Modeling and Analysis of Different Architecture for Civil Aircraft Hydraulic System

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Abstract. For the evaluation of civil aircraft hydraulic system, Fuel Consumption is a very important index. However, there is no effective method to perform analysis for different architecture. This paper proposes that taking fuel weight penalty as a major mathematical modeling method to analysis traditional architecture and more electric architecture. The result shows that the fuel consumption of more electric architecture is less than traditional architecture.

Keyword: Hydraulic system, modeling, analysis.

1. Introduction
Hydraulic system extracts mechanical energy and electric energy from engine and generator, and covert to hydraulic energy by pump, provide the hydraulic energy to its consumer. With the development of more electric technology, the hydraulic system also faces the option of traditional architecture and more electric architecture. For a traditional energy architecture aircraft, the hydraulic energy consumers include flight control system, landing gear system and so on. For a more electric architecture aircraft, take Airbus A380 and Boeing B787 as an example, Airbus A380 cancel a set of hydraulic system, flight control system partly uses electric energy instead of hydraulic energy, such as EHA, EMA end EBHA. For Boeing B787, the braking system uses electric brake instead of hydraulic brake. Therefore, it is very important and necessary to trade-off different architecture for hydraulic system that adopt more electric technology. However, there is no effective mathematical modeling method to perform analyze the fuel consumption of different architecture. It is very necessary to learn from evaluation methods of other systems.

2. System Overview

2.1. Traditional Architecture
The hydraulic system adopts three sets of central hydraulic energy network architecture, its pressure class is 5000psi, and it provides hydraulic energy to flight control system and landing gear system and so on. The architecture is shown in Figure 1.

2.2. More Electric Architecture
The hydraulic system adopts two sets of central hydraulic energy network architecture which is isolated from each other, its pressure class is also 5000psi, and it provides hydraulic energy to flight control system and landing gear system and so on. The architecture is shown in Figure 2.
3. Modeling Method

There is no effective method to perform analysis the fuel consumption of different architecture for hydraulic system. However, it can take fuel weight penalty as a major mathematical modeling method like air conditioning system does. And the generally accepted methods of evaluation of fuel weight penalty include the equivalent weight method, the total take-off weight method and the equivalent resistance method. The transportation cost is a very important consideration for civil aircraft. It is suitable to take the total take-off weight method as the evaluation of hydraulic system. The fuel weight penalty for the total take-off weight method include fixed weight penalty, variable weight penalty, shaft power extraction penalty, bleed air penalty and ram air penalty.

3.1. Fixed Weight Penalty

Fuel is required to carry the system fixed weight and the dead weight of fuel up to the point where it is expended. The total take-off weight penalty for fixed weight consist of the system fixed weight plus the weight of the fuel required to carry it, and it is given by

\[ M_{f,E} = M \left[ \exp \left( \frac{C_e \tau_0 g}{K} \right) - 1 \right] \]

Where is:
- \( g \) — acceleration of gravity, m/s\(^2\)
- \( K \) — lift-drag ratio
- \( C_e \) — specific fuel consumption for thrust, kg/(N\( \cdot \)h)
- \( \tau_0 \) — time of flight, h

3.2. Variable Weight Penalty

Expendable material (such as water for use in water boilers) may be carried aboard the aircraft. And it is assumed that the rate of consumption of the expendable material is constant. There are two cases in the following:
- Variable Weigh is used during any portion of the flight

The take-off fuel weight required for carrying the decreasing weight of expendable material, and also of fuel, is given by

\[ M_{f,V} = \frac{W_r K}{C_{e\theta}} \left[ \exp \left( \frac{C_e \tau_0 g}{K} \right) - 1 \right] - W_r \tau \]

Where is:
- \( g \) — acceleration of gravity, m/s\(^2\)
- \( K \) — lift-drag ratio
- \( C_e \) — specific fuel consumption for thrust, kg/(N\( \cdot \)h)
- \( \tau_0 \) — time of flight, h
- \( W_r \) — rate of consumption of expendable material, kg/s
Variable Weigh is used during specific portion of the flight. The take-off fuel weight required for carrying the decreasing weight of expendable material, and also of fuel, is given by:

\[ M_{f,v} = \frac{W_v K}{C_e g} \left[ \exp \left( \frac{C_e (\tau_m - \tau_1) g}{K} \right) - 1 \right] - W_v (\tau_m - \tau_1) \]  

Where is:
- \( g \) — acceleration of gravity, m/s\(^2\)
- \( K \) — lift-drag ratio
- \( C_e \) — specific fuel consumption for thrust, kg/(N\( \cdot \)h)
- \( \tau_1 \) — start time of statistical flight, h
- \( \tau_m \) — end time of statistical flight, h
- \( W_v \) — rate of consumption of expendable material, kg/s

3.3. Shaft Power Extraction Penalty

To maintain constant net thrust from the engine, the shaft power extracted must be compensated by an increase in fuel flow rate to the engine. Assuming power is consumed as a constant rate during the portion of mission being evaluated, the take-off fuel weight penalty is given by:

\[ M_{f,p} = \frac{C_e K}{C_e g} \left[ \exp \left( \frac{C_e \tau_0 g}{K} \right) - 1 \right] \]

\[ C_e = \frac{C_{p,g} T_{in,t} \eta_c}{1004.5 + H_u \epsilon_{kc} T_{in,c} (\tau_0^{286-1})} \]

Where is:
- \( C_e \) — specific fuel consumption for power, kg/(W\( \cdot \)s)
- \( P \) — Power being consumed, kW
- \( C_{p,g} \) — The specific heat capacity of gas at constant pressure, J/(kg \( \cdot \)K)
- \( H_u \) — The calorific value per unit of fuel combustion, J/kg
- \( T_{in,t} \) — Inlet temperature of engine turbine, K
- \( T_{in,c} \) — Inlet temperature of engine compressor, K
- \( \epsilon_{kc} \) — Complete combustion coefficient in the combustion chamber
- \( \eta_c \) — Engine compressor boost ratio

3.4. Bleed Air Penalty

If bleed air is extracted from the compressor of the turbine engine, the penalty can be evaluated on the basis of increase fuel flow required to maintain constant thrust. As a first approximation only, the increase in fuel flow rate due to bleed air extraction is given by:

\[ M_{f,bl} = \frac{q_{m,bl} K}{C_e g} \left[ \exp \left( \frac{C_e \tau_0 g}{K} \right) - 1 \right] \]

If bleed air from low pressure stage of Engine compressor,

\[ q_{m,bl} = \frac{q_{m,bl} C_{p,g} T_{in,t} (\tau_0^{286-1})}{H_u \epsilon_{kc} T_{in,c} (\tau_0^{286-1})} + q_{m,bl} V C_e \]

If bleed air from high pressure stage of Engine compressor,

\[ q_{m,bl} = \frac{q_{m,bl} C_{p,g} T_{in,t}}{H_u \epsilon_{kc}} + q_{m,bl} V C_e \]

Where is:
- \( q_{m,bl} \) — Increased fuel mass flow due to bleed air, kg/s
- \( q_{m,bl} \) — Bleed air flow, kg/s
- \( \tau_0 \) — Engine compressor boost ratio of bleed air
- \( \tau_c \) — Engine compressor boost ratio
- \( \epsilon_{kc} \) — Complete combustion coefficient in the combustion chamber
- \( H_u \) — The calorific value per unit of fuel combustion, J/kg
3.5. Ram Air Penalty
Assuming complete momentum loss, the ram air penalty in term of take-off fuel weight is given by:

\[ M_{f,D} = \frac{q_m V K}{g} \left[ \exp \left( \frac{C_{x0}\alpha}{K} \right) - 1 \right] \]  \hspace{1cm} (9)

Where is:
- \( q_m \) — ram air flow, kg/s
- \( V \) — Cruise velocity, m/s

3.6. Total fuel weight penalty
The hydraulic system is a fixed system, and there is no need to bleed air from engine and overcome ram air resistance. However, it need to extract mechanical energy from engine. Therefore, the fuel weight penalty of hydraulic system includes fixed weight penalty and shaft power extraction penalty.

The total fuel weight penalty of hydraulic system is given by:

\[ \Delta M_T = M_{f,E} + M_{f,P} \]  \hspace{1cm} (10)

4. Modeling Analysis

4.1. Definition of Flight Envelope
To perform analysis for traditional architecture and more electric architecture of hydraulic system, there is a strongly necessary to define the flight envelope. The flight envelope should have the necessary information which contain the flight phase, the flight time, the flight altitude and the flight velocity. And the defined flight envelope is shown in table 1.

| Phase   | Detailed phase | Time(min) | Altitude(m) | Velocity(Ma) |
|---------|----------------|-----------|-------------|--------------|
| Start preheating | 1 | 1~10 | 0 | 0 |
| Taxi out  | 2 | 11~20 | 0 | 0 |
| Take off | 3 | 21 | 10 | 0.22 |
| 4 | 22~25 | 450 | 0.22 |
| 5 | 26~28 | 450 | 0.38 |
| Climb | 6 | 29~38 | 3050 | 0.38 |
| 7 | 39~41 | 3050 | 0.46 |
| 8 | 42~55 | 10668 | 0.8 |
| 9 | 26~60 | 10668 | 0.85 |
| Cruise | 10 | 61~65 | 13106 | 0.85 |
| 11 | 66~220 | 13106 | 0.85 |
| 12 | 221~240 | 3050 | 0.46 |
| Descent | 13 | 241~245 | 3050 | 0.38 |
| 14 | 246~260 | 450 | 0.38 |
| Approach | 15 | 261~265 | 10 | 0.22 |
| Landing | 16 | 266 | 0 | 0.01 |

4.2. Modeling Analysis

4.2.1. The calculation of fuel weight penalty. According to the mathematical modeling method of fuel weight penalty, the different fuel weight penalty of traditional architecture and more electric architecture of hydraulic system in single flight envelope is shown in figure 3 and figure 4.
For a single flight mission, the total fuel weight penalty for traditional architecture is about 341.6kg. For the total fuel weight penalty of traditional architecture, the fixed Weight Penalty is about 205.47kg, which is about 60.1% of total fuel weight penalty. The shaft power extraction penalty is about 136.13kg, which is about 39.9% of total fuel weight penalty. The total fuel weight penalty for more electric architecture is about 277.52kg. For the total fuel weight penalty of more electric architecture, the fixed Weight Penalty is about 132.26kg, which is about 47.6% of total fuel weight penalty. The shaft power extraction penalty is about 145.26kg, which is about 52.4% of total fuel weight penalty.

4.2.2. The result of modeling analysis. The analysis of fuel weight penalty of traditional architecture and more electric architecture of hydraulic system in single flight envelope is shown in table 2.
Table 2. fuel weight penalty for different architecture.

| Item                                | Traditional architecture | More electric architecture |
|-------------------------------------|--------------------------|----------------------------|
| Fixed Weight Penalty (kg)           | 205.47                   | 132.26                     |
| Shaft power extraction penalty (kg) | 136.13                   | 145.26                     |
| Total fuel weight penalty (kg)      | 341.6                    | 277.52                     |

The statistical results which are from table 2 is shown in figure 5.

![Figure 5 Fuel weight penalty statistical result.]

It can be seen from Table 2, For a single flight mission, the total fuel weight penalty for More electric architecture is about 282.9kg, which is lower than traditional architecture about 13.5%. In other words, the fuel consumption of More electric architecture is less than traditional architecture.

5. Conclusion
The thesis proposes that taking fuel weight penalty as a major mathematical modeling method to analyze traditional architecture and more electric architecture. This method can help to calculate the fuel consumption of hydraulic system. However, it also has its limitations. It is only suitable for concept design of hydraulic system. And it does not adopt the maintenance cost as an evaluation index. In addition, the result of analysis is limited by the accuracy of some parameters for hydraulic system, such as weight and the power extracted from engine. In short, it still need to multi-dimensional evaluate the different architecture.

References
[1] Hui Yannian and Kang Yuanli 2018 OVERVIEW OF MEA KEY TECHNOLOGY AND SYSTEM INTEGRATION Journal of Engineerin p661-664.
[2] DENG Xishu, LI Ziguang 2003 Development status and trend of hydraulic system simulation technology[J]. Machine tool and hydraulics, no. 1, p20-22.
[3] M. E. Saleta, D. Tobia and S. Gil 2004 Experimental study of Bernoulli's equation with losses American Journal of Physic, vol. Volume 73, no. Issue 7, pp. 598-602.
[4] A. Queens, A. Korolev and A. Vaychulis 1996 Analysis of heat-hydraulic stability of multi-channel circulating thermal systems Automatic control of metallurgical processes, p89-103.