Aircraft hydraulic axial piston pump fundamental pulsation and simulation

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Abstract. The axial piston pump for aircraft hydraulics systems and other high pressure hydraulic system applications is presented. This paper discusses the pump’s pressure pulsation and the fundamental frequency. Pressure pulsation associated with single piston failure is explained in relation to its fundamental frequency. A predictive approach in maintenance and pump sub system health monitoring is proposed, using numerical modelling and applicable software.

1. Introduction

The aircraft hydraulics and mechanical systems are complex due to requirements, which are specific for aerospace applications. Aircrafts hydraulic systems must comply with very demanding requirements. These requirements often include a brief and sudden flow and pressure change as well as steady state run with constant pressure or constant flow.

An axial piston pump is the most common solution for delivering a flow at specified pressure, through the aircraft hydraulics system. Various types of pumps could be used (Piston, Gear, Vane, Fixed Displacement), but it is common to use variable-flow axial piston pumps for the aircrafts hydraulics system.

In any case, the pump of choice for high demanding hydraulics system is the axial piston pump. Such a pump is a critical component in the system overall operation. Its failure due to damage introduced by debris is the subject of this paper.

2. Description of the axial piston pump

2.1. Overview

Axial piston pump is probably the most used variable displacement type of pump. This type is capable of continuously changing fluid discharge, based on load requirements and maximum pressure cut-off settings. This is achieved by using different compensation methods [1], [3].

Axial piston in-line pumps, which make use of the swashplate principle (fixed and adjustable displacement) have a quality that is approximately the same as the bent axis model. They have the advantage of being more compact in design and have a longer service life. In addition, the pumps can be manufactured in an easier and more economical manner. By using different compensation
methods, the variable displacement type of these pumps can continuously change fluid discharge based on load requirements and maximum pressure cut-off settings.

Figure 1. Axial piston in-line pump

2.2. Pump piston design
The axial piston hydraulic pump’s major characteristics are: pressure and speed, displacement, flow, pulsation, temperature, case drain pressure, case drain flow, power requirements, inlet pressure, inlet flow, envelope and material.

Pressure pulsation is one of the axial piston pumps’ features that needs to be considered during design of the hydraulics system, the design of the pump, system health monitoring and troubleshooting. Fluctuation of pressure in the hydraulic fluid is generated during process of transforming input power (rotation) to flow and pressure. These pulsations are critical because of the high-energy potential they generate when the system loading requirements change. Pulsations are a result of each piston within the pump transferring a discrete amount of fluid to the system, leading to an overall pulsed input in the hydraulic system.

Lower pressure pulsation levels are important characteristic related to the working life of the pump and are needed for better hydraulics system performance. The pump with an even number of pistons has a higher flow variation than pump with an odd number of pistons. Common choice for aircraft hydraulics systems are axial piston pumps with 9 or 11 pistons [2], [3].

For the analysis of piston/cylinder pair it is assumed that the piston possesses only two degrees of freedom. One is the translational motion along the axis of cylinder bore, while the other is the rotation about the axis of main shaft.

The true motion of piston is much more complicated. It has radial micro-motion due to the existence of clearance and lateral forces. Therefore, the piston and cylinder bore are linked through a contact force instead of a cylindrical joint. In addition to the pressure field of lubricating oil film, the reaction forces from cylinder bore are acting onto piston only when the piston and cylinder get in contact at the positions where the oil film is too small as depicted in Figure 2.

Figure 2. Pump piston in bore
2.3. Pump piston frequency

As explained in the previous paragraph, pulsations are the result of each piston within the pump transferring a discrete amount of fluid to the pump outlet, producing a pulsed input in the hydraulic system [4]. The amplitude of the torque or flow rate variation for odd numbered pumps is much less than that for the even numbered devices.

Variations in pressure will influence the pulsation amplitude (it will increase approx. linear in proportion to the pressure). The product of shaft rotational frequency and the number of the pump pistons defines pump’s frequency. This is expressed mathematically by the following formula:

\[ f = \frac{n}{60} \cdot N_{\text{pist}} \]  

(1)

Where is:

- \( N_{\text{pist}} \) is the number of pistons [-],
- \( f \) is the pump frequency [Hz] and
- \( n \) is the pump rotational speed [rpm].

Angular frequency is defined as:

\[ f = \frac{\omega}{2\pi} \]  

(2)

where \( \omega \) is angular frequency [rad/s].

The Piston Pump Frequency for the Pump used for Test in Hydraulics Laboratory are respectively \( f = 930 \text{ Hz} \) and \( \omega = 5843 \text{ rad/s} \) when \( N_{\text{pist}} = 11 \) and \( n = 5073 \text{ rpm} \).

2.4. Fundamental frequency

Fundamental frequency is the lowest frequency of pressure (or flow) ripple considered in a theoretical analysis or measured by the frequency analysis instrument.

Flow ripple is the fluctuating component of flow rate in a hydraulic fluid, caused by interaction with a flow ripple source within the system. Pressure ripple is fluctuating component of pressure in a hydraulic fluid, caused by interaction with a flow ripple source within the system. Pressure pulsations are oscillations of the discharge pressure, occurring during nominal steady operating conditions, at a frequency equal to or higher than the pump drive shaft speed.

The pump test is used to determine the amplitude of pressure pulsations. When the frequency (speed) and harmonics of the pump is equal to the natural frequency of the hydraulic fluid column/tubing, a resonance condition occurs. A tubing line length whose natural frequency is resonant with pulsation frequency shall be avoided.

In this work, the single piston frequency as the lowest/fundamental frequency of pressure will be studied and its effect on the overall pump performance. The impact of the single piston frequency is often undervalued in relation to the pump’s working life.

3. Axial piston pump test

3.1. Test results

The pump catastrophic failure was demonstrated by pump’s housing crack during testing in laboratory. The fundamental frequency amplitude change is main suspect for the pump failure. The pump internal overload and fatigue was cause for failure due to the pump’s outlet pressure fundamental frequency amplitude change.

An axial piston pump test was performed at the hydraulics lab when a pump failure occurred. Failure investigation considered the pump pulsation as one of the causes of failure. During the test, in addition to all other data, the pump pressure at outlet and case drain ports is measured and recorded. A Pump Case Drain pressure values were used in the experiment. The Pump Case normal pressure for this type of pump is 140 psi.
The pump case pressure measurements shown in Figure 3 demonstrate pressure values after 40 hours of operation for healthy pump and pressure values after 3200 hours of operation for failed pump.

![Pump Case Pressure for 40 hrs and 3200 hrs operation](image)

**Figure 3.** Pump case pressure

In this paper, a pump with speed of 5073 rpm was subject of study. As already listed in paragraph 2.3, this pump has the following characteristics:

\[ f_1 = 84.55 \text{ Hz when } N_{pum}=1 \text{ and } n = 5073 \text{ rpm.} \]

The single piston time for one cycle in seconds is

\[ t_1 = \frac{1}{f_1} = \frac{1}{84.55} = 0.0118 \text{ s} \]  

(3)

The healthy units demonstrate pulsation like the pump case pressure after 40 hours of operation shown in Figure 3. The single piston frequency is considered as noise and without significant impact to operation or the unit work life. In available literature, overall pressure pulsation with amplitude shown like in Figure 3 is not considered as harmful pulsation to the pump or system. This is true until the single piston frequency changes as shown in Figure 3 for the pump case pressure after 3200 hours of operation.

The pump output pressure corresponding to the case pressure changes in pressure frequency and amplitude. Frequency after approx. 3200 hours in Figure 3 corresponds to the single piston frequency with significant amplitude change. In most cases, the available literature does not recognize the single piston frequency and amplitude impact. Whereas it is largely apparent that 3200 hours of operation have large pressure ripple (oscillation), as shown in Figure 3.

This can be directly traced back to the single piston operation. The pump could have had single piston frequency change as described here, if during operation one of piston’s conditions changed significantly compared to other pump’s pistons.

If these conditions are considerably different for one of piston compared to other pistons, then a significant change of the single piston frequency can be expected.
For the pump used in test, contamination with fine particles was identified as the root cause for failure and piston condition change.

The piston clearance and friction between piston and cylinder would have had significant effect on the piston motion and pressure pulsation, as illustrated in Figure 4.

**Figure 4.** Piston and cylinder bore clearance

The pump output pressure specified by national standards [1], sets limits for the pump without outlet pressure ripple attenuator.

The pressure ripple Helmholtz resonator is often used for attenuation of pressure pulsation. The monitoring of the outlet pressure changes and comparison with a healthy pump, shall lead to conclusion regarding this failure mode, rather than simple comparison to the national standards requirements.

In case of the pressure pulsation increase the Helmholtz resonator will protect he downstream hydraulics installation and components. The Helmholtz resonator cannot protect the pump. This paper, therefore, also makes a proposal on how to protect the pump as well, using observations discussed previously.

4. Maintenance

In this chapter a predictive maintenance approach with respect to the described failure mode is proposed. Predictive maintenance method should help to determine the pump condition and predict when maintenance should be performed. As such, pump’s catastrophic failure could be prevented. This type of maintenance is based on forecast if problems would increase to an operationally damaging level.

Measurements of pressure related to the single piston failure could be done at the case pressure or the outlet pressure. Most axial piston pump applications have a system that includes pressure measurement at either both or one of these two locations. These data should be analysed to enable decision making regarding the single piston failure and predictive maintenance.

The pump sub-system predictive maintenance involves a lot of data and more than one failure mode. The best option to analyse a lot of complex data is a model-based system and use of applicable software. Matlab [5], Amesim [6] or other similar software could be used for predictive maintenance and data analysis. To simulate and analyse failures using such software, engineers with knowledge about the system, components and failure modes must be involved.

This work offers better understanding of the single piston failure mode which could be used in modelling and predictive maintenance analysis.

5. Conclusions

The axial piston pump’s failure mode related to the single piston failure is explained. The understanding of this failure mode and how it can be detected by the outlet pressure change and relative comparison with healthy pump pressure characteristics has been shown to be crucial.
Most axial piston pump applications already have pressure measurement sensors that could be used for monitoring of the outlet pressure change. By implementing automated comparison with healthy pump state outlet pressure a feasible and practical solution is provided, which could prevent pump failure. Furthermore, such sensing capability also enables predictive maintenance introduction, which then reduces operational costs and down-time due to pumps failures.

The intensive use of computers and software in design, modelling, digital simulation, provide significant help regarding predictive maintenance, the system and components availability and reduce maintenance cost.

References
[1] SAE AS19692 Aerospace – Military Type Variable Delivery, Pressure Compensated Hydraulic Pump, Aerospace Standards, SAE, Warrendale, PA
[2] SAE AIR 1922 Aerospace - System Integration Factors That Affect Hydraulic Pump Life, Aerospace Standards, SAE, Warrendale, PA
[3] ISO 8278 Aerospace - Hydraulic, pressure compensated, variable delivery pumps - General requirements, International Organization for Standardization
[4] Husnić Z, Dedić R 2016 Uljna Hidraulika Univerzitet „Džemal Bijedić“ Mašinski fakultet Mostar
[5] Simulink - MATLAB, MathWorks (mathworks.com)
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