DEVELOPMENT OF A TEST STAND FOR DETERMINING THE TECHNICAL CONDITION OF A PLUNGER PUMP

Supported by tetfund

Ndekiri Ezekiel Andenyangtso[a], Abdussalam El-Suleiman[b], Teng David Chollom[c], Bello Yekini[d]

[a,b,c]Aerospace Engineering Department, Air Force Institute of Technology Kaduna
[d]Mechatronics Engineering Department, Air Force Institute of Technology Kaduna
Corresponding author: andekiiri@yahoo.com

Received: December 14, 2023 Accepted: March 28, 2024

Abstract: The effectiveness of the use of aircraft largely depends on its operational qualities, the timely identification and elimination of the causes of failures and malfunctions. The purpose of this work is to determine the technical condition of an Aircraft plunger pumps. An assessment was carried out on NP-89, which is a plunger pump, to determine any leaks across all four plungers. Also, the design and characteristics of plunger pumps were analyzed, leading to the development of a method for assessing the technical condition of the pump. Based on the result obtained, the volumetric efficiency is 98% which shows that the technical condition of the pump is acceptable. Furthermore, a technological process for conducting a test on the technical condition of a plunger pump using a stand was also developed.

Keywords: Aircraft, Plunger Pumps, Technical Condition, Test, Technological Process, NP-89.

Introduction

One of the most prominent types of reciprocating pumps is the piston pump, which was the preferred option for a wide range of applications before high speed drivers helped centrifugals gain prominence (Joe Evans, 2015; GUO et al., 2019). The reciprocating pumps are used to pump wastewater from commercial and municipal sources (Mechanical Boost, 2020). Today, they are most frequently used in applications with modest flow and moderate pressure (up to 2000 PSI) (Joe Evans, 2015). The plunger pump, its near relative, is made for higher pressures up to 30,000 PSI (Joe Evans, 2015; Mechanical Boost, 2020). The procedure used to seal the cylinders is the primary distinction between the two (Elsevier, Energy, 2016). The sealing system (rings, packing, etc.) of a piston pump is fastened to the piston and moves along with it as it makes a stroke (GUO et al., 2019). The plunger moves through the stationary sealing system for the plunger pump as it makes a stroke (G Toet et al., 2019). The idea behind reciprocating pumps is that a solid will move as much liquid as it does itself (Joe Evans, 2015). A chamber that expands and contracts is used by piston and plunger pumps to suction and pressurize the fluid. Due to the fact that these pumps are reciprocating, rather than rotating, the chamber expands and contracts as a result of the plunger's reciprocating motion (upward and downward; back and forth) (Mechanical Boost, 2020).

The most important issue in the analysis of the efficiency of the operation of the hydraulic system of an aircraft is the compliance of its design with the operational requirements and the problem of increasing operational reliability and availability (MA Zhonghai et al 2018). The component of the hydraulic system used as an object of research in this work is the plunger pump, which is a positive displacement (SAE international, 2017). There are many pump designs that fall into the positive displacement category but, for the most part, they can be nicely divided into two basic groups (Joe Evans, 2015). The reciprocating group operates via pistons, plungers, or diaphragms while rotary pumps use gears, lobes, screws, vanes, and peristaltic action (Joe Evans, 2015). Their common design thread is that energy is added to the pumped fluid only periodically where, in dynamic pumps, it is added continuously (G Toet et al., 2019).

A study was made on the contamination sensitivity model for plunger hydraulic pumps (L. Ułanowicz et al., 2018). The presented method for evaluating the contamination sensitivity of hydraulic plunger pumps adopts certain simplifications, which in addition brings the test conditions closer to the actual operating conditions of plunger pumps. The first assumption of this method is the performance of hydraulic pump tests with a working fluid containing a test powder with particles from 0 µm to ones present in a given class of working fluid cleanliness, as per the adopted standard (L. Ułanowicz et al., 2018). Furthermore, contamination sensitivity of a hydraulic pump is studied not for the selected particle size ranges, but for the selected working fluid cleanliness classes, as per the adopted standard. The second assumption of the method is assuming that the concentration of particles with sizes from a selected size range is constant over the course of pump activities (L. Ułanowicz et al., 2018).

The presented model also enables to determine the wear factor due to the impact of impurities α and is a particle destruction time constant T for a given particle size range (L. Ułanowicz et al., 2018). The product of a contamination-related wear factor α and the particle destruction time constant T for each particle size range enables to predict the durability of hydraulic pumps. The contamination sensitivity factor proposed in the article can be a convenient parameter used to compare hydraulic pumps and other hydraulic assemblies operating in the same conditions. The awareness of hydraulic plunger pair behaviour under the impact of contamination contained in the working fluid can be helpful in their correct design, manufacturing and operation.

Another study was made on the Characteristics of Plunger Pumps to which the operational efficiency of pumps was studied on the basis of dynamic modeling (NL Velikanov et al., 2018). The dynamic characteristics and efficiency of the system were analyzed. The mathematical model proposed takes account of nonlinear friction of the piston, hydraulic losses, and leaking through gaps in the pump (NL Velikanov et al., 2018)

In industry, plunger pumps are widely used, especially those with a crankshaft mechanism. Their kinematic system is shown in Fig. 1 (Joe Evans, 2015). In pump selection, the relation between the output pressure p and pump supply (productivity) Q is important. The theoretical p(Q) dependence for a piston pump is a vertical line. In practice, the supply is somewhat reduced on account of fluid leakage with increase in the pressure (Joe Evans, 2015). The p(Q) dependence of plunger was studied with the analysis of experimental data regarding this dependence for high-pressure plunger pumps. But a test stand was not constructed to perform this task. With the development of a stand, the operating conditions of the pump can be monitored and control before integrating it in a hydraulic system. This will give insight on the modifications of some design parameters and thus lead to improved operational efficiency.

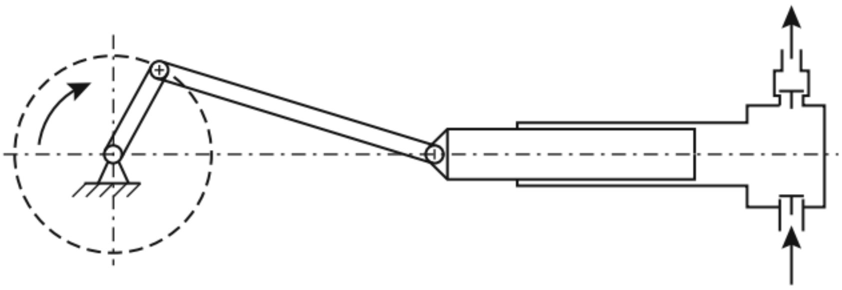


Figure. 1. Kinetic system of plunger pump with crankshaft mechanism. (Joe Evans, 2015)

Methodology

The aim of this work is to design and construct a test stand and also develop a methodology for determining the technical condition of the plunger pump. To achieve the set goal, it is necessary to resolve the following tasks:

i. Select the principle of testing the plunger pump; (J.M. Ma et al., 2015).
ii. Select the instantaneous flow and pressure sensors; (A. Yamaguchi et al., 1966).
iii. Set the calculated values of the output pressure and flow rate; (Paul Scott, 2023).
iv. Obtain results on the condition of the plunger pump and conclusions.

The design of the test stand must meet the following requirements:

i. The stand should be able to determine the actual performance of the pump depending on the pressure and speed of the drive shaft. (SAE international, 2017)
ii. The operating pressure of 15 MPa must be maintained in the system; (Paul Scott, 2023).
iii. The average flow rate of the working fluid must correspond to the performance of the pump during the "minimum revolutions" and "maximum revolutions" modes, provide the minimum performance mode at n = 1000 rpm, and the maximum performance at n = 3000 rpm. (Enerpac, 2022).
iv. The stand should be simple in operation and design.
v. Available basic aircraft hydraulic units should be used to construct the stand.
vi. The stand must meet the safety requirements when working with high pressure. (SAE. Warrendale, PA, USA, 1991; J.M. Ma et al., 2015).
vii. The stand should be cost-effective.

Design Process

The stand was designed using Compass software; and it contained the following components:

i. Hydraulic tank which serves as storage for the hydraulic oil.
ii. Electric motor which is responsible for driving the pumps.
iii. Pumps for generating the pressure needed in the system. Valves which are used to control and regulates flow in the hydraulic system.
iv. Manometers which are responsible for measuring pressure.
v. Filters for removing debris and foreign particles from the hydraulic oil.
vi. Pipe lines, tubes and connectors through which the fluid flows through.

A schematic Diagram of the Stand

The block diagram of the stand consists of injection lines, drain lines and test systems.

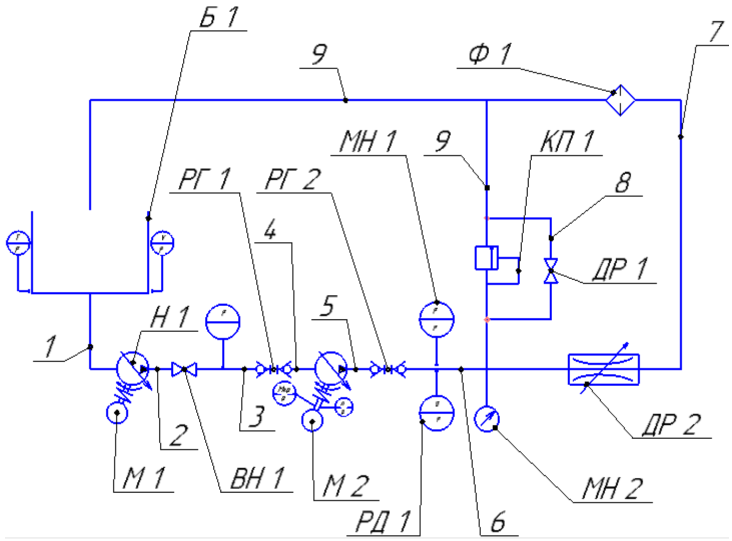


Figure 6 – Schematic diagram of the stand for monitoring the technical condition of the NP-89. Б1 - Hydraulic tank; M1…2 – Electric motors; H1 - Pump; КП1 - Valve; Ф1 - Filter; РГ - Connector; ДР1 - Hydrothrottle; ДР2 - Adjustable throttle; ВН - Flap; МН1…2 – Manometers.

Construction materials

The materials considered for the design of the stand are carefully selected to meet requirements such as durability to endure the operational environment, resist corrosion by the liquid when it comes into touch with the pumped medium and light weight. The following list includes the materials that were used to build the stand: Steels and stainless-steel alloys, aluminium alloys and plastic materials.

Procedure for diagnosing the pump

The preparatory operations include:
1. Connect the pump to the drive of the stand. The NP-89 plunger pump is mounted on the stand using fasteners (bolts and nuts).
2. Remove the plugs from the hydraulic hoses and connect the pump to the hydraulic connectors of the stand GR1, GR2.
3. Turn on the bench power by pressing the "NETWORK" button on the bench control panel.
4. Connect a laptop computer to the socket.
5. Open the valve VH1, turn on the booster pump and the pump drive to a minimum speed of 500 rpm, and allow it to pump for 10 minutes to remove air pockets. Make sure that the measurement system is working: pressure, temperature, flow, drive speed, torque.
6. Turn off the drive and the booster pump, make sure that there are no leaks of the working fluid.

Checking the technical condition of the pump

1. Turn on the power of the stand.
2. Open the tap, turn on the booster pump and the pump drive to a minimum speed of 500 rpm, and allow it to pump for 10 minutes.
3. Set the drive speed to 1000 rpm, set with the help of the valve Vn2 discharge: operating pressure 5.0, 10.0, 15.0 MPa
Regulating the controlled parameters:
4. Set the drive speed to 3000 rpm, set the discharge pressure to 15.0 MPa using the Vn2 valve, register the monitored parameters:

Table 1 – The rate of flow with increase in pressure during the maximum revolutions

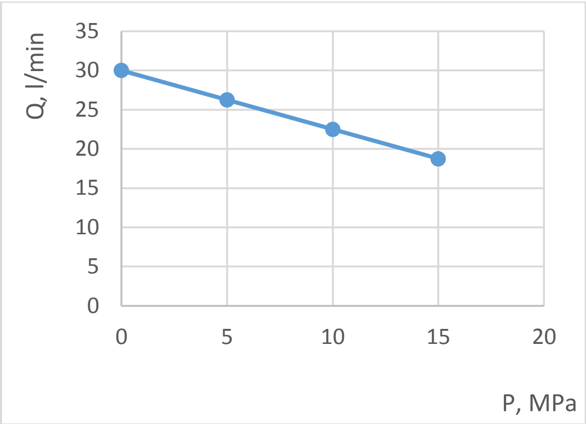
Q	30	26.25	22.5	18.75
P	0	5	10	15

5. Reduce the pressure to 1.0 MPa, set the drive speed to 500 rpm and turn off the drive after 5 minutes.
6. Turn off the booster pump, stand power.
7. Disconnect the hydraulic hoses and install plugs, remove the pump from the drive.
8. Process the controlled parameters.
9. Make an entry in the pump log about the results of the technical condition check.

Note:
During the diagnostic process, monitor pressure at the outlet of the pump using the manometer, "DISCHARGE PRESSURE", which are on the control panel. The pressure at the outlet of the pump must be 15 MPa.
Concluding operations include:
1. Turn off the power of the stand by pressing the button "OFF"
2. Disconnect the power cable of the stand.
3. Turn off the booster pump pressure and discharge hydraulic accumulators.
4. Disconnect from the computer.
5. Dismantle the pump from the stand.
6. Close the fittings with caps.
7. Disconnect the hydraulic hoses and install plugs, remove the pump from the drive.

Results and Discussion

During the experiment, observations were made and findings regarding the plunger pump's performance particularly in respect to the rate of flow were noted. The results of the experiments are presented below.
When conducting the experiment, parameters such as pressure and frequency is been controlled and resulting rate of flow is been monitored.
Conducting the test with the following controlled parameters:
P = 15,0 MPa ;n = 3000 rev/min; Q = 30 l/min; Mcr = 150 Nm



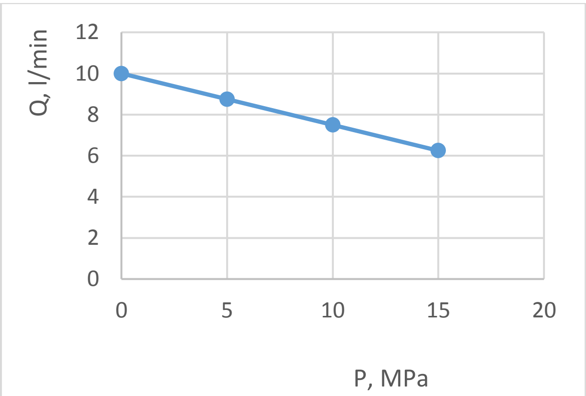
COP = 0.98

Figure 7 – Relationship between the rate of flow and pressure

Conducting the test with the following controlled parameters:
P = 15,0 MPa; n = 1000 rev/min; Q = 10 l/min; M_{cr} = 147,7 Nm;

Table 2 – The rate of flow with increase in pressure during the minimum revolutions

Q	10	8.75	7.5	6.25
P	0	5	10	15



COP=0.98

Figure 8 – Relationship between the rate of flow and pressure

The results of the test presented above shows that the rate of flow decreases with increase in pressure for both the maximum and minimum revolutions. The pressure outlines how much resistance the pump is designed to withstand. And the amount of resistance falls within the range of established technical standard of 90 – 100% volumetric efficiency of plunger pumps. This indicates that the plunger pump is in a good working condition. The serviceable condition of the plunger pump was determined in reference to the required technical standards which relate the rate of flow to change in pressure (X Suo et al., 2021). In order to ascertain the level of reliability of the pump, a calculation was done to determine leaks in the plungers.

Determining Leaks in the Plungers

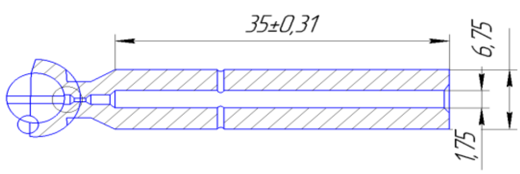


Figure 9 – Plunger

$$q_{ym} = \frac{Ap}{v} = \frac{5.086 * 10^{-17} * 2141404.05}{10^{-5}} = 1.089 * 10^{-5} m^3/s$$

Where q_{ym} is the leakage;

A –Design constant depending on the pump;
A = $5.086 * 10^{-17}$
V = Volume
P_1 - fluid pressure
The calculation was done for 4 plungers.

Result of the Calculation

Table 3 – Results of the rate of leakage with increase in pressure

P, MPa	5	10	15	21
q_{ym}, l/min	0,725	1,45	2,175	2,9

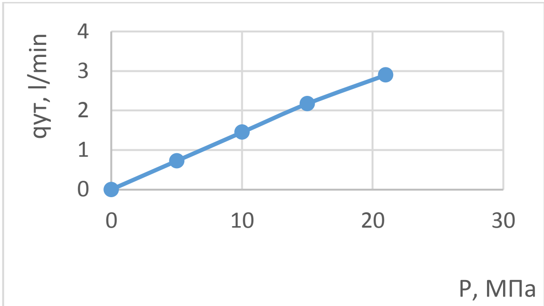


Figure 8 – Relationship between leakage and pressure

From the relationship presented in figure 8, the leak rate increases with increase in pressure but the values of the leaks correspond to the allowable range according to the technical standard the plunger pump (Zboiński M et al., 2011).. But modifications on the design of the plunger pump could reduce the leak rate, thus, improving its performance.

Reliability of the results

The reliability of the results of this work is confirmed by comparing the state of the plunger pump when considering the parameters of an operating plunger pump with a known technical condition (ISO, Geneva, Switzerland, 2008; Ndekiri E. A. et al., 2022). The scientific results obtained in this work are to clarify the methodology for the practical application of monitoring the technical condition of a plunger pump in steady-state modes of its operation (Triplex-style plunger pumps, wartsila, 2024).

Conclusion

The methodology for determining the technical condition of a plunger pump using a test stand was considered in this work. A block diagram of the stand used for testing a plunger pump was presented; and calculations were also made to determine leaks in the plunger pairs. The calculation results were presented in the table and in the form of graphs. A stand for determining the technical condition of a plunger pump was designed and constructed.

A technological process for testing the technical condition of a plunger pump using the constructed stand was developed. As a result of the developed methodology for determining the technical condition of a plunger pump, using the selected block diagram, it was possible to control the condition of plunger pumps by comparing their parameters with their reference values. Thus, improving the control of the technical condition of the plunger pump.

The result of the test conducted on the plunger pump shows that the pump is in a serviceable condition. But further work can be done to modify the design of the plunger pump in order to reduce leaks and improve its working efficiency.

References

A. Yamaguchi. Studies on the characteristics of axial plunger pumps and motorsBull JSME, 9 (34) (1966), pp. 305-327

Compact Steel Hydraulic Hand Pump, fromhttps://www.enerpac.com/en-us/hand-pumps/hand-pump-compact-steel/P20

G Toet, J Johnson, J Montague, K Torres 'The determination of the theoretical stroke volume of hydrostatic positive displacement pumps and motors from volumetric measurements'. Energies 2019

GUO, S., CHEN, J., LU, Y., WANG, Y., & DONG, H. (2019). Hydraulic piston pump in civil aircraft: Current status, future directions and critical technologies. Chinese Journal of Aeronautics. doi:10.1016/j.cja.2019.01.013

https://mechanicalboost.com/plunger-pump/

International Organization for Standardization (ISO). Hydraulic Fluid Power—Positive Displacement Pumps and Motors—Determination of Derived Capacity; ISO Copyright Office: Geneva, Switzerland, 2008. [Google Scholar]

Joe Evans. Positive Displacement Pumps.

J.M. Ma, L.Y. Ruan, Y.L. Fu, J. Chen, X.Y. Qi, J. LuoResearch on current situation and methods of accelerated life test of aircraft hydraulic Pump (serial 2) — typical failure modles and accelerated lifetime test methods for aircraft hydraulic pumpChin Hydrau Pneumatics, 7 (2015), pp. 6-12

L. Ułanowicz, G. Jastrzębski, M. Jóźko, R. Sabak, P. Szczepaniak. Hydraulic plunger pump contamination sensitivity evaluation. December 2018. Journal of KONBiN 48(1):371-383.

M. A. Zhonghai, S.P. Wang, J. Shi, T.Y. Li, X.J. Wang. Fault diagnosis of an intelligent hydraulic pump based on a nonlinear unknown input observer. Chin J Aeronaut, 31 (2) (2018), pp. 385-394 [2]

Ndekiri Ezekiel Andenyangtso, John Agidani Juniora, Joy Ali Kachallaa; Talatu Adamua; Ibrahim Ali Kachallaa, Paschal Uchenna, Chinedub; Abashe Tokan Caleb, 'Aircraft Hydraulic System Pump: A Reliability Analysis' Journal Of Science Technology And Education 10(1), March, 2022.

N. L. Velikanova, V. A. Naumovb , and S. I. Koryagin. "Characteristics of Plunger Pumps" (PDF). Russian Engineering Research. 18 (6): 428–252. Retrieved 14 September 2022.

Paul Scott (2023) "What is a Simplex Pump?" Retrieved on August 19, 2023, from https://www.aboutmechanics.com/what-is-a-simplex-pump.htm

Reducing the environmental impact of hydraulic fracturing through design optimisation of positive displacement pumps. - Energy, 2016 – Elsevier

SAE international. Aerospace hydraulic pump controls. Warrendale (PA): Aerospace, A-6C4 Power Sources Committee; 2017 May. Report No.: AIR5872A.

SAE. Hydraulic Power Pump Test Procedure. J745 (Recommended Practice). In SAE Handbook; Society of Automotive Engineers: Warrendale, PA, USA, 1991. [Google Scholar]

Triplex-style plunger pumps, from https://www.wartsila.com/encyclopedia/term/triplex-style-plunger-pumps

Wilson, W.E. Positive Displacement Pumps and Fluid Motors; Publication Corporation: New York, NY, USA, 1950. [Google Scholar] [3] Velikanov (2018). "Characteristics of Plunger Pumps" (PDF). Russian Engineering Research. 18 (6): 428–252. Retrieved 14 September 2022.

X Suo, Y Jiang, W Wang, 'Hydraulic axial plunger pump: gaseous and vaporous cavitation characteristics and optimization method'. 2021

Zboiński M, Spychała J., Deliś M.: The reliability analysis of hydraulic systems supporting aircraft control systems, Problemy eksploatacji, vol. 1/2011.