CHARACTERIZATION OF A PROTOTYPE PISTON-CYLINDER UNIT DESIGNED AND MANUFACTURED WORKING IN THE PRESSURE RANGE 0.5-35 MPA HYDRAULIC MODE

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ABSTRACT

The prototype piston-cylinder unit covering a pressure range of 0.5-35 MPa in the hydraulic mode and its assembly was designed and manufactured. The elastic distortion coefficient, lambda (λ) of the piston-cylinder unit of a prototype pressure balance, used in primary standard gauges, was experimentally and analytically determined using cross-floating method and a Finite Element Analysis (FEA) software respectively. Since it is a well-known phenomenon that the elastic distortions in the piston and cylinder materials contribute as a source of high uncertainty among the total uncertainty budget, this study mainly focuses on the precise determination of lambda and also is given a short summary for the design and the manufacturing processes of the device. Having been characterized and where the FEA model of the piston-cylinder assembly was a rather simple one in early studies (as a master's thesis given in reference [2]), this model was developed as described in the text and a better determination of the elastic distortion coefficient has been achieved using an analytical method taking into account the elastic distortions in both piston and cylinder in an iterative way.

1. INTRODUCTION

To measure an applied pressure using a pressure balance, the effective area of the piston-cylinder must be known and the total downward force acting on the floating element must be evaluated.

The system of a pressure balance basically consists of a piston-cylinder unit, where the upward force acting on the bottom of the piston, via the fluid pressure exerted on the cross-sectional area, is equilibrated with the dead-weights that are mounted on the piston head, so that the generated pressure will be determined by the simple formula:

$$p = \frac{W}{A_{p,t}} \qquad (1)$$

where:

p is the applied pressure

W is the total downward force

$A_{p,t}$ is the effective area of the piston-cylinder assembly at the applied pressure p and at a temperature of T °C.

The evaluation of the total downward force and the effective area are not as straightforward as it might at first appear, as there are many corrections, which must be applied if pressure measurements of a high accuracy are to be achieved. The significance of the various correction terms will depend upon the level of accuracy required for the pressure measurement.

The dependence of the effective area on applied pressure may be expressed either by a simple mathematical relation or in tabular form. Where only narrow ranges of applied pressure are involved, the pressure dependence may be negligible. Taking the most common case where the pressure dependence may be adequately expressed in a linear form:

$$A_{p,20} = A_{0,20}.(1+\lambda.p) \tag{2}$$

where λ (lambda) is commonly referred to as the elastic distortion coefficient of the assembly and represents the fractional change in area per unit pressure.

In a pressure range above about 50 MPa, the change of the effective area of the piston-cylinder assembly due to elastic distortions becomes the main source of uncertainty of the measured pressure. So in this study, the Finite Element Analysis of the piston-cylinder unit of the device has been carried out for an accurate determination of λ, the elastic distortion coefficient.

2. DESIGN AND MANUFACTURE OF THE PROTOTYPE PRESSURE BALANCE

Piston in this design is actually composed of two parts, which are the piston and the piston head, which are only geometrically coupled. The need for this can be summarized as; forces vertical to the piston axis due to poor levelling, which are acted on the cylinder bore by the piston to be reduced, so any upward or downward friction due to this fact shall be minimized.

Designed prototype piston-cylinder unit is showed below (Figure 1).

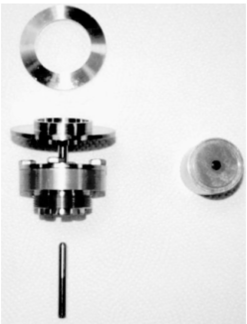

Figure 1: Piston-cylinder unit and its parts

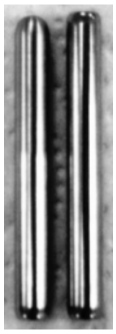

Figure 2: Piston made from needle roller

A nominal 6 mm diameter hard stainless steel needle roller was used as piston, where the cylinder is manufactured from a Tungsten Carbide – Cobalt alloy. The piston needed some treatment, that is; the top of the piston (Figure 2) was machined to a round form, for enabling it to work smoothly with the piston head assembly (Figure 3).

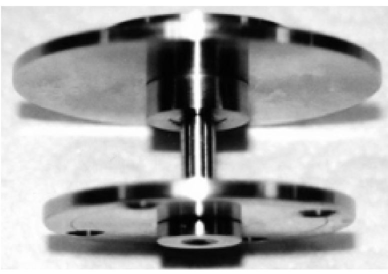

Figure 3: Piston head assembly

Figure 4: Piston-cylinder assembly

On the body of the device, there exists a slot for a temperature sensor to be mounted, and it was designed enough close to the measuring region of the p-c assembly. The slot is an open type hole to ensure the cleaning to be made easier (Figure 4).

The motion of the piston inside the cylinder bore is limited from up and down. It stops down where the fluid line inside the body begins at the bottom of the cylinder and the upper limit was established by a steel part, attached to a bronze nut that fixes the cylinder. It limits the motion of the piston head, so it limits the motion of the piston also and the consequent stroke for the piston would be 15 mm

3. EXPERIMENTAL RESULTS

The calibration was held, using the conventional pressure metrology, cross-floating technique, where the reference was selected as a Budenberg Co., 381 type pressure balance. General appearance of the set-up is shown below (Figure 5).

Figure 5: Experimental set-up. The prototype piston-cylinder assembly shown on the right side of the picture, the reference standard is on the left

Effective area and pressure distortion coefficient were calculated and listed in Table 3. 24 measurements, 16 in ascending and 8 in descending pressures, were carried out for determining effective area and distortion coefficient.

Table 3: Calibration (using cross-floating method) results for the prototype piston cylinder unit

A_{eff}, Effective Area at Atmospheric Pressure and Reference Temperature, 20°C (cm^2)	$(0.282750 \pm 0,0517) \times 10^{-4}$
Pressure Distortion Coefficient, λ ($MPa^{-1} x\ 10^{-6}$)	(4.7335 ± 0.2)

4. FEA MODEL

Piston and cylinder were modelled in ProMechanica FEA Analysis software as a 2D Axisymmetric and meshed using 2D elements using a AutoGEM (The algorithm that automatically creates a p-type finite element mesh mapped to part's geometry) module of the software and solved for each iteration to obtain elastic distortions both piston and cylinder with respect to applied pressures.

Coordinates of the key points on the piston-cylinder for 2D-CAD design, loads (as pressure) and constraints, which are applied on CAD model to perform FEA calculation, are listed in Table 4. Geometric model of the piston-cylinder unit was created using CAD software (mentioned above) as 2D Axisymmetric and shown in Figure 6.

Table 4: Data and key points of 2D Model

Coordinates of the Key Points		
# of Point	**x [mm]**	**y [mm]**
1	0	40
2	2.99909	40
3	2.99909	32
4	2.99909	0
5	3	-8
6	3	0
7	3	32
8	9	32
9	14	32
10	17.5	32
11	17.5	-8
12	14	-8
13	6	-8
(0,0)-1 Axis of symmetry		

Key Points	Loads and Constraints
3-4	Engagement Length (32 mm) Loaded (Pressure Distribution)
6-7	
2-3	Outer part of the piston
(0,0)-4	Loaded (Line Pressure)
5-6	
5-13	
1-2	Constrained
11-12	
12-13	
8-9	
9-10	

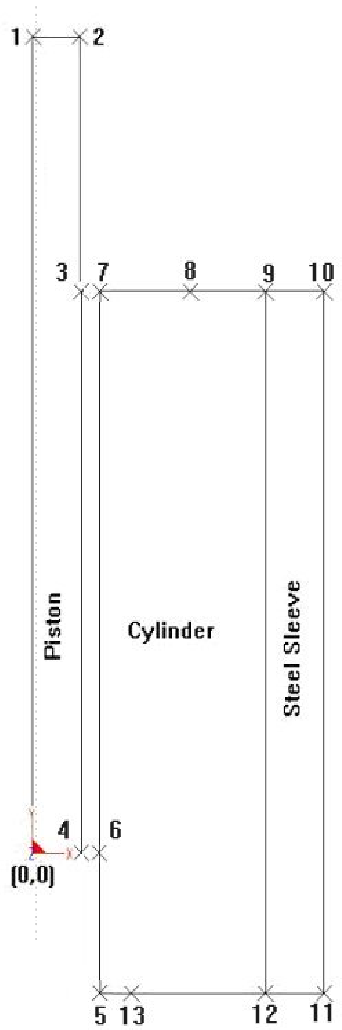

Figure 6: Geometric Model

5. FLUID FLOW MODEL

The fluid flow in the clearance between the piston and cylinder was assumed as a one-dimensional (axial direction of the piston) laminar flow, a stationary regime, a Newtonian fluid and constant temperature. According to these assumptions the derived Navier-Stokes equations used for calculation of pressure distribution along the clearance between piston and cylinder obtained [1,4]. A general expression, derived from equilibrium of the forcing acting on the piston along to the axial direction is useful to obtain the elastic deformations used for calculating pressure distortion coefficient of the piston and cylinder. From the theory of elastic distortion can it be shown that the variation of the effective area A_e of a simple piston-cylinder with applied of the piston-cylinder unit is linearly related to the pressure is essentially linear (2), i.e [6].

6. ITERATION AND CALCULATION

A calculation algorithm was built using MathCAD software to obtain pressure distribution in engagement length of the piston-cylinder unit using elastic deformation due to applied pressure and analysed in FEA. Iterative method is used to determine the exact pressure distributions in the clearance. The method was explained in [4],[5]. Firstly, a linear pressure distribution was applied in the clearance and obtained elastic deformations in the radial directions for both piston and cylinder and derived the gap profile from these deformations and constant gap width. Pressure distortion coefficient was calculated by using the formula (2) for each iteration step. Iterations were proceeded in order to get a convergence on λ and h(x) values [4]. The convergence criteria was taken 1 ppm change both λ and h(x) values compared to pervious iteration values.

7. RESULTS

Radial displacements on piston and cylinder, gap profiles for constant undistorted gap thought engagement length and also pressure distribution in piston-cylinder gap at 35 MPa and 20 MPa were obtained using iterative method and shown in Figure 7, Figure 8, Figure 9 and Figure 10. Elastic distortion coefficient values were determined experimentally and using FEA shown in Table 5.

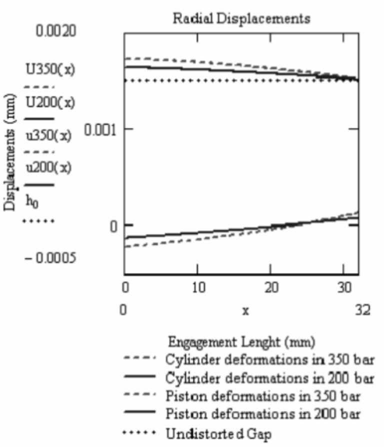

Figure 7: Radial displacements on piston and cylinder

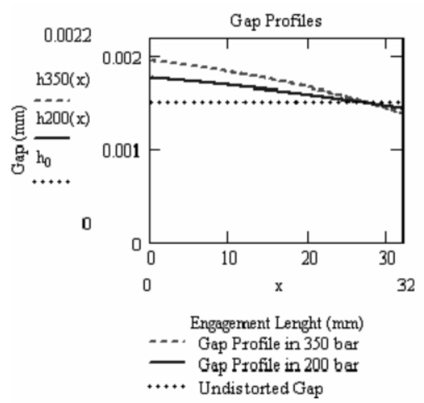

Figure 8: Gap profiles on engagement length

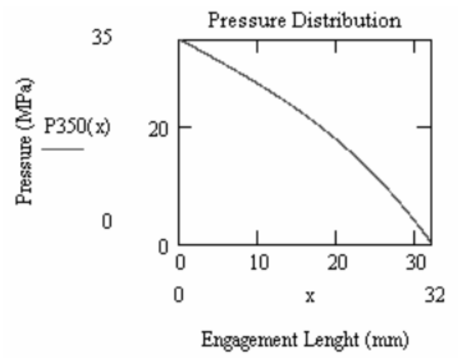

Figure 10 : Pressure distribution at 35 MPa

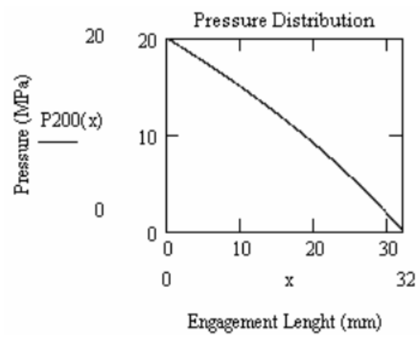

Figure 10 : Pressure distribution at 20 MPa

Effective areas of the prototype piston-cylinder unit at applied pressure were determined experimentally and also normalized areas were found. Experimental and dimensional results of effective areas were very close to each other with 8 ppm difference (Table 5).

Table 5: Comparing of elastic distortion coefficient values and effective areas

λ Values [$\times 10^{-6} \times$ 1/MPa]		
Experimental	*FEA*	*Difference [%]*
4.7335	4.8817	3.13
Effective Area of Piston-Cylinder Unit [cm^2]		
Experimental	*Dimensional*	*Difference [ppm]*
0.282750	0.282748	8

CONCLUSIONS

A prototype piston-cylinder unit and its assembly were manufactured and 3 calibration series were carried out to determine effective area of the piston-cylinder, and also some dimensional measurements on both piston and cylinder to obtain real gap profile were performed. Effective area of the piston-cylinder unit was obtained, experimental and also dimensional. There is an agreement between values. Verifications are done using FEA. Pressure Distortion Coefficients are obtained, approximately only % 3 difference is found on the value between experimental and FEA. Pressure in engagement length in both 350 bar and 200 bar are near to linear distributions because of the undistorted gap value (1.5 μm). Although this value is high for a piston-cylinder unit in order to float sufficient time for pressure measurements theoretically, experiments and measurement of piston fall rates are good enough to carry out measurement. The total uncertainty of the prototype piston-cylinder unit is app. 200 ppm and can be used in secondary pressure measurements and in calibrations of pressure gauges as a reference standard.

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