Research on Design Operation Pressure Determination of Civil Aircraft Hydraulic System Design

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ABSTRACT: Design Operation Pressure (DOP) is the most basic parameter of civil aircraft hydraulic system, To develop the DOP, this paper proposes the most basic factors that determine DOP are weight, volume, and cost. This paper compares the advantages and disadvantages of using 3000psi and 5000psi, and then calculates system weight and volume under the pressure system of 3000psi and 5000psi to determine optimal DOP decision.

Keywords: Hydraulic System, Design Operation Pressure, Aircraft

1. INTRODUCTION

At the beginning of hydraulic system design, we face a fundamental problem, how to choose the system Design Operation Pressure (DOP)? Which DOP should be selected? From related reference, the normal DOP used in the majority of commercial aircraft hydraulic systems is 3000psi. Higher or lower working pressures can be used but they will suffer from lack of commonality of ground equipment, components, etc [1]. However, recently years, with the first use 5000psi in civil aircraft A380 hydraulic system, the 5000psi hydraulic system has been certificated and operated well. The 5000psi components become more and more reliable with the A350, 787 and A350 use 5000psi hydraulic system. With many years of operation in airline, LRU and ground support equipment of 5000psi hydraulic system are easy to get, so it's no difference to use 3000psi and 5000psi for airline companies now. So some scholars think 5000psi pressure system has become an important factor reflecting the technical development level and competitiveness of civil aircraft, and is the direction of future development of civil aircraft hydraulic system[2](JIAO, 2019).

Encountering this problem, viewpoint of this paper is that a trade off study analysis is needed to determine which pressure to be used, and the weight, volume, and cost are the main determinant of choosing DOP. A comparison between weight, volume, and cost should be prepared.

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2. BASIC COMPARISON

2.1 PROS AND CONS of 5000psi DOP

According to the definition of pressure, P = F/A, where P is the pressure, F is the normal force, A is the area of the boundary, when the force F is constant, the higher pressure P, the smaller area A, so the smaller fluid, tubing size and weight, actuators size. This is the scientific basis for high pressure to reduce the weight and volume of hydraulic systems.

The normal working pressure used in the majority of commercial aircraft hydraulic systems is 3000psi (20,684 kPa). Higher working pressures will generally provide a reduction in system weight and smaller installation envelopes[1]. Figure 1 is a plot of the data showing Weight vs. Pressure, that increases in operating pressure would achieve significant further reductions in weight. Although it is a research results for military aircraft, it is also a good guideline significance to development of hydraulic systems of civil aircraft. In Figure 1, the abscissa is system pressure, and the ordinate is total system% of 3000psi system. As can be seen, the weight of 5000psi system is about 81% of 3000psi system. The weight includes hydraulic energy systems, tubes, hydraulic fittings, flight control actuators, landing gear actuators, and other hydraulic source-related equipment, and includes the weight of hydraulic fluid[3].

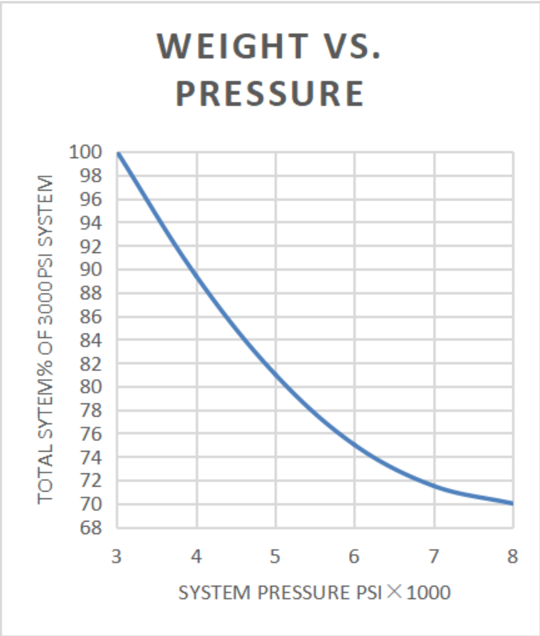

Figure 1. weight vs. Pressure

The airborne hydraulic system will develop in the direction of light weight, small size, high pressure, high power, variable pressure, redundancy, etc. the 5000psi hydraulic system is a representative of advanced technology which can effectively meet the above direction[4] (Wang, 2012).

The increase of the system pressure will greatly increase the system power-to-weight ratio, but it will also greatly increase system power loss, resulting in increased system heat, higher temperature, reduced fluid viscosity, increased system leakage, and reduced system efficiency, which in turn affects system safety and reliability[5].(Guo, 2021)

The development of hydraulic system in the direction of high pressure and high power will bring about an increase in the ineffective power of the system, and the ineffective power of the hydraulic system is mainly reflected in the generation of a large amount of thermal energy, which in turn requires forced heat dissipation[6] (Wang, 2000).

At the same time, the high pressure of the hydraulic system will make the pressure pulsation, tube vibration and leakage more serious.

2.2 PROS AND CONS of 3000psi DOP

3000psi hydraulic system technology is mature, rich off-the-shelf products, route experience and reliability data; the standards and specifications are perfect; the design and process experience are experienced, and the development risk is low. At present, the hydraulic pressure internationally is 3000psi, which is convenient for maintenance by airlines. Compared with 5000psi hydraulic system, 3000psi hydraulic system is heavy weight, large installation space, relatively high fuel consumption.

3. WEIGHT AND VOLUME ANALYSIS

3.1 Assumptions

This paper rises the conclusion, weight, volume, and cost are the main determinant of choosing DOP in the section 1. In order to discuss the discrepancy, there is a comparison from 5000psi system to 3000psi system. Some assumption are here, 1.The increase of pressure system will not change the hydraulic system architecture. 2. Both 5000psi system and 3000psi system are three sets subsystems. 3.The system components are same, which have reservoir, control valves, pumps and other components, but without heat-exchanger. 4.The layout of tubing and its installation direction are same. 5. External factors, such as the load of the aircraft, the layout of the actuator, are not changed.

3.2 Fluid Volume analysis

According to the definition of pressure in section 2.1. When the external force F is fixed, P increases, S decreases, so it can be seen that when the working pressure rises, the fluid volume will decrease.

Further more, the output power of the hydraulic system P0 (Kw)=Q (L/min) * P (Mpa), where P is the working pressure of the system, Q is the flow volume of the system in unit time. Therefore, under the same output power P0 and the same tubing layout, the fluid volume Q required by the hydraulic system is reduced. Therefore, the flow volume of the 5000psi system will decrease and can be approximately considered as 60% of the flow volume of the 3000psi system. For a certain type of aircraft, if 3000psi DOP is adopted, the weight of hydraulic fluid is 486kg; If 5000psi DOP is used, the weight of hydraulic fluid is 486 * 0.6=291.6kg. The use of 5000psi design pressure can reduce the weight of fluid by 194.4kg.

3.3 Tubing weight analysis

From section 3.2, when the fluid volume is reduced, the fluid radius of 5000psi system can be considered as 77.5% of the fluid radius of 3000psi system, that is, under the same output power, the tube diameter of 5000psi system should be 77.5% of 3000psi system. But in fact, in addition to the tube diameter, the tube wall thickness should also be considered for the tube weight. Generally speaking, with the increase of pressure, the tube wall thickness will increase correspondingly to meet the pressure and explosion requirements. Therefore, the higher the pressure, the thicker the required tube. With reference SAE AIR5005 and relevant data, the wall thickness of 3000psi and 5000psi pressure tube is shown in Table 1 below.

Table 1. High pressure tube wall thickness

DASH No. (Diameter)	Wall thicknesses (5000psi)	DASH No.(Diameter)	Wall thicknesses (3000psi)
-4(0.25in)	0.025 in	-4(0.25in)	0.016 in
-6(0.375in)	0.03 in	-6(0.375in)	0.019 in
-8(0.5in)	0.04 in	-8(0.5in)	0.025 in
-10(0.625in)	0.05in	-10(0.625in)	0.032 in
-12(0.75in)	0.059 in	-12(0.75in)	0.039 in
-16(1in)	0.079in	-16(1in)	0.048in
-20(1.25in)	0.098in	-20(1.25in)	0.058in

The high pressure line material for both 5000psi system and 3000psi system is Ti-3Al-2.5V per AMS4945. The tube wall thickness are difference for same diameter, and the tube wall thicknesses of 5000psi is thicker than 3000psi. The low pressure line material for both 5000psi system and 3000psi system is 6061-T6 per AMS4083, and the tube wall thickness is same with the same diameter.

In order to meet power demand, the tube diameter of 5000psi system is at least 0.775 times of the 3000psi system. Using tube diameter of 3000psi system as a baseline, the available tube diameter for 5000psi system under the same power demand are shown in Table 2.

Table 2. High pressure tube Diameter requirements

Diameter（3000psi）	Diameter requirement (Convert to 5000psi)	Available tube diameter（5000psi）
-4(0.25in)	0.19375in	-4(0.25in)
-6(0.375in)	0.290625 in	-6(0.375in)
-8(0.5in)	0.3875 in	-8(0.5in)
-10(0.625in)	0.484375 in	-8(0.5in)
-12(0.75in)	0.58125 in	-10(0.625in)
-16(1in)	0.775 in	-12(0.75in)
-20(1.25in)	0.96875 in	-16(1in)

According to this analysis, the tube size above - 10 (0.625 inch) can be reduced, and the system weight can be reduced. The tube size below - 10 (0.625 inch) can not be reduced, which will lead to increase of the system weight.

For the return line, available tube diameter for 5000psi are shown in Table 3. Like the pressure line, only the return line which above - 10 (0.625 in) can reduce the Dash No. and reduce system weight.

Table 3. Low pressure tube Diameter requirements

Diameter（3000psi）	**Diameter requirement (Convert to 5000psi)**	**Available tube diameter（5000psi）**
-6(0.375in)	0.290625 in	-6(0.375in)
-8(0.5in)	0.3875 in	-8(0.5in)
-10(0.625in)	0.484375 in	-8(0.5in)
-12(0.75in)	0.58125 in	-10(0.625in)
-16(1in)	0.775 in	-12(0.75in)

Assuming that 3000psi and 5000psi tube have the same direction in the aircraft based on section 3.1, that is, the same length. Then according to the above ratio, combined with the hydraulic fluid density and tube density, the pressure tube weight corresponding to 5000psi and 3000psi can be calculated. After calculation, for a certain aircraft, the weight of 5000psi hydraulic system tube is reduced by 19kg, and the tube weight reduction is not obvious.

3.4 Actuator weight analysis

Taking flight control system actuator as an example, the pressure changes from 3000psi to 5000psi, and the material and size of the actuator rod will not change. However, the area of the piston can be reduced. The original actuator shell uses a large number of aluminum alloys with 3000psi. When 5000psi working pressure is used, the aluminum alloy needs to be replaced by steel (or titanium alloy). The weight of 5000psi hydraulic actuator can be reduced by about 4% , but the development difficulty and cost increase. If the landing gear retraction and nose steering system, engine reverse thrust system, cargo door system, etc. adopt 5000psi system, the advantages of control valve and actuator are the same as those of flight control system. So the weight Actuator reduction is not obvious.

3.5 Hydraulic power components weight analysis

When the DOP rises from 3000psi to 5000psi, the weight of the system components is reduced due to the smaller flow demand and the smaller volume of system components. Taking Parker's engine driven pump (EDP) as an example for comparison in table 4.

Table 4 EDPs comparison[7]

EDP / Parameter	AP9VM	AP19V
Maximum Displacement (in3/rev)	1.20	3
Normal Operating Pressure (psi)	5000	3000
Maximum Recommended Speed (rpm)	5085	4106
Maximum Output Flow (gpm)	25.1	50.7
Approximate Dry Weight (lbs)	21.5	27.5
L(in)	9.5	12.8
H(in)	6.7	9
W(in)	6.7	9

It can be seen from Table 4 that the hydraulic energy output of the AP9VM and AP19V is 63.2kW and 62.2kW respectively. The output power of the two pumps are almost same. The pump volume and weight using the design pressure of 5000psi have obvious advantages, including 22% weight reduction and 45% volume reduction.

Adopting 5000psi DOP, the volume and weight of hydraulic fluid tank are also greatly reduced due to the reduction of 40% in the volume of hydraulic fluid.

3.6 Airframe structure weight analysis

After the DOP is changed from 3000psi to 5000psi, the weight of some hydraulic components will be reduced, so the load on the aircraft structure will be reduced, and the weight of corresponding mounting bracket will be reduced. The amount of weight reduction is related to the installation form of hydraulic components. In general, the reduction of the airframe structure weight is limited because it only reduces the weight of the hydraulic power system components.

4. TEMPERATURE ANALYSIS

The system temperature is one of the key factors to decide which DOP to be adopted. It affects system architecture, especially the size of heat-exchanger. It comes from system heat loss. The heat generation mainly comes from: mechanical loss and volumetric loss of hydraulic pump, pressure drop loss and heat generation of hydraulic fluid during tube flow, throttling loss of hydraulic fluid flowing through hydraulic accessories such as fluid filter and valve, internal leakage throttling loss of hydraulic users.

With the development of aircraft hydraulic system towards high pressure, it will inevitably lead to an increase in the volumetric power loss of aircraft hydraulic system. The increase of the system power of will also lead to increase of the invalid power of the system[6].

For the hydraulic system, at a certain temperature,

$$Q_1 = K_1 P_s \tag{1}$$

$$W_v = P_s Q_1 \quad (2)$$

$$W_v = K_1 P_s^2 \quad (3)$$

Where Q_1 is pump flow loss; W_v is Volume loss (power); P_s is the pump source pressure; K_1 is the leakage coefficient of the pump. It can be seen that the higher the pressure, the greater the volumetric loss. All the volumetric loss is converted into system heat energy.

Pump volumetric loss (power) is proportional to the square of pump pressure. Leakage of other components in hydraulic system also has this rule, only their leakage coefficient is relatively small, so a small increase of system pressure can produce a large power loss. According to a literature, for the DRPV 3-240-1 hydraulic pump, if the system pressure increases from 10.35MPa {1500psi} to 20.7Mpa {3000psi} (the system pressure increases by 100%) at the speed of 3000r/min, the volumetric loss (power) of the pump increases from 0.735kw to 2.94kw[6]. It is estimated that when system DOP increases to 35 MP, the volumetric efficiency of the pump increases from 2.94kW to 8.41kW, which is about twofold, and the volumetric loss is converted into system thermal energy.

With the volumetric loss will change to system heating and increase the system temperature, the case temperature will increase. Generally speaking, case temperature is the highest temperature in system. The case temperature with pump speed 3000 rpm are in the table 5. The case temperature has previously been proven to have an impact on the power loss due to thermal deformation of the structure in the lubricating gaps.The case temperature is increasing for an increased pump speed and pump pressure[9] (ONBERG, 2011).

Table 5. Case temperature change with pressure increase[9]

Δ p[bar]	**Q_{leak}[l/min]**		**Q_{tot}[W]**		**T_{case}[°C]**	
	Calculated	Measured	Calculated	Measured	Calculated	Measured
100	2.41	4.71	1522.93	-	76.49	69.22
200	2.86	5.05	1797.76	-	76.75	76.39
300	3.20	5.94	2076.67	-	77.99	81.65

Case temperature of 3000psi(20.7bar) is about 77℃, so case temperature of 5000psi(34.5bar) is about 85℃. In the condition of higher pump speed, it will cause higher case temperature. From the table 4, the hydraulic pump speed is more than 5000rmp, so the case temperature will higher than 85℃ according to Table 5.

Through this thermal analysis and calculation, it can be concluded if the hydraulic system needs a heat-exchanger or not. If the conclusion is that the 3000psi hydraulic system does not need a heat-exchanger but the 5000psi system needs a heat-exchanger, then the 5000psi system weight and volume should be recalculated to compare with 3000psi weight and volume again.

5. CONCLUSIONS

According to the above analysis, when the hydraulic system DOP is increased from 3000psi to 5000psi, the conclusions are as follows: the system volume can be significantly reduced; weight and volume of the fluid are reduced; weight of actuators has no obvious change; tube weight above -10 has a weight advantage, so the weight advantage can only be reflected when a large number of tube Dash NO. above -10 are used; weight of pressure tube is inferior when the tube Dash NO. -8 and below are used; The temperature rise is obvious, and the heat-exchanger may be necessary, which will inevitably affect the weight of the system.

The above conclusions play a decisive role in balancing 3000psi and 5000psi. Cost is also a very important factor. It needs to be calculated after completing the weight and volume analysis to support adoption of the hydraulic system DOP.

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