A Simulation Study on the Feasibility of Valve Spool Stabilization Under the Influence of Spool Core Elasticity

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Spool valves suffer from friction between spool and sleeve when the spool is not radially stabilized in a central position but unstably moves outwards and touches the sleeve or housing. Circumferential grooves for pressure equalization are a classical remedy for the problem offering some relief but not a real solution for stabilizing the spool in the middle. The use of conical geometries offering a stabilizing mechanism has been suggested repeatedly in the fluid power literature and a few very elegant solutions for generating these geometries solely from pressure induced elastic deformations of initially cylindrical geometries have been published. Some of these proposals are based on strongly simplified models assuming a rigid cylindrical core of the spool surrounded by elastically modelled lands deforming under pressure. The geometry of these lands typically assumes an initially perfect cylindrical geometry. The purpose of this paper is to look into the situation when the first assumption is dropped. What if the whole spool is modelled with elastic deformation? This question is answered by a simulation model based on finite element analysis combined with a solution of the Reynolds equation for the pressure in the gap between spool and sleeve.

Keywords:
spool valve stability,
elastic spool deformation,
Reynolds user-element,
simulation of narrow bearing gap,
simulation

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1 Intruduction

Spool valves are one of the most common elements used in fluid power circuits. As several variable orifices can be integrated in a single spool and sleeve assembly this valve design allows for the complete directional control of a hydraulic cylinder or motor by just one moving element and thus, by a single mechanical or electromechanical control input. This geometrical design flexibility comes at the expense of demanding manufacturing tolerances in order to fit the spool precisely enough into the sleeve or housing to prevent excessive leakage. If the cylindrical shapes of the two parts differ too much from the ideal geometry due to manufacturing errors or pressure-induced deformations, the friction on the spool becomes a severe issue making precise spool positioning impossible in proportional or servo control applications.

The friction effects on the spool are known to be sensitive to the pressure field in the gap [1]. Asymmetries in this pressure distribution may result in the spool being pushed out of its centre position with an increase due to more pronounced mixed friction or even pure metallic contact at the smaller gap side. A classical countermeasure against pronounced pressure asymmetries along the circumference of the gap is known in the form of circumferential grooves on the cylindrical lands of the spool.

A further important mechanism is related to the stabilizing or destabilizing process of conical sealing gaps depending on the convergence or divergence of the gap from the high-pressure side to the low-pressure side. The principle is long known from hydraulic servo-cylinders with deliberately manufactured precise gaps with tiny cone angles [2]. The effect may also occur in spool valve geometries by deviations from the ideal cylindrical manufacturing or by a pressure-induced elastic deformation [3, 6]. Recently, the design rules for getting a stabilizing pressure-induced deformation from simple-to-manufacture geometries has come into focus. In [4] the effect is studied for an elastically deforming sealing land on a rigid spool core. In the present paper, this study is expanded for the fully elastic spool.

2 Problem modelling

To provide the possibility to retrace the process described in this paper this chapter sketches the most relevant modelling parameters. Next to the basic geometry parameters and material properties the loads and boundary conditions are in focus.

2.1 Fundamental geometry and material parameters

The geometry consists of two lands which are connected by a rod and guided in a rigid pipe.

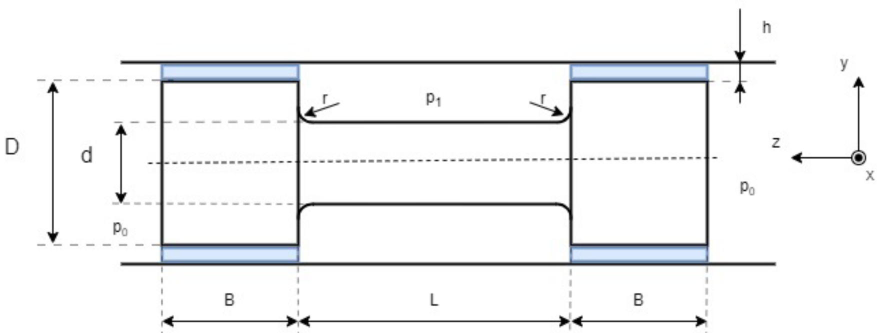

Figure 1: General problem setup.

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Table 1: Geometric and material parameters

symbol	name	value
h	gap height	10 µm
D	outer spool diameter	12 mm
d	inner spool diameter	6 mm
B	land width	10 mm
l	rod width	20 mm
r	radius	1 mm
p_0	outer pressure	1 bar
p_1	inner pressure	200 bar
E	Young's modulus of steel	210 e3 N/mm²
μ	Poisson's ratio	0.3
ν	fluid viscosity	34.4 mm²/s

Figure 1 sketches a cut through the rotationally symmetric setup, while widely overrepresenting the height of the fluid gap. Along the simulations the width of the lands *B* is varied along with the diameter of the rod connecting both lands. All solid deformable parts are assumed to be made from steel; the parameters of the fluid can be taken from table 1.

2.1 Simulation setup in Abaqus

In order to maximize the efficiency and reduce calculation time a symmetric boundary condition is set and therefore the number of elements can be halved. As the reaction to a small displacement along the z-axis and tilting around the x-axis shall be examined, the according displacements have to be introduced. To avoid distorted mesh elements the outer areas of the lands are separated into extra sections with different mesh-controls as noticeable in Figure 2. As the pipe is modelled as a rigid body, the boundary conditions are applied directly to the elements of the fluid gap. Special attention comes to modelling the fluid gap, as described in the following section.

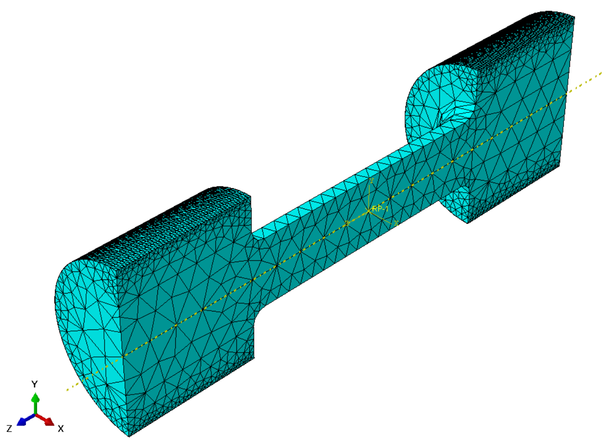

Figure 2: General problem setup.
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2.1.1 Reynolds user-element

Finite element methods require that the dimensions of an element don't differ too much to obtain numeric stability and acceptable convergence rates. Therefore, in case of hexahedral elements, cubes would be the preferred case. Assuming the radial direction is resolved with five elements one fluid gap would contain about 500.000 elements, resulting in an unbearable computing effort.

The pressure along the z-axis provides valuable insight. The pressure along the radius is of little interest and can be assumed constant due the small gap height. Furthermore, the inertial forces of the fluid are negligible, the geometry can be unreeled onto a flat plane and hydraulic oil behaves like a Newtonian fluid. As a result, the Reynolds-equation can be used, to implement a so-called user-element in Abaqus. The theoretical and mathematical derivation can be found in [5].

2.1.2 Boundary conditions and external forces

The fluid elements need to be tied onto the spool and pinned at their outer radius. Pressure is applied as an external load onto the surfaces of the spool. In addition, these pressures have to be implemented as boundary conditions for the fluid gaps.

The introduction of the displacement takes place over a coupling with decreasing weighting over the influence radius at the middle of the spool. Thus, unrealistic stresses and supporting effects in the areas of interest can be avoided. After the pressures are applied the spool will be shifted parallelly by 0.5 µm along the z-axis and afterwards rotated by 10^{-5} radians around the x-axis. Additionally, a contact between spool and pipe is introduced, therefore a minimal height of the user-element can be guaranteed and the acquisition of the height values simplifies. The gap pressure is read directly form the output database and visualized in a different program.

3 Analysis and interpretation of the simulation results

Along with the course of pressure and deformation the stability is evaluated depending on the geometry. The simulation was performed for a variety of parameter combinations of the spool width *B* and the inner diameter *d*.

3.1 Deformation and pressure course

Figure 3 shows the deformed spool with a deformation scale factor of 30000. The deformation decreases while going from high to low pressure.

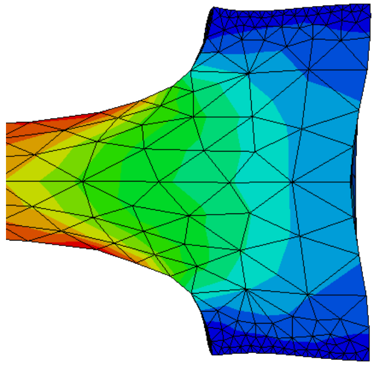

Figure 3: Elastic deformed spool with a width B of 5 mm (deformation scale factor 30000)

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The pressure course over the length of the spool is dominated by the linear pressure gradient resulting of the boundary conditions; comparable as it would occur using an ideal cylindrical gap without eccentricity or tilt. Therefore, the pressure gradient is subtracted from the solution before visualisation. Figure 4 shows the unrolled pressure over the radius and angle. As the symmetry boundary condition applies to the pressure as well, the angle is limited by ±90°. Due to the pressure boundary conditions the derivation is zero at both borders of the cylinder. The coordinate system of figure 1 applies and has its origin in the middle of the spool.

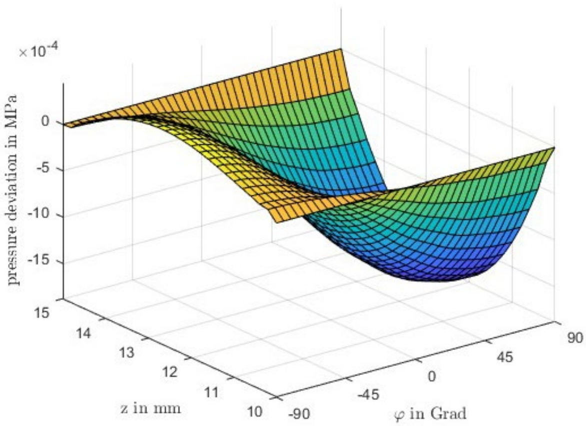

Figure 4: pressure deviation compared to the ideal cylindrical fluid gap without eccentricity or tilt; B = is 5 mm, d = 5

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3.2 Determination of stable areas

To determinate conditions for stability the simulation was performed for a variety of parameter combinations of the spool width *B* and the inner diameter *d*. This way the development of the reaction force and the momentum as in figure 5 and a stability map as in figure 6 can be derived.

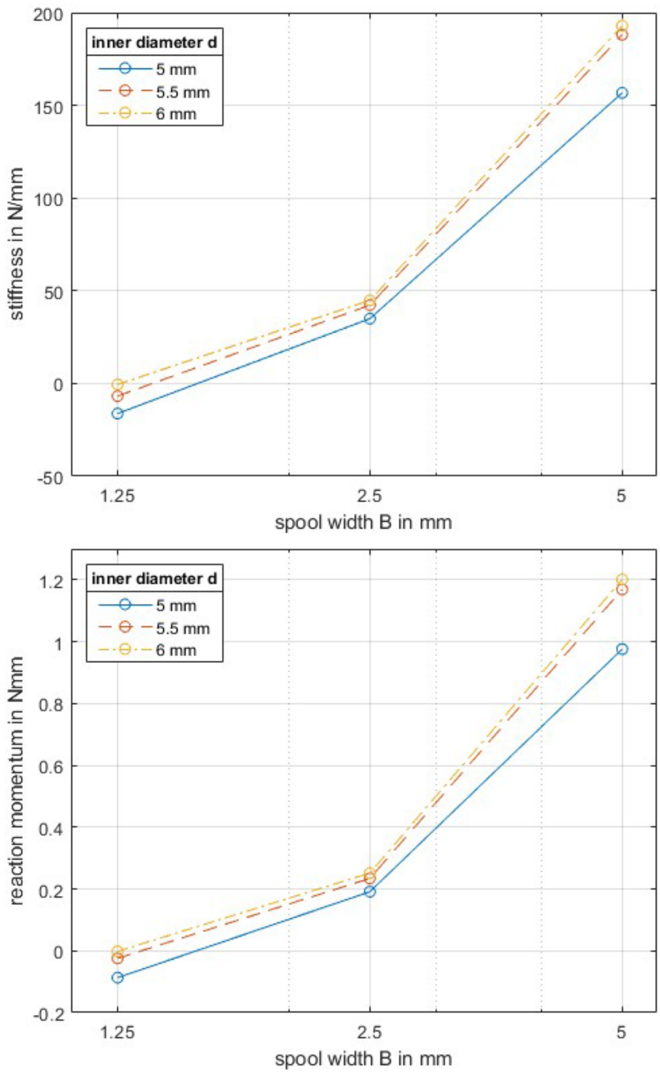

Figure 5: Reaction force and momentum in dependency of the spool width *B*

Source: own.

For a given rod diameter the system gets instable if the width gets too small. As figure 3 displays the stability depends from the inner diameter. The courses of the reaction forces and the reaction momentums look similar.

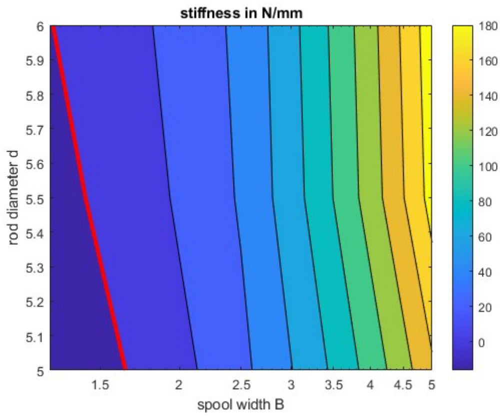

Figure 6: Stability criteria with red marked stability limit
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3.3 Conclusion

In this paper the theory can be supported, that the width of the rod has major influence on the stability of the spool; the diameter of the rod has only little impact. In contrary to previous papers, the stabilizing effect can be shown to occur also if the rod is modelled as an elastic body.

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