, without reducing the ultimate vacuum or interfering with the reference vacuum integrity.
- Integration into pressure balance operation – to be easy to use locally and remotely, the mass handling system must integrate smoothly into pressure balance operation and system architecture, preferably not requiring separate, add-on devices, interfaces or software.

## 2.2 Overall design

The new mass handling system is designed to operate with a line of pressure balances designated PG7000 [1] produced by DH Instruments, Inc. With different models, the PG7000 line covers the complete pressure range from 10 kPa absolute gas pressure to 500 MPa oil pressure. With one model, absolute pressure can be defined relative to vacuum established in a bell jar around up to 38 kg of mass (Figure 1). With the others, that do not support a reference vacuum, up to 100 kg of masses can be loaded (Figure 2).

As the mass handling system is intended to operate with the existing PG7000 platforms, the platforms' define the physical boundaries of the mass handler and mass set. To avoid issues of alignment of the mass handler relative to the mass set and to take advantage of the sturdy and precisely machined cast base, the mass handler mounts onto the platform itself. However, to accommodate automated mass manipulation, and to provide adequate mass loading resolution, a new mass set design, specifically for the automated mass handler, is necessary.

The basic principle of operation is to lift the entire mass load off the piston, to a mass selection position. In the mass selection position, masses not to be loaded are retained by the mass handling system, then the remaining mass is lowered back onto the piston.



**Figure 1.** PG7601 pressure balance for gas pressure to 7 MPa (1000 psi) and absolute against vacuum reference with manual mass set.



**Figure 2.** PG7102, 7202, 7302 pressure balance gas pressure to 100 MPa (15000 psi) and oil pressure to 500 MPa (72500 psi) with manual mass set.

### 2.3 Design of the mass set

The first consideration in the design of the mass set is the level of mass loading resolution that is necessary. From a practical and cost standpoint, less resolution requires fewer individual masses, which is favorable. On the other hand, when using pressure balances, mass values are sometimes loaded with resolution of 10 mg, for example to set a particular pressure point more exactly or when performing crossfloats.

Loading mass automatically with 10 mg resolution is prohibitive from a complexity and cost standpoint. In practice, achieving exact, cardinal pressure points is very rarely necessary and the vast majority of pressure balance work is not crossfloating. Another consideration is that, with very high resolution mass loading, mass loading errors can occur that are small enough to not be detected. If the mass loading resolution is significantly lower than the measurement uncertainty of the system, any error in mass loading is easily identified by a large error in the actual pressure relative to the expected pressure.

The automated mass loading resolution selected is 100 g. This provides 370 increments with the 38 kg mass set and more than 1000 with the 100 kg mass set. Even with the 38 kg mass set, more than 30 increments can be achieved when running a calibration in a range that is only 10% of the piston's full range. More specifically, it gives pressure setting steps of 20 kPa (3 psi) on a piston-cylinder with a range of 7 MPa (1000 psi). For cases in which it is indispensable to load mass values with higher resolution, a mass loading tray is accessible so that smaller masses to complement the mass loaded automatically can be loaded manually.

The 100 g mass loading resolution is achieved using a mass set made up of a group of masses whose values are in binary progression and a group of main masses of nominally equal values.

The binary masses are tubes with diameters that increase with mass value (Figure 3). The individual binary mass tubes fit inside each other with no contact between them. Each mass is loaded directly onto the piston or mass carrying bell, independently from the others (Figure 4). For the 38 kg mass set the binary masses are nominally 0.1, 0.2, 0.4, 0.8, 1.6, 3.2 kg. For the 100 kg mass set there is, in addition, a 6.4 kg binary mass.

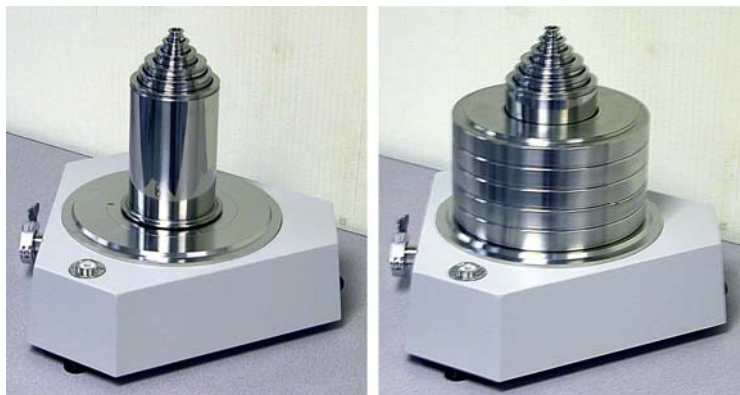


**Figure 3.** Complete mass set for automated mass handling system.

The main masses are discs (Figure 3). The main mass discs are loaded onto a ledge at the bottom of the mass carrying bell. They are loaded sequentially, one on top of the other (Figure 4). For the 38 kg mass set there are five main masses of 6.4 kg nominal value. For the 100 kg mass set there are nine main masses of 10 kg nominal value.

To load a specified mass value, the necessary number of main masses is loaded along with the selection of binary masses needed to reach the required load as closely as possible within the 100 g value of the smallest binary mass.

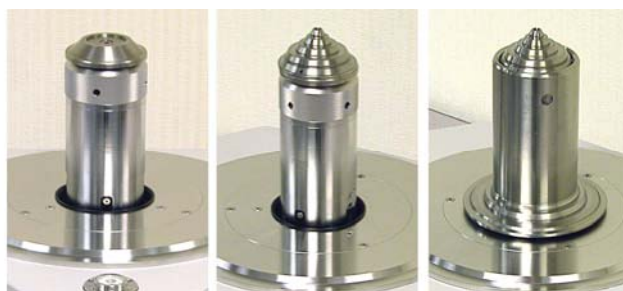
The minimum load is the piston assembly plus the mass carrying bell. All piston assemblies are 200 g (500 g for tungsten carbide 35 mm). The bell of the 38 kg mass set is 300 g with manual mass loading and 500 g with automated mass loading. The mass carrying bell of the 100 kg mass set is 800 g in both cases. So, the only change to the minimum load when using automated mass handling rather than manual mass handling is the 200 g increase of the 38 kg mass set bell.



**Figure 4.** Piston gauge platform with binary mass tubes loaded (left) and binary masses and main masses (right).

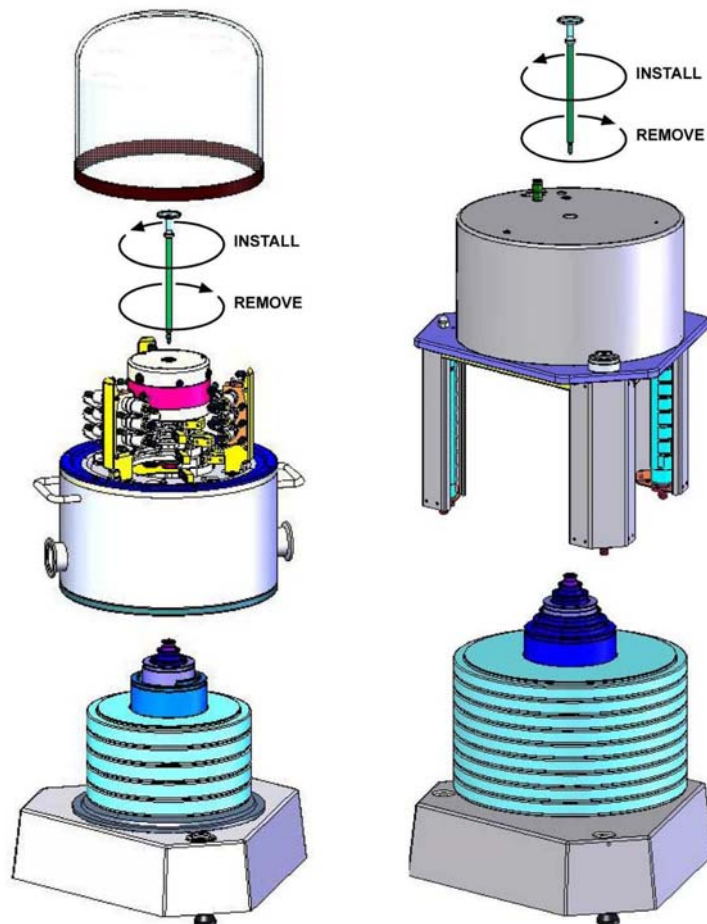
Each mass in the mass set is adjusted to its nominal value and then its actual value is determined by calibration. The PG7000 system handles the calculations necessary to determine the nominal mass to load to achieve a desired mass value within the 100 g loading resolution and the actual value of the final load.

Installing the automated mass handling system starts by loading all the masses manually onto the piston. First, the binary mass carrier is placed on the standard piston cap (Figure 5). Next the mass carrying bell is slipped down over the binary mass carrier so that its upper edge rests on the carrier. Then the binary masses are placed on the binary mass loading carrier or the mass carrying bell and the main masses are loaded sequentially onto the bell (Figure 3, 4).



**Figure 5.** Piston cap only, binary mass carrier loaded, binary mass carrier and mass bell loaded (left to right).

Once the masses are all loaded, the automated mass handler is placed onto the platform over the masses (Figure 6). Finally, the mass lifting shaft (part of the mass load) is installed. To remove the mass handler and masses, the mass handling system is instructed to load all of the masses onto the piston and the procedure is reversed.



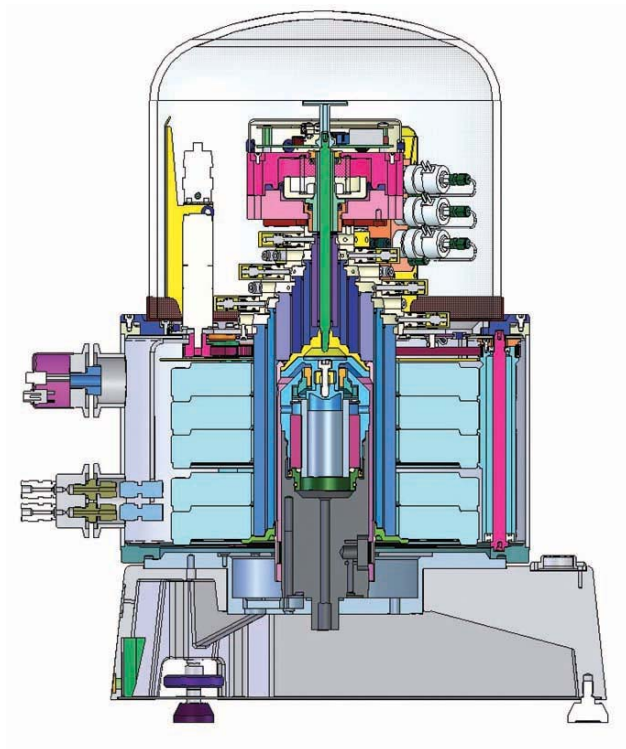
**Figure 6.** Installing and removing the automated mass handlers.

## 2.4 Design of the mass handling system

The mass handling system is made up of four main subsystems. The four sub-systems are the mass lifting and lowering mechanism, the binary mass selection system, the main mass selection system and an electronic measurement and control system. The four systems are built into one assembly (Figure 7, 8). The 38 and 100 kg versions use the same subsystems but the 100 kg version has longer main mass selection columns, spaced further apart to accommodate 10 kg main masses. It also has an extra tubular, binary mass (6.4 kg) that loads onto the mass carrying bell. The 38 kg version includes a vacuum chamber to allow establishment of a reference vacuum around the masses and it uses the standard PG7601 bell jar to cover the mass lifting mechanism and binary mass selection system.



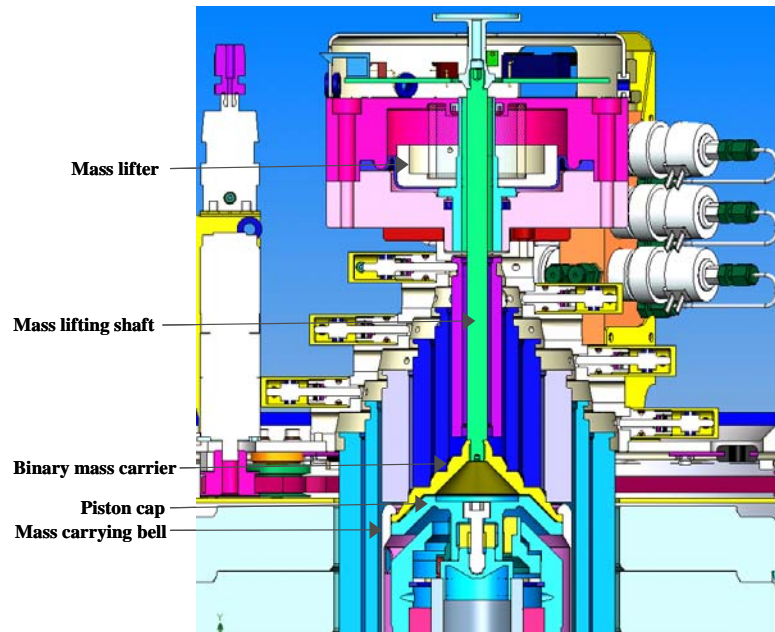
**Figure 7.** Automated mass handling systems on PG7000 pressure balance platforms, 100 kg (foreground) and 38 kg with vacuum reference versions.



**Figure 8.** Cross section of automated mass handling system, 38 kg version with vacuum chamber for absolute pressure relative to vacuum on PG7601 platform.

### 2.4.1 Mass lifting and lowering mechanism (Figure 9):

The mass lifting and lowering mechanism is used to move the mass load off of the piston to the mass selection position and back down onto the piston. The lifter is pneumatically actuated. A flexible diaphragm is connected to a lifting assembly. A three way solenoid valve admits or exhausts pressure from the volume under the diaphragm, lifting or lowering the lifting assembly. As the mass lifting assembly rises, it engages a ledge on the mass lifting shaft pushing it up. The mass lifting shaft is connected to the binary mass carrier and the mass carrying bell sits on the binary mass carrier. So, as the mass lifting shaft rises, it pulls up the binary mass carrier and the mass carrying bell, along with all the loaded masses. Eventually, the moving mass load meets the masses that were retained by the mass handler. When the lifting assembly reaches the top of its stroke all the masses are in contact with the binary mass carry or the mass carrying bell and lifted. This is the mass selection position in which the binary and main mass loading systems are operated to determine which masses will be retained by the mass handling system or loaded. Once the selection is complete, the load, including the non-retained masses, is lowered back down onto the piston.



**Figure 9.** Cross section of automated mass handling system mass lifter and binary mass selection system, mass in lowered position, on piston.

### 2.4.2 Binary mass selection system (Figure 9):

The binary mass selection system is used to select which binary masses are to be included in the mass loaded onto the piston. Three pins for each mass are evenly distributed around the outside, top circumference of each binary mass tube. When the mass load is lifted to the mass selection position, the pins align with a notch around the upper, outside circumference of each binary mass and can be engaged and disengaged without touching the mass. The pins are pneumatically actuated and double acting. Two three-way solenoid valves control drive pressure to each set of three pins. One valve admits pressure to one side of the pin to extend it into the notch, the other admits pressure to the other

side of the pin to retract it. When selecting binary masses, the pins are extended to hold masses that are to be retained and retracted to allow masses that are to be loaded to be included in the mass load that is lowered onto the piston.

### **2.4.3 Main mass selection system (see Figure 8):**

The main mass selection system is used to select how many main masses are to be included in the mass loaded onto the piston. The main mass selection columns are used to retain the main mass discs that are not to be loaded. Each column has a number of sides equal to the maximum number of main masses plus one (six sides for the 38 kg version, ten sides for 10 kg version). One side, which retains all the masses so that none are loaded, has a ledge for each mass. Each subsequent side has one less ledge, moving from the bottom up. The last side has no ledges and is used to load all the main masses. When the mass load is in the mass selection position, the ledges on the column are across from the gaps between the main masses and the columns can be rotated without making contact with the masses. The columns are rotated synchronously by a DC motor and a drive belt. Contact switches are used to monitor the position of the columns. The motor is operated to rotate the columns to retain the desired number of masses, starting with the top mass and moving down. When the mass load is lowered, the masses to be retained are stopped by ledges on the column and the masses to be loaded are free to descend onto the piston.

### **2.4.4 Electronic measurement and control system:**

The electronic measurement and control system measures status conditions of the automated mass handler and controls its operation. The electronics mounted on the top of the mass lifter, include a microprocessor, memory, serial communications and embedded software. The system accepts and executes commands to load specific masses and other macro commands. It returns various status messages. Measurements include an optical detector of the position of the mass load which is used to confirm that the load is in the mass selection position before operation of the mass selection systems is allowed and to determine when the load is down and a loading sequence has been completed. Indexing switches on the main mass selection columns allow the position of the columns to be identified when rotating them.

The control systems include electrical actuation of the drive air solenoid valves used to operate the mass lifting and lowering mechanism and the binary mass selection pins. The main mass selection column position is controlled by DC motor and drive belt.

## **2.5 Considerations for operation with a vacuum reference**

Automated mass handling when using a pressure balance to define absolute pressure relative to a vacuum reference presents some additional design challenges. For mass load changing to occur without having to break the reference vacuum, the complete mass handling system must be built into a vessel within which a vacuum can be established and maintained. All the components within the vessel must be able to operate without being surrounded by air.

To avoid overheating of electrical and electrically powered components, the components used were selected and tested for operation in a vacuum. Generally, very low power components are

used and they are powered only for brief periods. For example, the binary mass selection pin pneumatic actuators are double acting. Air drive is needed only to change their position so the solenoid valve needs to be opened only a couple seconds to admit air and move the pin rather than having to be left on to maintain the pin in place.

To minimize opportunities for air drive leaks to affect vacuum integrity, drive pressure is used only momentarily to complete an operation, it is never applied permanently. The double acting binary mass selection pins are pressurized to move the pin and are then vented. The mass lifting mechanism is pressurized only for the time required to lift the masses and make the mass selections. Then the pressure is released to lower the masses. When operating in absolute mode, a utility vacuum supply is connected to the drive air vent port. The vacuum removes the air from drive air circuits when they are not pressurized so the differential pressure with the inside of the vacuum chamber is insignificant.

In practice, the level of vacuum obtained when using the automated mass handler in absolute mode is not measurably different from operation with the one piece Pyrex® bell jar used in manual mode. Typical vacuum obtained with a conventional rotary vane pump is on the order of 2.5 Pa (20 mTorr). However, since the vacuum does not need to be broken and reestablished for each mass increment, it becomes practical to use a turbo-molecular vacuum pump. Two KF40 vacuum connections are provided on the vacuum chamber to support setting and measuring a lower reference vacuum. Using a turbo pump, reference vacuum is typically less than 0.5 Pa (4 mTorr).

### **3. Integration of the automated mass handling system into pressure balance operation**

The automated mass handling system's COM1 port is connected to the pressure balance's COM2 port and it is controlled by the pressure balance. The pressure balance accepts commands of pressure or mass values and instructs the mass handling system to load the mass combination that results in a total mass load that is as close as possible to the specified mass load. Masses can also be loaded discreetly with direct commands to load specific masses. Before operating the mass handler, the pressure balance platform's motorized piston rotation system is used to stop piston rotation so the masses are static when contact is made with the mass lifting mechanism.

### **4. Benefits of automating mass handling in pressure balances**

DHI has been using automated mass handling on PG7000 pressure balances in its production and service pressure calibration laboratories since the spring of 2003. This direct experience reveals that automating mass handling brings both practical and metrological benefits.

Practical benefits include:

- Improved operator working conditions – Eliminating the chore of manually loading and unloading masses reduces the physical labor associated with pressure balance operation.
- Reduction of operator errors – When automated, the mass loading procedure is consistent and the value loaded is always the intended value.

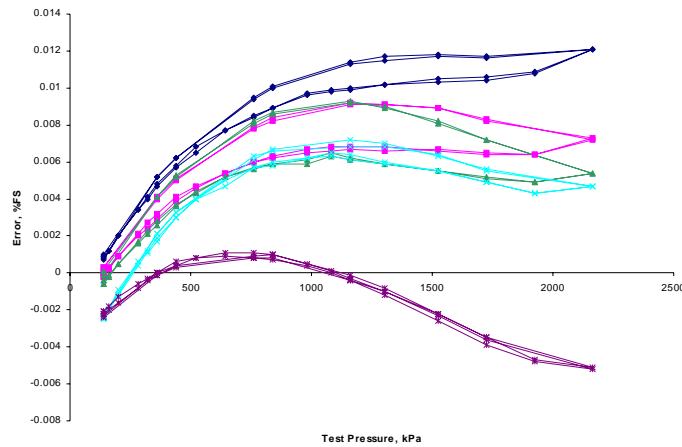
- Improved throughput – The time required to complete pressure increments is reduced. This is particularly true in absolute mode in which it is no longer necessary to make and break the vacuum reference for each pressure increment.
- More efficient use of equipment – Automated mass handling combined with automated pressure control and automated data acquisition from the device under test allows fully automated, unattended operation. This makes it possible for one operator to run multiple pressure balances and for pressure balances to continue operating when operators are not present.

Metrological benefits of automating mass handling include:

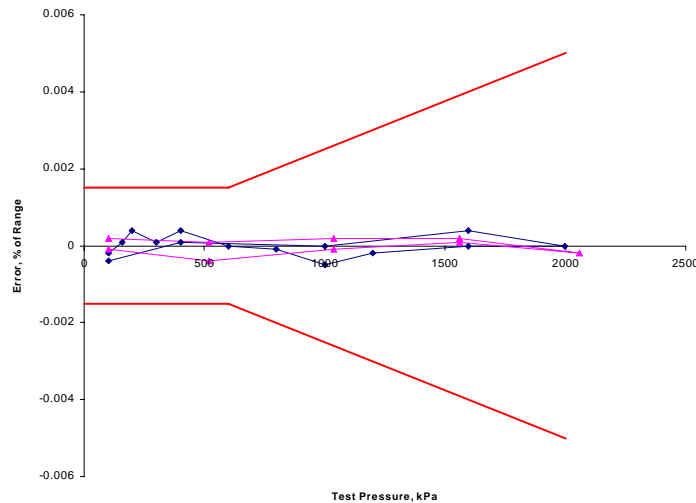
- Improved stability of mass over time – Greatly reduced handling of the masses and of wear from manually sliding masses on and off of the mass carrier reduces changes in mass values over time [2].
- More consistent leveling of the piston – The weight distribution on the pressure balance platform and the bench upon which it rests remains constant rather than changing as mass is added and removed to change pressures.
- Greater availability of data – Automated operation makes it practical to perform more complete tests such as repetitive runs to evaluate repeatability or increasing the number of calibration points when characterizing transfer standards.
- In absolute mode with vacuum reference:
  - Not having to make and break the vacuum at each pressure point results in more consistent reference vacuum values from measurement to measurement.
  - Operating at lower levels of reference vacuum reduces the absolute uncertainty in reference vacuum measurement [2].

In our experience, one area in which the benefit of automated mass handling and automated pressure balance operation has been the most noticeable is for the original characterization and maintenance over time of pressure transfer standards. DHI produces transfer standards in ranges from atmospheric pressure to 200 MPa. With the most current technology introduced in the summer of 2003, these provide measurement uncertainty specifications of  $\pm 0.008\%$  of reading. Achieving these specifications in the original product and maintaining them over time requires the use of pressure balances in the characterization process and for their accredited calibration and recalibration. Without automation of the pressure balances used it would not be feasible to offer these products. The labor costs required to characterize the transducers manually would be prohibitive. Consistently achieving the necessary level of performance from the pressure balances, on a day to day basis, in a production laboratory environment would also be nearly impossible. This is particularly true in the ranges requiring operation of the pressure balance in absolute mode with a vacuum reference.

With automated mass handling, the pressure balance operation can be fully automated and operated uninterrupted when operators are not present. The influences of making and breaking the vacuum and of inconsistency in operator procedure are eliminated. Figure 10 shows the results of a characterization run of five 2 MPa absolute transducers before the transducers have been compensated. Each run includes two full scale pressure sequences with 28 pressure points in each sequence. The plot shows the deviation of transducers relative to the pressure balance. The two sequences repeat so well for each transducer that it is barely possible to distinguish them. For each individual transducer, hysteresis and localized non-linearity at the level of a few ppm are very well defined. The test is completed in less than three hours including 1.5 minutes of dwell and data acquisition at each point. Manually, the test required a full day with a dedicated operator and the results were of lower quality with frequent aberrant points.



**Figure 10.** Deviations of five 2 MPa absolute pressure transducers from automated pressure balance reference before characterization.



**Figure 11.** Deviation of two 2 MPa absolute pressure transducers from automated pressure balance reference after characterization.

## 5. Conclusions

The practical benefits of automating the handling of masses for pressure balance are evident. There are also less obvious metrological benefits such as more consistent procedures and more consistent vacuum reference in absolute mode. The introduction of automated mass handling systems that are accessories to standard pressure balance platforms in a reasonable, bench top footprint and at cost that increases the price of a system by well under 50%, makes automated mass handling and fully automated pressure balance operation much more accessible than they have previously been. This is likely to make automated mass handling a common feature of high performance pressure balances, removing the manually intensive procedures for which pressure balance are known. It also makes it possible to enjoy the unequalled precision and measurement uncertainty of the pressure balance in applications for which its use manually could not be justified.

### References:

1. DH Instruments, Inc., PG7000 Reference Level Piston Gauges, DH Instruments Product Brochure 9960.1.B.10, 1999.
2. Bair, M. and Delajoud, P., “Uncertainty Analysis for Pressure Defined by a PG7601, PG7102, PG7202 or PG7302 Piston Gauge”, DH Instruments, Inc. Technical Note 7920TN01C, 2003.