Design and simulation of the accumulator for servomechanisms of launch vehicle

Bo Zheng1, Chun Zhao1, Xin Liu1, Shoujun Zhao1, Xiaosha Zhang1
1Beijing Institute of Precision Mechatronics and Controls, Beijing, People’s Republic of China
E-mail: bobby_53@sina.com

Abstract: The accumulator is a crucial component of the hydraulic power for servomechanisms of the launch vehicle, which has a significant effect on the performance and the mass power. Traditional design methods are mostly based on empirical formulas, which do not meet the requirements of the fine design of aerospace products. The physical model, the mathematical model of the accumulator and joint simulation model of the energy and the control loop are established, and parameters satisfying the extreme flight operation profiles are obtained, including the discharge volume, charge volume and charge pressure. The flight data of third-stage servomechanisms of the Long March 3 series Launch Vehicle were analysed, which is consistent with the simulation data, indicating that the accumulator has exerted the maximum capability in the extreme flight condition, and the maximum mass power has been realised.

1 Introduction

As a key component of the electro-hydraulic servomechanism of the launch vehicle, the accumulator provides instantaneous peak energy during the large operation of the servo actuator and also acts as a pressure fluctuation damper and the pressurisation of the inlet of the pump. In the Ariane V solid booster and the first sub-stage of Long March 11 Launch Vehicle, the accumulator is the only power source of the servomechanism [1].

Parameters to be determined in the design of the accumulator are the effective volume and charge pressure. In the civil industry, size and weight are not major limiting factors, and methods provided in the hydraulic engineering manual are adequate and a range of products are available [2]. However, space products have strict requirements on size and weight, especially the three sub-stages of the Long March 3 series Launch Vehicle applied to launch earth-orbit satellites, which requires the highest specific power under the premise of satisfying the performance.

The schematic diagram for the third-stage servo system of Long March 3 series Launch Vehicle is shown in Fig. 1. It contains two hydraulic power sources and four servo actuators and is installed on two bidirectional pendulum hydrogen–oxygen engines. The system is equipped with two solenoid valves between the accumulator and servo valve. The accumulator stores high-pressure oil which is aimed to provide instantaneous hydraulic power before the engine ignition [3]. In addition, the accumulator provides supplementary energy during large operations.

The integrated design of the accumulator and the pressurised oil tank is shown in Fig. 2. In order to improve the mass power, the accumulator adopts the spherical capsule design. Minimum accumulator volume is required under extreme flight operation profiles. In the traditional design, it is difficult to realise the fine design by relying on empirical formulas to determine the discharge volume, charge volume and charge pressure.

The physical model and the mathematical model of the accumulator are established, respectively, and joint simulation model of the energy and the control loop is built as well, and finally obtains parameters that fulfil extreme flight operation profiles.

2 Design model

2.1 Physical model of the accumulator

The simplified physical model of the accumulator can be considered as one closed chamber filled with nitrogen which also contacts with hydraulic oil. The typical operation process is shown in Fig. 3, and operation states of the accumulator in the full temperature scope are shown in Fig. 4.

Considering Fig. 3 as an example, the operation process of one accumulator is as the following:
(ii) $\Delta V_{\text{max}}$ and $P_{2\text{min}}$ are design parameters which require that $\Delta V_{\text{max}}$ meets the instant flow demand of actuators and $P_{2\text{min}}$ is greater than the minimum load pressure.

It can be seen that the design of the accumulator is actually equal to the design of $\Delta V_{\text{max}}$ and $P_{2\text{min}}$ which can be computed by applying the load characteristics to the joint simulation model of the energy and the control loop.

### 2.2 Mathematical model of the accumulator

The mathematical model of the accumulator is the gas state equation. Owing to the short actuation time of servomechanisms during flight, it can ignore the influence of the temperature, which can be represented as

\[
\begin{align*}
P_{1\text{o}}V_{0} &= P_{1\text{v}}V_{1}, \\
P_{2\text{o}}V_{0} &= P_{2\text{v}}V_{2}, \\
P_{1\text{v}}V_{0} &= P_{2\text{min}}V_{0}, \\
\Delta V_{\text{max}} &= V_{0} - V_{1}.
\end{align*}
\]

During the flight, servomechanisms are working under wide ranges of temperature scope which are from $-40$ to $+135^\circ\text{C}$. Considering the temperature, it can compute $P_{1\text{o}}$ and $V_{0}$, which meet the full temperature scope and design parameters ($\Delta V_{\text{max}}$ and $P_{2\text{min}}$).

### 2.3 Differential equation of the accumulator

It can derive the dynamic differential equation of the accumulator with time differentiation. Take state ①-③ for example, the instantaneous value of $P_{2}$ and $V_{2}$ are $P_{2(0)}$ and $P_{2(0)}$

\[
V_{2}(t) = \left( \frac{P_{2}}{P_{2(0)}} \right)^{(1/n)} V_{1},
\]

The flow differential equation is shown as follows:

\[
Q_{t} = \frac{d(V_{2}(t) - V_{1})}{dt} = \frac{dV_{2}(t)}{dt} = \frac{d\left( \left( P_{2} \right)^{(1/n)} V_{1} \right)}{dt} = -\left( P_{2}^{n-1} \cdot V_{1} \right) \cdot \frac{1}{n} \cdot P_{2} \cdot \frac{dP_{2}(t)}{dt}
\]

where $Q_{t}$ is the discharge flow of the accumulator; ‘+’ represents inflow; ‘-’ represents outflow.

### 2.4 Mathematical model of the hydraulic power

For servomechanisms, the hydraulic power contains the accumulator, hydraulic pump and pressure adjuster. The pressure adjuster can be simplified as a switch

\[
Q_{t} = \begin{cases}
0 & P_{t}(t) > P_{s}, \quad \text{non-operation} \\
Q_{b} - Q_{t} - \frac{Q_{s}(t)P_{2}(t)}{P_{s}} & P_{t}(t) \leq P_{s}, \quad \text{operation}
\end{cases}
\]

where $Q_{b}$ is the flow rate of the pump; $Q_{t}$ is the flow rate of the load, which is determined by the speed of the servo actuator; $Q_{b}$ is the leakage of the servomechanism, including the servo valve and the hydraulic pump itself.

Equations (3) and (4) are non-linear differential equations, which describe the basic characteristics of the hydraulic power with the accumulator, and it can be presented by block diagram as shown in Fig. 5 [5-8].

In Fig. 5, $S$ is the Laplace operator; $t$ is the simplified time constant of the pressure adjustment [9] and $u$ is the independent variable of the function. After input relevant parameters, the energy pressure curve $P_{2}(t)$ can be obtained. As long as it is not lower than the minimum energy pressure $P_{2\text{min}}$, it can meet the task.
requirement. Meanwhile, it can also obtain the curve of oil discharge volume $\Delta V$. The leakage of the servomechanism normally is slight, and $\Delta V_{\text{max}}$ is mainly determined by the pump flow and load flow. Once the speed displacement of the pump and the typical actuation of the servomechanism are determined, $\Delta V_{\text{max}}$ can be obtained. For most servo mechanisms of launch vehicle, the load is pendulum rocket nozzle and the inertia moment is one main component, and the load pressure is closely related to the actuation of servomechanisms. According to the load, $P_{2\text{min}}$ can be estimated, $V_{\text{max}}$ can be calculated with Fig. 5, $V_0$ and $P_{V0}$ can be solved in the full temperature scope, and finally, whole solutions can be calculated with Fig. 5. In any case, $P_2(t)$ is greater than or equal to $P_{2\text{min}}$.

### 2.5 Joint simulation model of the energy and the control loop

The joint simulation model of the energy and the control loop is shown in Fig. 6 [10]. $Q_L$ is as one input to the model of hydraulic power and output of hydraulic power, $P_2(10)$, is similar to the input of the joint simulation model. After the simulation, it can obtain real-time curves of the load pressure $P_{2(10)}$.

In extreme flight operation profiles, the oil discharge volume is about 180 ml, the gas charge volume is about 400 ml and the gas charge pressure is about 6.5 MPa after simulations which are close to current design parameters of the accumulator.

### 3 Flight data analysis

The normal flight data of third-stage servomechanisms of Long March 3 series launch vehicles are shown in Figs. 7 and 8.

Before two third-stage engines ignition, solenoid valves are open and then accumulator 1 and 2 release pre-stored high-pressure oil providing instantaneous power for four servomechanisms, so the pressure in two accumulators decreases. When two third-stage engines ignition, pneumatic motors drive hydraulic pumps for refilling accumulators, and then the pressure increases and finally is equal to the pressure of servomechanisms. During normal flight, servomechanisms are smooth and steady, servo actuators only have small-scale actuation, therefore accumulators do not work and the pressure keeps steady. In one flight of anomalies, servomechanisms have large scale and rapid actuation in order to stabilise the attitude of the launch vehicle, the angular velocity of servomechanisms reaches up to 450°/s (the design objective is 400°/s), the flight data is shown in Figs. 9 and 10.

When servomechanisms have large scale and rapid actuation, pumps cannot provide enough flow in a short time, accumulators provide instantaneous power and the pressure decreases. Curves between simulation and flight are almost consistent. The slight difference may come from design margins and actual environmental conditions. Some conclusions can be obtained as follows:

(i) The simulation curve is in good agreement with flight curves, which indicates the correctness of the simulation calculation model and the reasonable design of the actual product of the accumulator;

(ii) Before two third-stage engines ignition, solenoid valves are open and accumulators provide instantaneous power, servomechanisms only have a slight actuation at that period, so the pressure decreases from 17.5 to 12.5 MPa, and it can cover the load pressure;

(iii) While in extreme flight operation profiles, the pressure decreases from 20 to 9.5 MPa which is close to the charge pressure of accumulators (∼7 MPa). The accumulator exerts its maximum working capacity, which also indicated that the design of the accumulator realised the maximum mass power.

### 4 Conclusion

In this paper, the design and simulation of the accumulator of servomechanisms for launch vehicle are carried out. Through the comparative analysis of the simulation curve and flight data, the
The correctness of the accumulator related simulation model is verified. Under severe flight conditions, the accumulator has exerted its maximum working capacity, and the rationality of design parameters has been demonstrated.

This design and simulation analysis method can check the parameters of the accumulator precisely and improve the quality and efficiency of product design. It has some practical value in engineering and can be applied to the accumulator design of other servomechanisms.

5 Acknowledgments

This study was supported by the supervisors, Shoujun Zhao and Xiaosha Zhang by providing instructive advice and useful suggestions. Authors also thank the Department head and colleagues who have put considerable time and effort into their comments on the proposed work.

6 References

[1] Caye, P., Descamps, D., Ariane, V.: ‘Thrust vector control development Status’. AIAA 94–3069, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conf., Indianapolis, IN, USA, June 27–29 1994
[2] Zhao, S., Zhao, Y., Jiang, Q.Y., et al.: ‘The 2nd stage servomechanism system for liquid oxygen-kerosene manned launch vehicle’, Manned Spaceflight, 2012, 18, (5), pp. 1–7
[3] Lei, T.: ‘New hydraulic engineering manual’ (Beijing Institute of Technology University Press, People's Republic of China, 1998)
[4] Green, W.L.: ‘Accumulator time constants and the ‘INdex’ method: some comparisons based on experimental data’, National Conf. on Fluid Power, USA, 1979
[5] Merritt, H.E.: ‘Hydraulic control systems’ (Wiley, New York, 1967)
[6] Wang, Z.L.: ‘Hydraulic control system’ (Beihang University Press, People's Republic of China, 1987)
[7] Edwards, J.W.: ‘Analysis on electrohydraulic aircraft control-surface servo and comparison with test results’, NASA Technical Note. NASA TN D-6928, August 1972
[8] Liu, R.: ‘Nonlinear Control of Electro-hydraulic Servo-Systems: Theory and Experiment’, M.S. Degree Thesis, University of Illinois at Urbana-Champaign, 1998
[9] Zhao, S., Jing, G.: ‘Study on the design of the accumulator and oil-tank for the servomechanism using numerical optimization’. The Servo-Forum Papers of the Chang Kong company in 2005, Beijing, People's Republic of China, 2005
[10] Yin, C.: ‘Study on servomechanism's control algorithm optimization to suppress load resonance’, China Aerospace Science and Technology Corporation, 2012