'Deformation of a Barrel Hole Due to Preloads and Operating Loads and its Effect on Spool Fit Size'

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1. Introduction

In a hydraulic manifold for construction machinery, spool valves are used to control the movement of the machine. Spool valves have two elements: a cylindrical barrel hole (1) in which a spool (2) slides. By moving the spool in the barrel hole, apertures open and close which enables the control of the connected hydraulics. To achieve the best control stability and to avoid internal leakage, a radial clearance as small as possible and a fine surface finish are required. At the same time, some clearance is required for lubrication between the valve spool and the barrel hole to prevent friction that would prematurely age the components or cause the spool to seize.

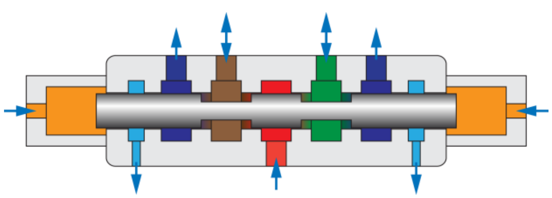

Figure 1. Basic principal of a hydraulic valve

Consequently, an optimum must be found between the conflicting requirements.

Unfortunately, the clearance between spool and barrel is not constant: while the initial geometry of the parts is known and only determined by manufacturing accuracy, the actual shape of the barrel is also affected by deformation caused by external forces on the manifold as well as the hydraulic pressure acting on the structure. The spool is less affected by these influences, because the external forces are commonly acting symmetrically by design. The deformation of the barrel should therefore be carefully considered.

Figure 2. Deformed barrel hole

In summary, the following factors influence the fit of the spool in the barrel:

1: Barrel hole form and size deviations due to the machining process: This is a direct consequence of the quality of the manufacture. In general, both barrel and spool should be as cylindrical as possible within the constraints given by the fabrication process. This is often a trade-off between accuracy and cost.

2: Barrel hole deformation due to preloads, such as bolt pretension. The bolts acting on the manifold compress the material in their immediate vicinity. This can result in the barrel assuming an elliptic cross section or in a deflection of the barrel's axis.

3: Barrel hole deformation due to operating loads, such as internal hydraulic pressure: The acting pressure inflates the barrel, causing an increase of the cross-section. This effect is limited to areas with high pressure acting on the surfaces. Imbalance of these pressure fields can cause significant deformation of the barrel from the ideally straight shape.

To find the necessary fit between the barrel hole and the spool all three points must be taken in to account. In order to gain deeper understanding of the influences, a simulation using COMSOL Multiphysics was carried out.

2. Pre-processing

2.1. 3D CAD Model

A model of a typical barrel hole of a hydraulic control valve is created in 3D CAD and imported into COMSOL Multiphysics. The 3D assembly consists out of the hydraulic valve block bolted to a mounting block.

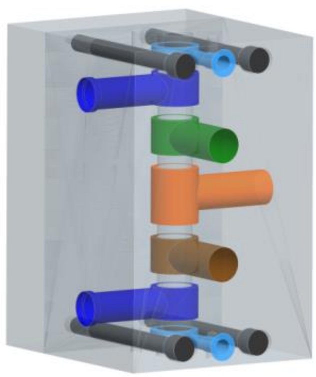

Figure 3. 3D CAD Model

2.2. Parameters and variables

The Parameters and variables used in the study are shown in the table 1 and table 2.

The parameters are used for the auxiliary sweep for the load cases. With the help of the variables the gradient pressure load on the barrel hole boundary is set.

The variables xc and zc are used to calculate the center of the barrel hole after deformation, for the in the definition tab a variable 'average' is set on the barrel hole boundary

Parameter			
Name	**Value**	**Unit**	**Description**
ps	1	-	Spring parameter
bvs12	64	kN	Bolt pretension
Ppa	10	bar	Pressure load
Pla	100	bar	Pressure load
Pta	200	bar	Pressure load
Pa	300	bar	Pressure load
Pp	400	bar	Pressure load
Pb	300	bar	Pressure load
Ptb	200	bar	Pressure load
Plb	100	bar	Pressure load
Ppb	10	bar	Pressure load
Y0	0	mm	Distance to barrel boundary
Y1	8	mm	Distance to barrel boundary
Y2	19	mm	Distance to barrel boundary
Y3	27	mm	Distance to barrel boundary
Y4	50	mm	Distance to barrel boundary
Y5	60	mm	Distance to barrel boundary
Y6	85	mm	Distance to barrel boundary
Y7	95	mm	Distance to barrel boundary
Y8	135	mm	Distance to barrel boundary
Y9	145	mm	Distance to barrel boundary
Y10	170	mm	Distance to barrel boundary
Y11	180	mm	Distance to barrel boundary
Y12	203	mm	Distance to barrel boundary
Y13	211	mm	Distance to barrel boundary
Y14	222	mm	Distance to barrel boundary
Y15	230	mm	Distance to barrel boundary

Table 1. Parameter

Variables			
Name	Expression	Unit	Description
Pla_pa	Pla+((Ppa-Pla)/(Y15-Y14))*(Y-Y14)	Pa	Pressure gradient
Pta_la	Pta+((Pla-Pta)/(Y13-Y12))*(Y-Y12)	Pa	Pressure gradient
Ppb_lb	Ppb+((Plb-Ppb)/(Y1-Y0))*(Y-Y0)	Pa	Pressure gradient
Plb_tb	Plb+((Ptb-Plb)/(Y2-Y3))*(Y-Y2)	Pa	Pressure gradient
Ptb_b	Ptb+((Pb-Ptb)/(Y5-Y4))*(Y-Y4)	Pa	Pressure gradient
Pb_p	Pb+((Pp-Pb)/(Y7-Y6))*(Y-Y6)	Pa	Pressure gradient
Pp_a	Pp+((Pa-Pp)/(Y9-Y8))*(Y-Y8)	Pa	Pressure gradient
Pa_ta	Pa+((Pta-Pa)/(Y11-Y10))*(Y-Y10)	Pa	Pressure gradient
xc	comp1.aveop1(X+u)	m	x coordinate of center
zc	comp1.aveop1(Z+w)	m	z coordinate of center

Table 2. Variables

2.3. Material

For this example, “Structural Steel” was applied to the model from 'built in' library of COMSOL.

2.4. Meshing

Once the material was selected, a mesh was generated. ‘Free tetrahedral’ mesh elements were selected for meshing. Element sizes vary from ‘Normal in regions of less interest to ‘extra fine’ on the barrel hole boundary. The mesh quality can be considered as good, the elements with a quality less than 0.3 are not located in the area of interest.

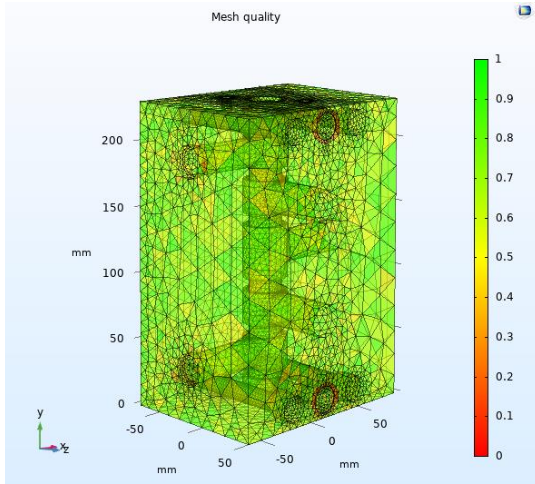

Figure 4. Mesh

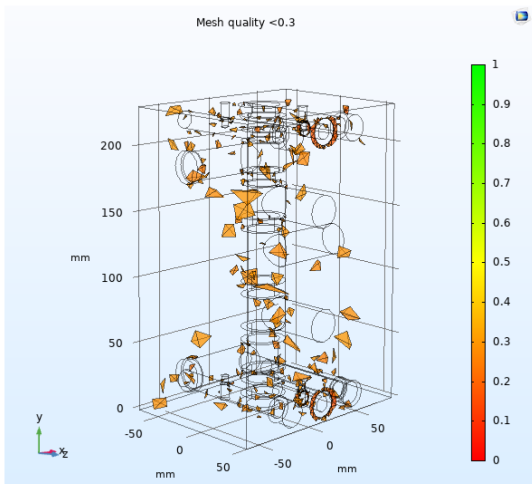

Figure 5. Mesh <0,3

2.5. Boundary conditions

To position the 3D model in space, a fixed constraint is set on the back of the mounting block.

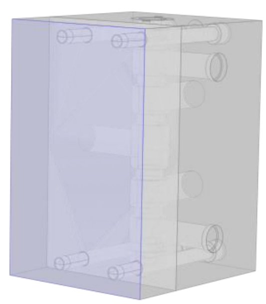

Figure 6. Fixed constraint

Bolt pretension constraints are added to the bolts.

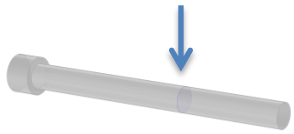

Figure 6. Bolt pretension

Between the valve block, the mounting block and the bolt heads contact pairs were added.

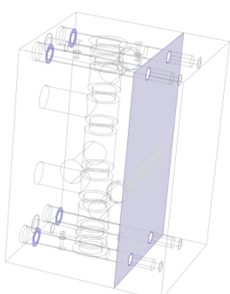

Figure 7. Contact pairs

Continuity pairs were added to the contacts between the bolts and the mounting block.

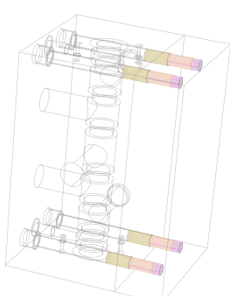

Figure 8. Continuity pairs

For better convergence during calculation a spring foundation to the complete model is added. The spring constant is initially set very high, as the spring constant is reduced to zero the initially unconstrained domains will relax into their deformed state. Following expression is used:

$$1^{10} \times (1 - ps)$$

Furthermore a prescribed displacement constraint is added to 4 corner points of the Barrel hole block for better convergence. The prescribed displacement is set as u_{0x}= 0 mm. and u_{oy} =0 mm.

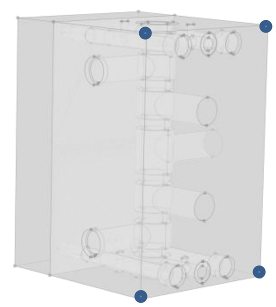

Figure 9. Prescribed displacement

Pressure is added on the boundaries of the valve system. The cavity ports have a defined pressure and the boundaries between 2 ports have a pressure load that is defined as a gradient between the pressure loads of the two connecting ports.

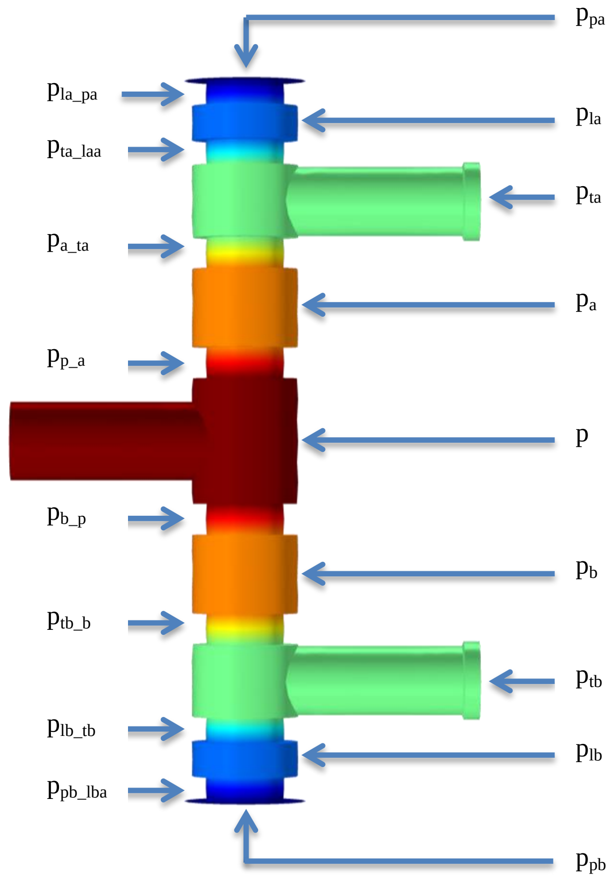

Figure 10. Pressure loads

2.6. Boundary probes

The aim of our study is to calculate the deformation of a barrel hole. This barrel hole can be located everywhere in a valve manifold. Within ‘COMSOL Multiphysics’ calculation of the global displacement is not a problem, but the global displacement does not provide useful information about the local deformation around the center of the barrel hole which is the decisive value for the fit of the spool. To be able to calculate the local deformation around a barrel hole, the new centerline coordinates must be calculated. This is done by adding an average node under definitions, with the boundaries of the valve hole selected. With this node variables xc and zc are calculated.

Using a boundary probe on the barrel hole the minimum, average and maximum radii of the deformed barrel hole are calculated using the following formula:

$$\mathrm{r} = \sqrt{((X+u)-xc)^2 + ((Z+w)-zc)^2)}$$

The maximum diameter of the spool valve without interference is:

$$d_{\max\_spool} = r_{\min\_hole} \times 2$$

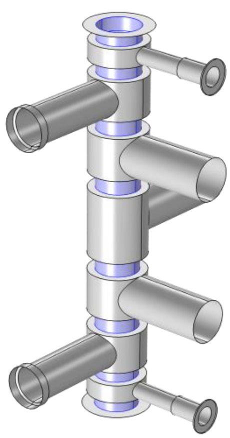

Figure 11. Boundary probe

3. Processing

The structural mechanics module is used to calculate the deformation of the 3D model, using a study that consists out of 2 steps;

- Step 1: bolt pretension, with an auxiliary sweep for the spring foundation.
  (ps = 0 and 1)
- Step 2: stationary, with an auxiliary sweep as shown in table 3.

The ‘Direct Constant Newton Solver’ is used for both study steps.

	Parameter	Ppa	Pla	Pta	Pa	Pp	Pb	Ptb	Plb	Ppb
Load cases (bar)	**No pressure load**	0	0	0	0	0	0	0	0	0
	1	0	0	2.5	30	380	30	2.5	0	0
	2	0	2	2.5	30	380	30	2.5	2	0
	3	0	2	15	30	380	30	15	2	0
	4	0	0	15	30	380	30	15	0	0
	5	38	0	2.5	380	380	30	2.5	0	0
	6	38	2	2.5	380	380	30	2.5	2	0
	7	38	2	15	380	380	30	15	2	0
	8	38	0	15	380	380	30	15	0	0
	9	0	0	2.5	30	380	380	2.5	0	38
	10	0	2	2.5	30	380	380	2.5	2	38
	11	0	2	15	30	380	380	15	2	38
	12	0	0	15	30	380	380	15	0	38
	13	38	0	2.5	380	30	30	2.5	0	0
	14	38	2	2.5	380	30	30	2.5	2	0
	15	38	2	15	380	30	30	15	2	0
	16	38	0	15	380	30	30	15	0	0
	17	0	0	2.5	30	30	380	2.5	0	38
	18	0	2	2.5	30	30	380	2.5	2	38
	19	0	2	15	30	30	380	15	2	38
	20	0	0	15	30	30	380	15	0	38

Table 3. Load cases

4. Post-processing

4.1. 3D Deformation plot

Figure 12 shows a 3D surface plot of the displacement and the deformation (factor 800) of the barrel hole. It gives a good impression of the effect of the loads to the fit of the spool.

Figure 12. Deformed barrel hole

4.2. 1D deformation plot

Figure 13 shows the relationship between the pretension and the deformation.

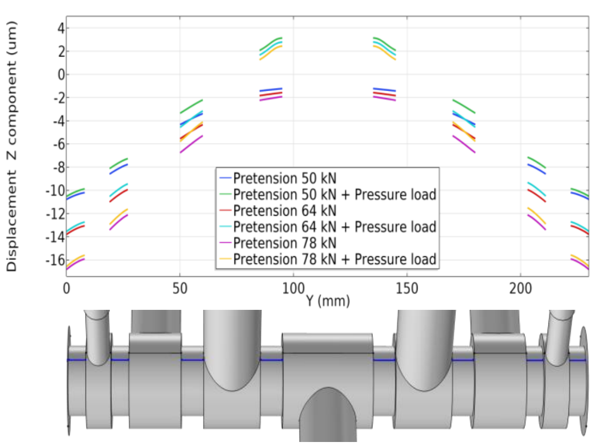

Figure 13 1D plot

The 1D plot shows that if the pretension increases the plotted curves get steeper, the difference between minimum and maximum displacement gets bigger and the barrel hole will deform more.

4.3. Summarized results of the boundary probes

The results of the boundary probes with the minimum, average and maximum radii of the deformed barrel hole were exported to 'MS-Excel'.

The results of the 3 different bolt pretensions combined with the 20 load cases are summarized in table 5.

50 kN pretension	Valve max. Radius (mm)	Valve average radius (mm)	Valve min. Radius (mm)	Spool max. diameter (mm)
Pretension	12.5021	12.4991	12.4919	24.9839
Min. Lc_1-20	12.5044	12.4999	12.4908	24.9816
Max. Lc_1-20	12.5068	12.5006	12.4916	24.9832

64 kN pretension	Valve max. Radius (mm)	Valve average radius (mm)	Valve min. Radius (mm)	Spool max. diameter (mm)
Pretension	12.5027	12.4989	12.4898	24.9796
Min. Lc_1-20	12.5048	12.4997	12.4887	24.9773
Max. Lc_1-20	12.5072	12.5004	12.4894	24.9789

78 kN pretension	Valve max. Radius (mm)	Valve average radius (mm)	Valve min. Radius (mm)	Spool max. diameter (mm)
Pretension	12.5033	12.4987	12.4876	24.9752
Min. Lc_1-20	12.5052	12.4995	12.4865	24.9730
Max. Lc_1-20	12.5077	12.5002	12.4873	24.9746

Table 4 Summarized results

5. Conclusion

Optimal performance of a hydraulic valve spool is found when the pretension is chosen as low as possible within the boundaries of the technical requirements. Decreasing the pretension allows a bigger maximum valve spool diameter, thereby the deformation of the barrel is reduced and leakage is minimized.