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DESIGN OF A NEW SERIES OF PRESSURE BALANCE IN LIQUID MEDIUM

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Abstract – The design and development of a series of pressure balances, operating in liquid media up to 120 MPa, have been started during a recent collaboration between the Italian company SCANDURA & FEM and the I.N.Ri.M. (Italian National Research Institute of Metrology) in Italy.

The details of the project design for these pressure balances are here presented. Two different pressure balance's lines have been develop: one, the RedLine, only mechanical, the other one, the BlueLine, with an on board electronic compensation system. The main chosen strategy has been decided in such a way to produce a compact pressure balance easy to move, but at the same time equipped with all the measuring sensors needed to compensate the errors due to the main influence quantities (for the BlueLine model).

The main metrological characteristics of some piston-cylinder units were experimentally analysed and some interesting results are here presented. To better characterise these pressure balances several investigations, by using the FEM Analysis, have been done in cooperation with the University of Cassino.

Keywords: pressure balance, piston-cylinder assembly, FEM Analysis.

1. BASIC INFORMATION

The goal of this design was to produce a series of pressure balances with appreciable metrological characteristics and suitable for an industrial use as well.

To fulfil these requirements, a compact balance, easy to carry, with a limited total weight and at the same time accurate and efficient, has been developed.

For all the pressure balances a tungsten carbide piston-cylinder was used. The cylinder has been inserted in a stainless steel body that contains the piston-cylinder assembly on its top side in such a way to keep low the centre of gravity of the masses used to balance the force dues to the pressure applied to the effective area of the piston-cylinder unit.

The piston-cylinder assembly is of the "free deformation" type.

The top side of the piston has been integrated in another stainless steel part that sustains the disc carrying the masses. After the insertion of the bottom side of the piston into the cylinder, this part is screwed to the body containing the same cylinder. In this way, a mechanical assembly, with the following main tasks will be achieved:

- to allow the piston to flow across the cylinder defining at the same time the full piston stroke,
- to define the points of the force application on the assembly,
- to guarantee the assembly verticality,
- to sustain the disk carrying the masses,
- to purge the fluid that slowly flow through the piston-cylinder gap,
- to use a probe for the temperature measurement of the piston-cylinder unit.

A stainless steel weight carrier is put on the mechanical component containing the piston and its surface wraps up this component without any mechanical interference with the same. A small extension, at the bottom part of the weight carrier , sustains the masses inserted from the top and lying on each other in order to achieve the desired total mass.

The stainless steel masses are of different sizes and shapes in order to realize all the pressures between the minimum and the full scale with a resolution according to the smallest mass in use. In the central part of each mass a cavity, closed by a lid, has been realized, in which different stainless steel spheres, with different diameters, can be inserted to adjust the mass value to the nominal one.

In the BlueLine model, a motor drives the piston rotation and a series of sensors measure the main influence variables. In this case a microprocessor based electrical board collects the data from these sensors and, combining the data with the constants of the system, gives the pressure value according to the pre-defined mathematical model. The total mass value is calculated from each mass value, indicated in the certificates and reported into the memory of the electrical board. A barcode identifies each mass and can be read at the time of mass use.

The integrated sensors are: a barometer for the atmospheric pressure measurement, an ambient temperature probe, a relative humidity sensor, a thermo-resistance for the measurement of the piston-cylinder temperature and a proximity sensor to collect information about the floating level of the piston.

Fig. 1 - Pressure Balance MPA series

Fig. 1 the complete system is shown. On the left side of the balance's base, a display gives the user all the information about the measurements of the influence variables and presents the corrected pressure. In the right side, a keyboard allows the user to set up different parameters like: the pressure engineering unit, the mass values, the p/c unit's area, the elastic and thermal coefficients of the p/c assembly, the density and the dynamic viscosity of the used fluid at the NTP, and others.

2. METROLOGICAL CHARACTERISTICS DETERMIANATION

Different piston-cylinder assemblies have been produced. For some assembly, the following experimental tests have been performed for the evaluation of:

- piston fall rate as a function of pressure,
- piston and mass assembly rotation speed decay as a function of time,
- effective area of the assembly as a function of pressure,
- sensitivity of the cross-floating of two pressure balances.

For all assemblies verified the behaviour of the piston's fall rate is linear as a function of pressure. For example in Figure 2 the piston fall rate versus pressure for a 36 MPa full-scale unit is given.

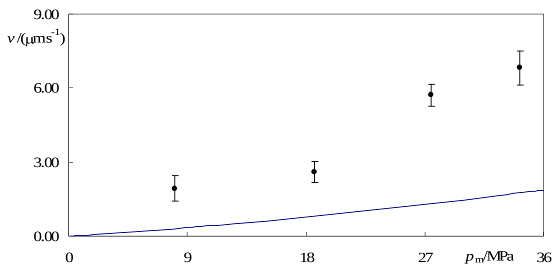

Fig. 2 - 36 MPa full-scale unit. Comparison between experimental (•) and numerical piston fall rate (at 20 °C) as the measurement pressure varies. Error bars represent experimental fall rate standard uncertainties.

As can be seen from Figure 2 there is not a good agreement between experimental and FEM calculations; this may be due to roundness and perpendicularity errors on the piston and cylinder.

In a couple of cases the variation in piston-cylinder gap along the piston-cylinder engagement length has been carried out from a series of dimensional measurements done at the INRIM laboratories. In Figure 3 the results of dimensional measurements are given for the 36 MPa full-scale unit.

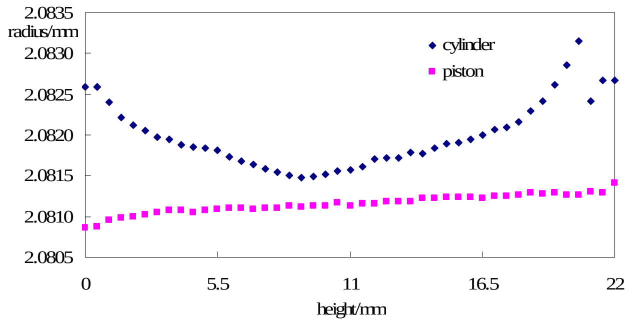

Fig. 3 - 36 MPa full-scale unit. Dimensional measurements at INRiM for the piston and cylinder of the 36 MPa unit.

The expanded uncertainty of radial measurements are $U(r) = U(R)$ = 25 nm for piston and cylinder respectively, but due to irregularities of shapes (error of circularity and perpendicularity) a value of 50 nm was adopted (a posteriori from the analysis of data this value is to be considered too optimistic.

For all the piston-cylinder assemblies the behaviour of the reduction of the rotation speed is extremely regular as a function of time. This qualitatively represents a proof of the regularity of the pressure distribution in the gap of the pistons and cylinders. In Figure 4 the variation of rotation speed versus time is given for a unit (Scand 3) operative up to 120 MPa.

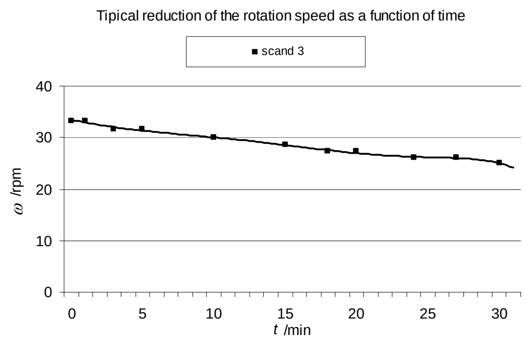

Fig. 4 - 120 MPa full-scale unit. Variation of rotation speed versus time.

As can be seen from Figure 4 the revolution speed is linear and regular and after 30 minutes the reduction is of less than 10 revolutions per minutes (rpm).

The effective areas of different piston-cylinder assemblies have been determined from pressure cross-floating with one of the INRIM pressure national standard and taking into account each influence quantity during the cross-floating. In Figure 5 the cross floating results are given in terms of effective area for a unit operating up to 120 MPa, even if the cross floating was made only up to 100 MPa.

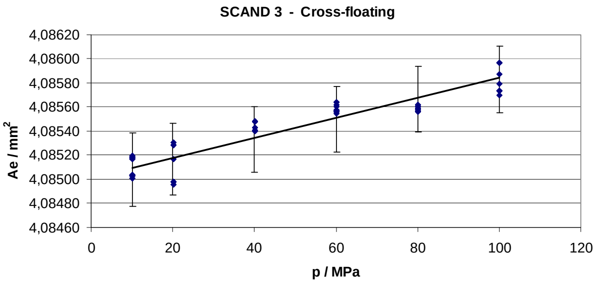

Fig. 5 - 120 MPa full-scale unit. Effective area versus pressure as experimentally determined.

The mean value of effective area of the piston-cylinder unit at atmospheric pressure and at reference temperature of 20 °C, is equal to 4,08501 mm^2.

This value, considering its estimated expanded uncertainty of the order of 80 ppm, is in agreement with the effective area value derived from dimensional measurements [1].

The value of pressure distortion coefficient λ is equal to $2{,}0 \cdot 10^{-6}$ MPa^{-1} and this value was also confirmed by using the finite element calculation method FEM as previously done for other pressure balances.

The sensitivity tests have been performed, by cross-floating, comparing the pressures measured by the national standard pressure balance and by the piston-cylinder assembly SCAND3. For this assembly the sensitivity value is always smaller than 12 ppm over the full measuring pressure range (10 to 100 MPa).

For example, for three 120 MPa full scale piston-cylinder assemblies, SCAND1, 2, 3, the mean values of the affective areas at the atmospheric pressure and at the reference temperature of 20 °C, are respectively equal to 4,08940 mm^2, 4,08576 mm^2 and 4,08501 mm^2.

The respective values of the pressure distortion coefficients are $1{,}32 \cdot 10^{-6}$ MPa^{-1}, $1{,}51 \cdot 10^{-6}$ MPa^{-1} and $2{,}03 \cdot 10^{-6}$ MPa^{-1} and have been evaluated also by a more accurate experimental analysis and by using the finite element calculation method FEM [2][3][4][5].

3. THE AUTOMATIC ROTATION SYSTEM

The motor drive system is designed in such a way that the application of the rotation to the piston is given only when the piston is in its lowest position. When pressure is increased the piston moves-up to reach its floating position, where the piston is in its free rotation. To avoid a useless increment of temperature, a proximity sensor detects the piston floating position and conveys this information to an electronic card that automatically switches off the motor. Moreover, to avoid any mechanical interference, between the motor system and the piston-cylinder unit, these two parts are totally independent and not in mechanical contact between each other during measurements. The rotation is transferred to the piston by friction of three rubber wheels with the masses carrier. The wheels are put into rotation by a motor, connected to a series of gears and a driving belt. A series of eccentrics permits the positioning of the wheels and maintains the driving belt at the correct tension.

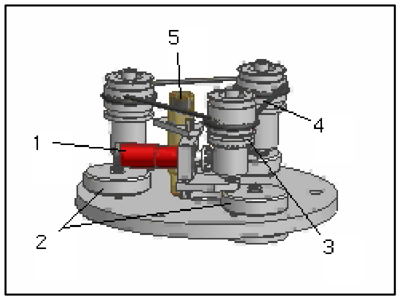

Fig. 5 - Automatic rotation system (1-motor, 2-eccentric system, 3-wheel with gears, 4-driving belt and 5-proximity sensor)

4. THE ELECTRONIC ERROR COMPENSATION BOARDS

A microprocessor based on an electrical board collects the data from the different sensors and, combining these data with the constants of the system, gives the pressure value according to the pre-defined mathematical model.

All the information needed to carry out the correct measured pressure is elaborated from the microcontroller of this board.

Here a list of function that the electronic board can control:

- to switch on or switch off the motor according the floating position of the piston
- to detect in real time the floating position of piston and display this information
- to calculate in real time the temperature of the piston-cylinder assembly
- to calculate in real time the density of the air by measuring the relative humidity, the barometric pressure and the temperature of the air
- to calculate the piston fall rate to be used for the characterization of the piston-cylinder assembly and for a performance check based on this important parameter
- to detect the rotation speed of the piston, weight carrier and masses
- to memorize all the information regarding the nominal section of the assembly, the mass value of each weight, the value of the elastic distortion coefficient, the values of the thermal expansion coefficients of piston and cylinder, the density of the masses, the density and the dynamic viscosity of the oil
- to use all the variables and constants to calculate the correct pressure value by using a pre-defined mathematical model

Three different boards compose the electronic device: one main board with the power supply management and the bus, one analogue board that collects all the signals from different sensors and a digital board with the microcontroller that manages all the logic status and performs the calculations. The memory is hosted on the digital board and contains all the constants used for a correct evaluation of the actual pressure at the time and under the conditions of the measurement.

The uncertainty of the main influence variable's measurements, contributes to the total uncertainty of pressure measurements when using these pressure balances.

The numerical evaluation of these contributions on the pressure uncertainty budget and the method of their determination, are presented in [6]. This contribution to the pressure standard uncertainty is always less than 5 ppm, also considering the editing and measuring resolution of each variable.

Among the most important contributions there are: the reference level determination by a proximity sensor, the relative humidity sensor, the ambient temperature sensor, the barometric sensor, the piston-cylinder temperature sensor, the resolution of the constants stored in the system's memory and the resolution of the pressure calculation.

5. CONCLUSIONS

A new series of pressure balances operating in liquid media is now available with the main following features:

- Modularity: with only one mass set it (total of 50 kg) is possible to use up to four different p/c units to cover a large pressure range up to 120 MPa: 1) from 0.055 MPa to 12 MPa, 2) from 0.15 MPa to 36 MPa, 3) from 0.25 MPa to 60 MPa and 4) from 0.5 MPa to 120 MPa.
- Automatic piston rotation assuring free rotation when the piston is in its equilibrium and without heat transfer to the piston-cylinder unit.
- All units have been tested by FEM analysis: the results were extremely useful to understand possible limitations of the basic metrological characteristics. It was possible to understand effects of circularity and perpendicularity errors that can be used to improve the geometries of the units.
- An on board automatic errors compensation system: to compensate the pressure value from the main influence variable's errors. The electronic error compensation contribution to the pressure standard uncertainty is always less than 5 ppm, also considering the editing and measuring resolution of each variable. It has to be remembered that this low value has not to be confused with sensitivity, which normally ranges from few ppm to 12 ppm, and also not with the pressure measurement uncertainty which typically ranges from 40 ppm to 80 ppm depending on the type and full scale of the pressure balance used.

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