Stress analysis and Design Optimization of Piston Slipper assembly in an Axial Piston Pump

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Abstract - The amount of research carried out on piston assemblies of axial piston pump is a good indication of the problems which have been encountered. Fortunately this is one branch of engineering where research is usually well ahead of production failures. A representative domain for the high development of the axial piston pumps manufacturing is the aeronautics. In this industrial branch, light hydraulic transmissions that operate in very safe conditions are required. The mass reduction must be done according to an optimal design of the machines geometry, taking into account the static and dynamic stress and deflection states of the mechanical components. In this paper, a steady state stress analysis and also an optimization of the piston slipper assembly has been carried out by using ANSYS software. Optimization is done using Sub-problem approximation method where the main objective is to minimize the volume of the piston and slipper. Dimensions of the assembly are taken from SPV 22 axial piston pump, made by ZTS Company. This optimization technique minimizes the volume of the piston and also slipper. The paper concludes with the Comparison of the piston and slipper dimensions before and after optimization.

Keywords: Axial piston pump, Piston-Slipper assembly, Stress analysis, Optimization

1. INTRODUCTION

Axial piston pumps are being used extensively in aircraft, industrial and agricultural systems since they can transmit large specific power and the flow rate from them can be varied. The operating concept of this type of pumps is based upon rotating a cylinder block of spring loaded pistons against an angled 'swash' plate in order to provide a pumping action. Controlling the angle of the swash plate controls the output displacement. A basic difference in the design of various models of axial piston pumps is how the pistons contact the swash plate. Many design use a bronze slipper positioned between the piston and the swash plate. With this design, hydraulic fluid is fed through internal passages to the piston/slipper and slipper/swash plate interfaces to supply lubrication at these surfaces. Some axial do not use a slipper, but rather finish each piston with a case-hardened spherical dome. The spherical dome contacts the swash plate in such a fashion, much like the contact that occurs in ball bearings. Elimination of the slipper reduces costs and eliminates the disadvantages of the slipper design, but unfortunately, it creates other problems. One of these is wear at the spherical dome/swash plate interface. The piston and slipper of an axial piston pump is undergone through high loading condition. Under such high load there can be plastic deformation of the piston and slipper. The material used in piston is stainless steel. Sometime the high compressive strength of such material cannot withstand the high load coming from the hydraulic circuit. Under such condition it is essential to study the stress analysis and proper design of the piston slipper assembly. A good analytical understanding of slipper behavior in piston pumps is crucial to good design. In open literature it is found that few efforts are made to study the present problem. Hui Wang and Fan Long Meng1 studied the simulation and optimal design of cylinder block of axial piston pump Based on

ANSYS. Norhirni M. Z *et al*2 studied the load and stress analysis for the swash plate of an axial piston pump/motor. The design analysis of the cylinder block of an axial piston pump has been studied by McConnachie J. and Fagan M.J.3. Rosu C *et al*4 studied the structural analysis of a high pressure hydraulic pump by Finite Elements Method. The computation of dynamic stresses in piston rods caused by unsteady hydraulic loads has been studied by Wang Z W *et al*5. In 1990, Schoenau *et al*.6 conducted numerical and experimental studies on a variable displacement pump in which they used regression techniques that generated linear and nonlinear terms for describing the control torque on the swash plate. The coefficients of these terms were generated from the numerical results and the attempt of this research was to simplify the work presented originally by Zeiger and Akers. In 1996, Manring and Johnson7 presented a closed-form approximation of the control torque on the swash plate. Unlike previous research, this work simplified the control torque expression without eliminating critical terms.

2. METHODOLOGY

Dimensions of the assembly are taken from SPV 22 axial piston pump, made by ZTS Company. First the solid model is done in Pro E software. Then it was transformed to ANSYS. Solid 20 node 95 Brick element has chosen for meshing the piston and slipper assembly. This element can tolerate irregular shapes without as much loss of accuracy. Solid 95 elements have compatible displacement shapes and are well suited to model curved boundaries.

3. BOUNDARY CONDITIONS

The piston and slipper assembly in an axial piston pump is a moving part. The pressure acting on a piston varies periodically. In this case the piston and slipper are considered to be in a quasistatic equilibrium state. After generating the nodes and elements, different constraints are applied to the models. In case of the piston and slipper assembly, the bottom surface of the slipper is constrained with zero displacement in all direction. Working pressure of the pump will act on the top surface of the piston

Governing Equation

In stress analysis, the governing equations for a continuous rigid body can be obtained by FEThe total potential energy Π can be expressed as:

$$\Pi = \frac{1}{2}\int_{\Omega} \sigma^T \ \varepsilon \ dV - \int_{\Omega} d^T \, b \, dV - \int_{\Gamma} d^T \ q \, dS$$

where σ and ε are the vectors of the stress and strain components at any point, respectively, *d* is the vector of displacement at any point, *b* is the vector of body force components per unit volume, and *q* is the vector of applied surface traction components at any surface point. The volume and surface integrals are defined over the entire region of the structure and that part of its boundary subject to load . The first term on the right hand side of this equation represents the internal strain energy and the second and third terms are, respectively, the potential energy contributions of the body force loads and distributed surface loads.

Simulation and analysis of the piston and slipper assembly

Stress analysis of the Piston and Slipper assembly The analysis of the piston and slipper assembly is done at 300bar working pressure. From the analysis it has been observed that stresses at some of the nodes are above the safe region. A stress concentration region, represented by red colour has been observed around the neck portion of the piston as shown in figure 1(a). The stepped shape of neck portion of the piston is modified to a smooth one by a fillet. Analysis is performed again for the new modified part at 300 bar working pressure. The result of this analysis is very good as the stress concentration is reduced to a great extent, as shown in figure 1(b).The graph, shown in figure 2(a) presents a comparative study of the Von-Misses stresses along the Outer path of the piston and ball of the existing the modified model of the piston. Fig: 2(a).

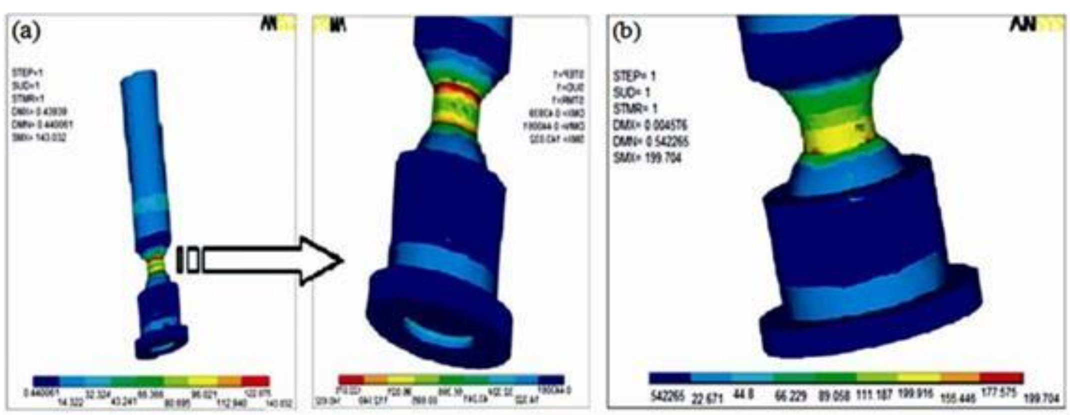

Fig. 1—Stress concentrations at the neck portion & Stresses on the new model

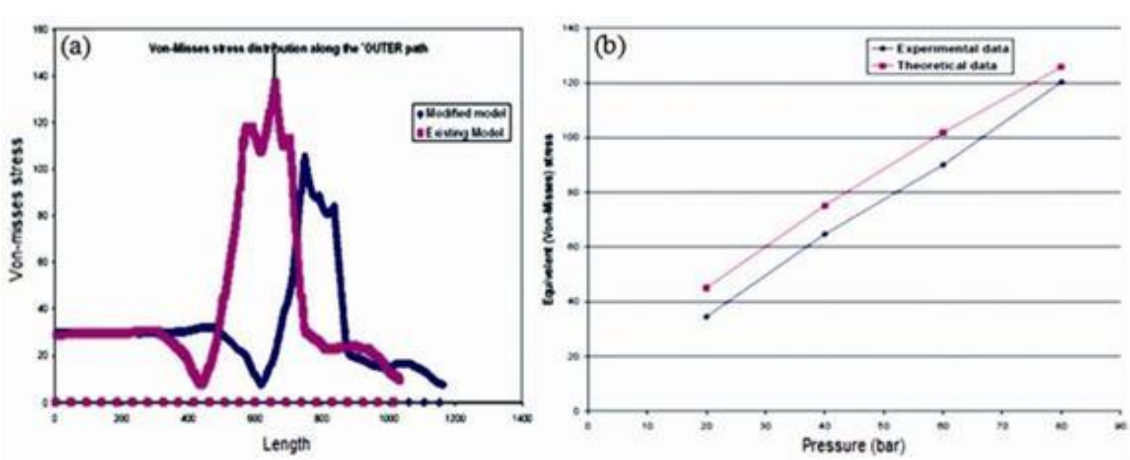

Fig. 2—Comparison of stresses of the existing and modified model at the outer path & experimental and theoretical Von-Misses stresses

Experimental Validation

For validation, analysis results are compared with the experimental data8. The components used in the experimental rig were taken from the same SPV 22 axial piston pump. The pressure in the hydraulic motor had been set to the 0, 20, 40, 60, 80 bar. To measure the deflections of the piston-slipper four-tensometric rosettes had been used. The Von- Misses stresses as found from ANSYS as well as experiment are shown in fig.2(b)

Optimization of the piston and slipper

Optimization of the piston

An optimization is done in ANSYS with actual loading data. The Sub-problem approximation method is used for optimization. An axisymmetric parametric model of the piston is created as shown in figure 3. The objective of the optimization is to minimize the volume of the slipper subjected to, the stresses in each node lies below the yield point of the material.

Design and State variables

The maximum von Misses equivalent stress will be limited to 260 N/mm2. The model is parameterized as A, B, C, D and E. The ranges are as follows: Table-1(a).

Optimization of the slipper

An axisymmetric parametric model of the slipper is created as shown in figure 3.

Design and State variables

The maximum von Misses equivalent stress will be limited to 250 N/mm2. The model is parameterized as G, S, T, U and R. The ranges are as follows: Table-1(b).

Results and discussion

Optimization of the volume of piston is run in ANSYS using Sub-problem approximation .

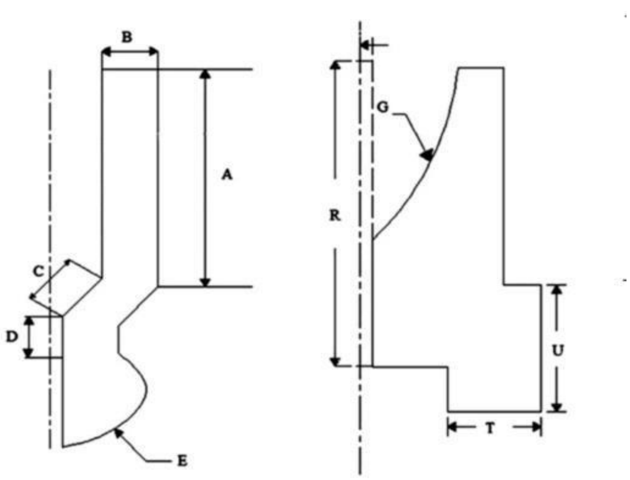

Fig. 3—Axisymmetric parametric model of the piston and Slipper

Table 1—Range of design variables for piston & slipper

PARAMETER	MINIMUM VALUE (mm)	MAXIMUM VALUE (mm)
A	10	15
B	0.8	1.2
C	1.5	2.5
D	1.5	2.5
E	1.5	2.5

(b)

PARAMETER	MINIMUM VALUE (mm)	MAXIMUM VALUE (mm)
G	1.5	3.5
R	2.5	3.5
S	1	3
T	0.5	1.5
U	3	6

method. In the process 5 iterations have been performed, which are listed below: Table-2(a). From the table-2(a), it is easily observed that set number 3 gives the most feasible result, among all the iterations. This optimization technique minimizes the volume of the piston from 306.65 mm3 to 100.65 mm3. Comparison of the piston dimensions before and after optimization is below: Table-2(b). Optimization of the slipper is run in ANSYS using Sub-problem approximation method. In the process 5 iterations have been performed, which are listed below: Table-3(a). It has been observed that set number 2 gives the most feasible set of result, among all the iterations. The optimization technique minimizes the volume of the slipper from 106.31mm3 to71.688mm3. Comparison of the slipper dimensions before and after optimization is stated below: Table-3(b).

Table 2- optimization iteration & existing vs final dimensions of piston

PARAMETER	SET1	SET2	SET3	SET4	SET5
	FEASIBLE	INFEASIBLE	FEASIBLE	INFEASIBLE	INFEASIBLE
SMAX	215.46	384.42	235.21	812.9	313.97
A	14.500	12.473	12.598	12.162	12.138
B	1.200	1.7104	0.88283	0.82475	0.81368
C	2.330	2.6564	1.9318	2.0137	1.8193
D	2.200	2.5090	1.9155	1.9152	1.8429
E	2.250	1.9077	1.9069	1.8673	1.8305
VOLUME	156.83	306.65	100.75	240.94	131.69

(b)

PARAMETER	BEFORE OPTIMIZATION	AFTER OPTIMIZATION
SMAX	384.42	235.21
A	12.473	12.598
B	1.7104	0.88283
C	2.6564	1.9318
D	2.5090	1.9155
E	1.9077	1.9069
VOLUME	306.65	100.75

Table 3—Optimization iterations & existing dimensions vs. Final dimensions of slipper

PARAMETER	SET1	SET2	SET3	SET4	SET5
	FEASIBLE	INFEASIBLE	FEASIBLE	FEASIBLE	FEASIBLE
SMAX	78.072	136.06	67.779	82.717	167.89
G	1.9069	2.4273	1.3441	1.3434	3.4951
R	3.5000	3.5902	3.2892	3.2900	3.5447
S	2.5000	1.6774	2.2840	2.0076	2.5056
T	2.0000	1.1267	1.1641	1.1295	1.0881
U	1.0000	1.3862	0.53204	0.50912	0.50575
VOLUME	194.8	71.688	126.95	91.491	106.31

(b)		
PARAMETER	BEFORE OPTIMIZATION	AFTER OPTIMIZATION
SMAX	167.89	136.06
G	3.4951	2.4273
R	3.5447	3.5902
S	2.5056	1.6774
T	1.0881	1.1267
U	0.50575	1.3862
VOLUME	106.31	71.688

CONCLUSION

A steady state stress analysis and also an optimization of the piston slipper assembly have been carried out by using ANSYS software. It has been observed that in the neck portion of the existing design, the von-misses stress goes to plastic state. However this problem is mitigated by incorporating a proposed design that is by using the proposed design the von-misses stress lies within the elastic limit. In the later part of this work an optimal design of the piston slipper assembly is simulated by sub- problem approximation method under ANSYS environment. For the piston design, the volume of piston of the existing design is 306.65 mm3. After optimization the volume of the piston is minimized and the volume is 100.75 mm3. And also for the slipper design, the volume of slipper of the existing design is 106.31 mm3. After optimization the volume of the slipper is minimized and the volume is 71.688 mm3.

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