Thermal Properties of C919X EHAs Operating During Whole Flight Envelope

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ABSTRACT

Study on the electro-hydrostatic-actuator (EHA) based on C919X aileron is ongoing for the next generation of Chinese large commercial aircraft considering to employ power-by-wire actuators operating during whole flight envelope. The structural design of an EHA prototype with variable pump and variable motor (EHA-VPVM, dual-variable EHA) was finished and this paper will discuss the thermal characteristics of this prototype with AMESim. Meanwhile, comparative thermal characteristics analysis of EHA-VPVM and EHA with fixed pump and variable motor (EHA-FPVM) is illustrated. Simulation shows that thermal performance of the two EHAs operating during the C919X full flight envelope meets requirements. The difference between the two EHAs is also obtained.

KEYWORDS

active EHA, thermal characteristics, AMESim, modeling and simulation

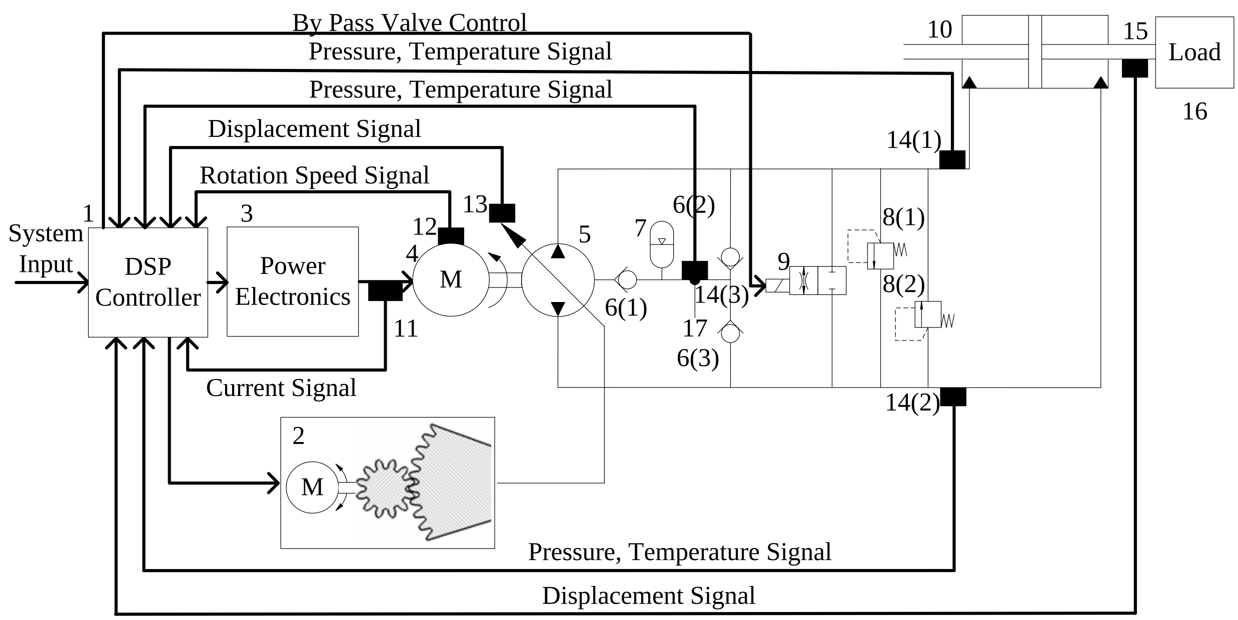
1 INTRODUCTION

China's first large commercial aircraft C919 adopts a conventional central hydraulic system as the power of flight control actuation system. The trend towards more electrical aircraft is gradually being implemented to back up or replace with electrical powering hydraulic circuits hence power the flight-control actuators. Currently, the new type aircrafts A380, B787 and A350 employ power-by-wire actuators, which bring in more advantages in security, power weight ratio and clean sky performance. Therefore, Commercial Aircraft Corporation of China, Ltd. (COMAC) maintains equip the next generation of Chinese large commercial aircraft C919X with power-by-wire actuators, i.e. active EHAs to operate during the whole flight envelope. Within the design procedure, issues of reliability, maintainability, automatic operations and basic performance are to be evaluated. However, the most fundamental parameter related is the thermal characteristics, which represents the thermal equilibrium temperature in the whole flight envelope.
This paper studies the thermal characteristics of an EHA prototype based on C919X aileron. Thermal models of EHA-VPVM and EHA-FPVM are established with AMESim and thermal properties of two kinds of EHA under non-active heat-exchanging condition are analyzed. In addition, the discussion on thermal characteristics differences between EHA-VPVM and EHA-FPVM is exhibited.

2 THE EHA PROTOTYPE BASED ON C919X AILERON

Beihang University develops an aileron EHA prototype for operating whole flight envelope based on the idea of equipping C919X with power-by-wire actuators. This prototype can control the output flow by means of variable pump and variable motor (VPVM), fixed pump and variable motor (FPVM) and variable pump and fixed motor (VPFM) due to a dual variable structure. According to the power-by-wire demand, pump rotation speed and displacement are both driven by DC motors. Figure 1 shows the schematic block diagram and Table 1 gives the performance specifications. The velocity of hydraulic cylinder is controlled by the flow. Therefore, the change of the BLDCM speed or the DC servo motor angle could be used to adjust the hydraulic cylinder velocity. The accumulator and two check valves were used to keep the minimum pressure of the system and avoid the cavitation. The EHA system was protected by the bypass valve and two relief valves.

Figure 1: schematic block diagram



1.EHA Controller 2.DC Servo Motor And Drive 3.BLDCM Drive 4.BLDCM 5.Dual-Variable Pump 6.Check Valve 7.Accumulator 8.Relief Valve 9.By Pass Valve 10.Actuator 11.Current Sensor 12.Hall Sensor 13.Angle Sensor 14.Pressure, Temperature 15.LVDT 16.Load 17.Inject Valve

Table 1: performance specifications

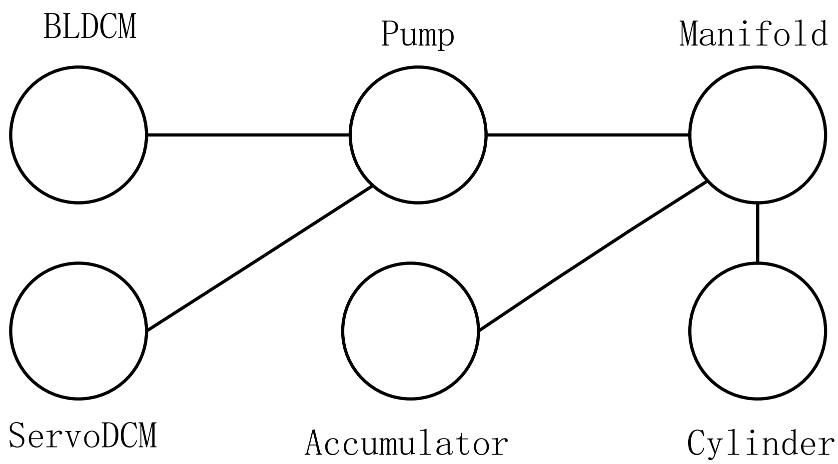
PERFORMANCE	DATA	PERFORMANCE	DATA
BLDCM Nominal Voltage	270VDC	DC Servo Motor Nominal Current	5210rpm
BLDCM Nominal Current	34A	Nominal Pressure	28MPa
BLDCM Nominal Speed	10000rpm	Nominal Flow Rate	25L/min
BLDCM Nominal Torque	7Nm	Max Force	31.416kN@188mm/s
DC Servo Motor Nominal Voltage	24VDC	Max Velocity	315mm/s@18.850kN
DC Servo Motor Nominal Current	2.3A	Cylinder Area	12.56mm^2
DC Servo Motor Nominal Speed	71mNm		

3 THERMAL MODELLING WITH AMESIM

EHA is a highly integrated self-contained hydraulic system with few heat exchange capability, so the simulation tool is obviously necessary especially when operating during whole flight envelope. A brief literature review shows three main ways to calculate the thermal characteristics of EHA. JOHANSSON Björn established EHA-FPVM lumped parameter thermal simulation model with Modelica. Simulation results showed that the heat was not a problem during normal operation. But during extreme missions, there is a risk for high temperatures both in the electric motor, control electronics as well as in the hydraulic fluid. [1-4] EHA thermal design tool developed by Wataru Takebayashi, which consists of Bondgraph Analysis and FEM (Finite Element Method) Analysis, got EHA temperature field of fluid and structure. But it not contained the heat resource models of electric and mechanical parts.[5] Klaus Stadlbauer used an electrical network

representation to establish a geometrically distributed but mathematically lumped parameter thermal model. But modeling was complex and time-consuming due to the need of geometry discretization and equivalence. In addition, the boundary conditions need presented by external model in real time.[6]
Therefore, a complete EHA thermal model is suggested and the thermal boundary conditions are presented. So it requests description of the EHA dynamic performance. A network simulation method similar to KAI LI is chosen.[2] EHA is divided into several hot nodes connected together based on components architecture. Characteristics of each node are described with lumped parameters, as shown in Figure 2. Particularly, the model is established in AMESim, which can improve the modeling efficiency, accuracy and reliability.

Figure 2: Structure of Thermal Simulation Model



The thermal performance of a system can be divided into four categories: heat generated by work, heat stored or dissipated by enthalpy, heat transfer between the components and heat transfer between components and environment.[7] Each of the hot nodes contains the aforementioned characteristics. The branches are responsible for the delivery of variables between nodes.

3.1 Thermal Modeling of EHA-VPVM

In this section, the AMESim thermal model of each node will be introduced, and then the establishment of the complete EHA-VPVM model will be illustrated.

General thermal modelling

Of the four thermal characteristics, the heat transfer between components and environment of each node can be modeled in a similar way. Heat between components and environment is mainly transferred by component surface through radiation and convection, and are defined by AMESim submodels in figure 3 separately.[1]

Figure 3: submodels for heat transfer between components and environment

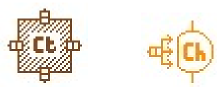
The related mathematical expressions are:

$$Q_1 = \sigma \cdot \varepsilon_{gw} \cdot S \cdot (T_g^4 - T_1^4) \tag{1}$$
$$Q_2 = KHeat \cdot hconv \cdot cearea \cdot (tFluid - tWall) \tag{2}$$

Q_1 is the heat flow rate,

σ is the Stefan-Boltzmann constant, $\sigma = 5.67 * 10 - 8\,\mathrm{W/m}\,2\,/\mathrm{K}\,4$,
ε_{gw} is the equivalent emission factor of the combination gas/wall,
S is the exchange surface considered,
T_g is the temperature of the gas,
T_1 is the temperature of the node,
Q_2 is the heat exchange,
kHeat is the gain on heat exchange,
hconv is the convective exchange coefficient fluid/wall,
cearea is the convective heat exchange area,
tFluid is the temperature of the fluid,
tWall is the temperature of the node.
The heat stored or dissipated by enthalpy of node with mechanical output is modeled as a thermal mass and other nodes are modeled as a thermal-hydraulic capacity or volume, as shown in figure 4.[2]

Figure 4: submodels of node surfaces



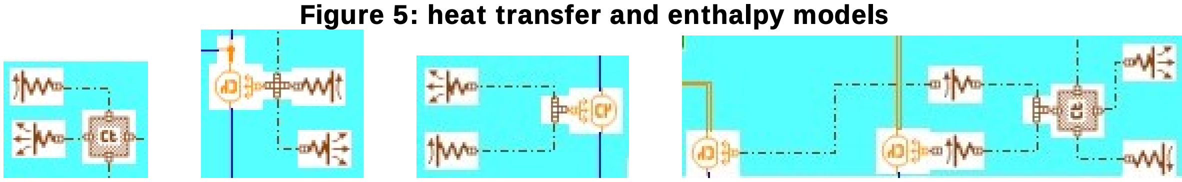
The related mathematical expressions are:

$$\frac{dT_1}{dt} = \frac{\sum_{i=1}^{4} dh_i}{mass \cdot c_p} \tag{3}$$

$$\frac{dT_2}{dt} = \frac{dmh_1 + dmh_2 + \dot{Q} - (dm_1 + dm_2) \cdot h}{\rho c_p V} + \frac{\alpha T}{\rho c_p} \cdot \frac{dP}{dt} \tag{4}$$

T_1, T_2 is the node temperature,
$\mathrm{d}h_i$ is the input heat flux at port i,
c_p is the specific heat of the material at temperature T,
mass is the mass of the node,
$\mathrm{dm}h_1$ and $\mathrm{dm}h_2$ are the incoming enthalpy flow rates,
$\dot{Q}$ is the heat exchanged with outside,
dm1 and dm2 are the incoming mass flow rates,
h is the mass enthalpy in the volume,
c_p is the specific heat of the fluid,
ρ is the density of the fluid,
V is the volume of the component,
α is the volumetric expansion coefficient,
$\frac{dP}{dt}$ is the pressure derivative with respect to time.
Then the heat transfer between components and environment and heat stored or dissipated by enthalpy of motor, pump, manifold with accumulator and cylinder are modeled as shown in figure 5. The cylinder's model also includes convection between fluid in two chambers and surface.

Figure 5: heat transfer and enthalpy models

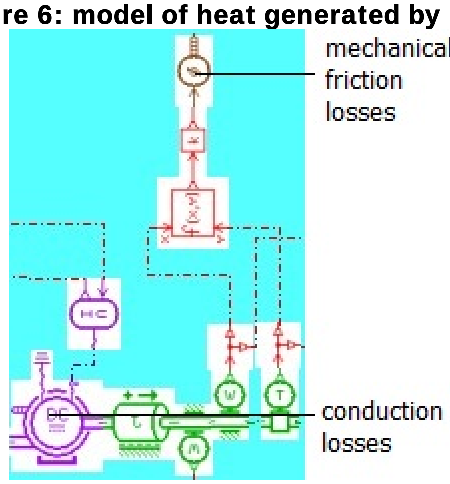


The heat transferred among the hydraulic components mainly depends on the hydraulic oil. According to a lumped parameter model, oil temperature of previous node outlet is same to the last node inlet. Then the heat transfer between hydraulic components can just be modeled by connecting them together by hydraulic lines in AMESim.[2] The heat transferred between motors and pump is neglected because it is a small proportion.

Thermal modelling of heat generated by motor work

The pump has a BLDCM and a DC servo motor to drive it. The two motors can be modeled in a same approach. There are two main types of heat generated by motors, conduction losses and mechanical friction losses.[1] The AMESim model is shown in figure 6.

Figure 6: model of heat generated by motor



The related mathematical expressions are:

$$W_{mc} = R_a \cdot I_a^2 \quad (5)$$
$$W_{mm} = n \cdot k \cdot M \cdot \omega \quad (6)$$

W_{mc} is the power dissipated by the armature current flowing through armature resistance,
R_a is the armature winding resistance,
I_a is the armature winding input current,
W_{mm} is the mechanical friction losses,
n is the conversion ratio,
k is the mechanical efficiency,
M is the shaft torque,
ω is the shaft speed.

Thermal modelling of heat generated by pump work

There are four main types of losses for a piston pump

1. Mechanical friction losses
2. Piston leakage losses
3. Piston shoe leakage losses
4. Valveplate leakage losses

The model of mechanical friction losses by pump is same to the motor. The other three types of losses are described in each piston model. Piston leakage and piston shoe leakage losses are modeled as figure 7 and both built as supercomponents in figure 8. In the complete EHA-VPVM model, piston and piston shoe are connected together. A thermal-hydraulic capacity or volume model is added to them to represent piston volume.[8-10] The related mathematical expressions are:

$\mathrm{dm2} = (p_1 - p_2)\frac{\pi \cdot dp \cdot cr^3}{12 \cdot \mu \cdot lc}\rho(p, T_{up})$ (7)

$\mathrm{dmh2} = \mathrm{dm2} \times \mathrm{h}(\mathrm{p}, T_{up})$ (8)

$\mathrm{dm2}$ is the mass flow rate at outlet,
$\mathrm{dmh2}$ is the enthalpy flow rate at outlet,
$\mathrm{h}(\mathrm{p}, T_{up})$ is the is the enthalpy at pressure p and upstream temperature T_{up},
p_1,p_2 is the absolute pressure at inlet and outlet,
dp is the external piston diameter,
lc is the length of contact,
μ is the absolute viscosity,
cr is the half of clearance on diameter,
$\rho(p, T_{up})$ is the density at pressure p and upstream temperature T_{up}.

Figure 7: thermal model with dynamics of piston and piston shoe

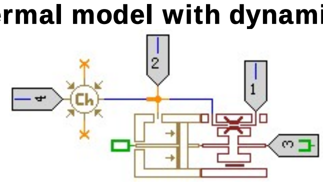
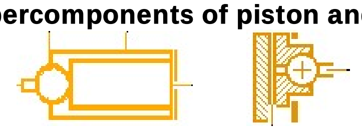


Figure 8: supercomponents of piston and piston shoe

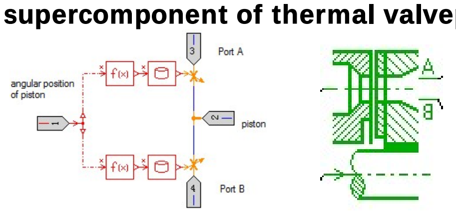


Valveplate leakage loss is modeled by a variable thermal-hydraulic orifice AMESim submodel in figure 9 and is built as a supercomponent. The related mathematical expressions is:

$T_{out} = T_{in} + v(1 - \alpha \cdot T_{in}) \cdot |\Delta p|/cp$ (9)

T_{out} is the outlet temperature,
T_{in} is the inlet temperature,
v is the specific volume of the fluid,
α is the volumetric expansion coefficient of the liquid,
$\Delta\mathrm{p}$ is the pressure differential in the restriction,
cp is the specific heat of the fluid.

Figure 9: model and supercomponent of thermal valveplate with dynamics



Thermal modelling of heat generated by cylinder work

There are two main types of losses for a cylinder

1. Mechanical friction losses
2. Piston leakage losses

The model of mechanical friction losses by cylinder is same to the motor and the model of piston leakage losses is same to the pump.

Thermal modelling of manifold with accumulator

Under normal operation, checkvalves, pressure relief valves and accumulator are not used. Therefore, these components are modeled as thermal-hydraulic capacity or volumes by AMESim submodels.

Dynamic modelling of EHA-VPVM

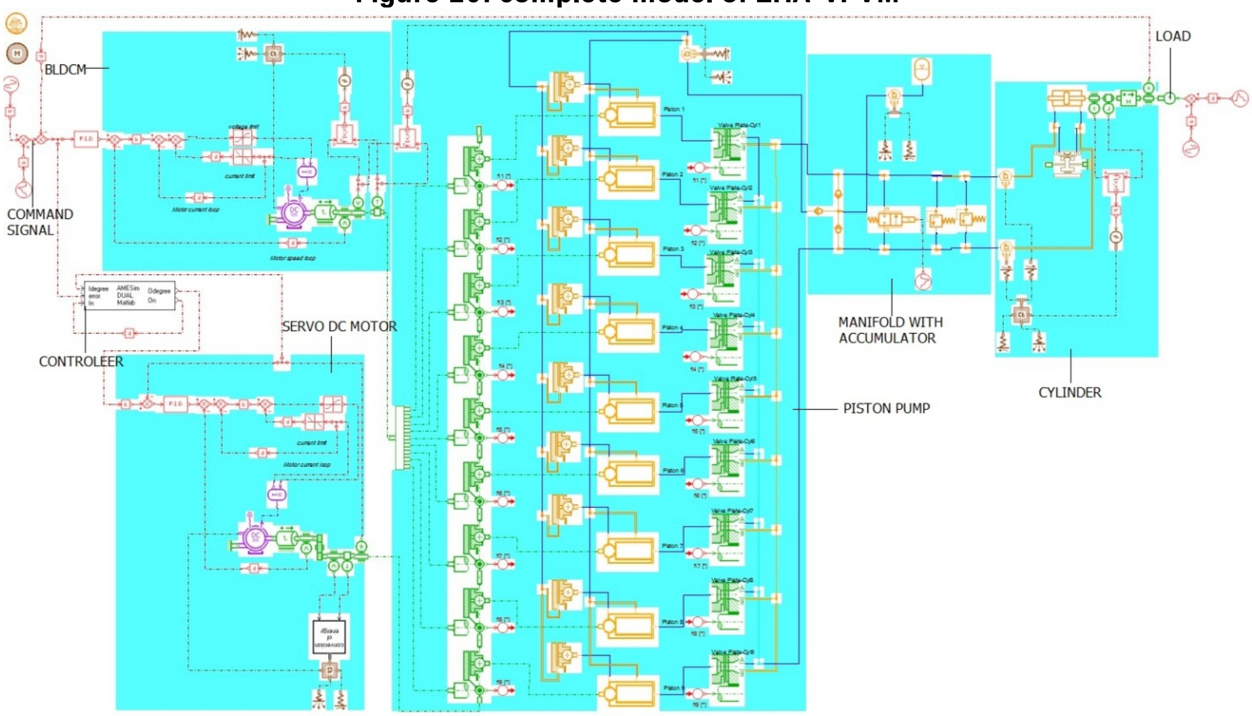
A dynamic model of EHA-VPVM was established before. The technique can be referred to [11].

Thermal modelling of complete EHA-VPVM

The complete model is based on components architecture. Above, the dynamic model of each part has been completed. Then, add thermal properties to dynamic model. At last, put each part together, the entire EHA-VPVM model is achieved. The model ports of each part for connected together should have same variables and one is as input, the other is as output. The complete EHA-VPVM model is shown in figure 10. It has 8 parts to represent related component of EHA.

This EHA prototype uses a controller to achieve higher efficiency and dynamic performance through regulating the two drive motor at same time. The AMESim model employs a Simulink block to imitate the controller.

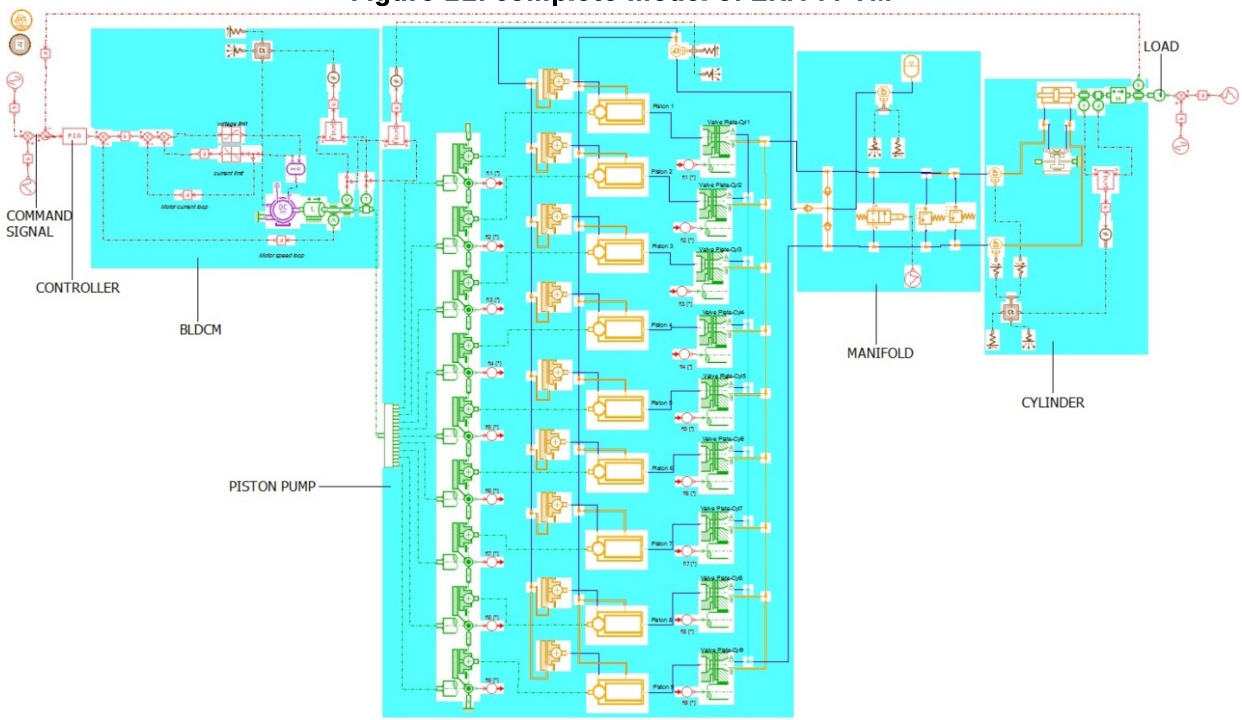
Figure 10: complete model of EHA-VPVM



3.2 Thermal Modeling of EHA-FPVM

Since a dual EHA prototype was developed, the performance differences among EHA-VPVM, EHA-FPVM and EHA-VPFM are easy to assessed. By keeping the pump displacement control motor stall, the dual EHA can operate as a EHA-FPVM. So, a EHA-FPVM thermal model can be achieved through removing the pump displacement control motor and keeping the pump displacement fixed. In order to compare the thermal characteristics between EHA-VPVM and EHA-FPVM, the pump displacement of EHA-FPVM is set maximum and other parameters are same to EHA-VPVM. The model of EHA-FPVM is shown in figure 11.

Figure 11: complete model of EHA-FPVM

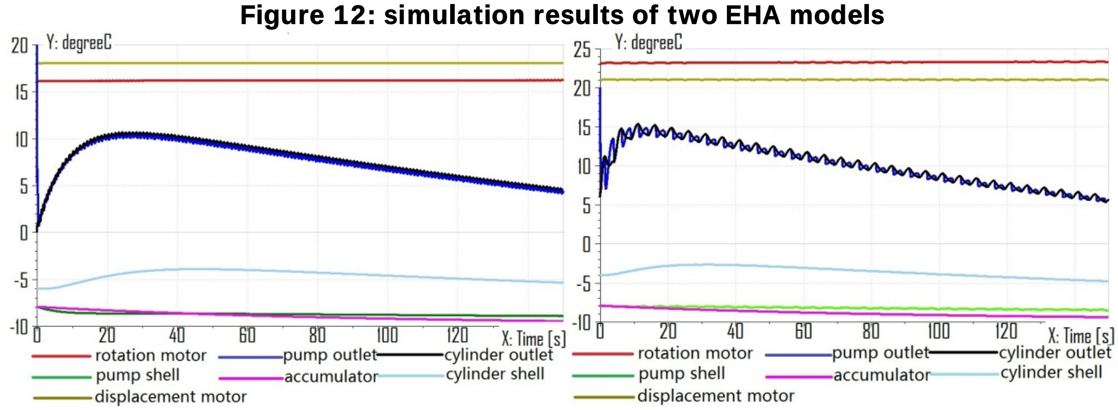


4 SIMULATIONS

This paper mainly talked about the EHA prototype thermal properties when it operates the whole envelope. But it is time consuming if a whole flight envelope is simulated. So a representative work cycle which can instead of the whole flight envelope is preferred. Then a simulation conditions is set as below for two EHA models:

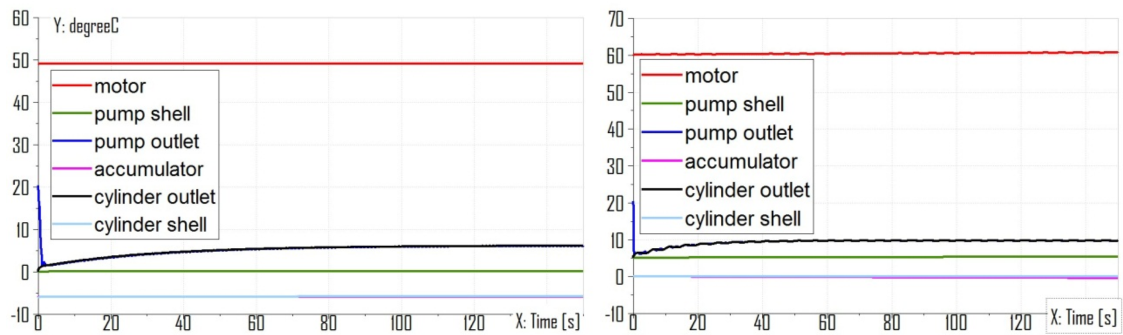
1. A cruise condition enough long is going at beginning until EHA maintains a thermal steady state
2. A condition equivalent to taking off or landing when EHA operates heavily goes on until EHA changes to a new thermal state

Figure 12: simulation results of two EHA models



PHASE 1 **PHASE 2**

EHA-VPVM



PHASE 1 **PHASE 2**

EHA-FPVM

The simulation results are summarized in figure 12. The temperature of each test node in phase 2 is higher than phase 1 as expected. When works in VPVM mode, EHA reaches 24$^{\circ}C$ as the highest temperature. When works in FPVM mode, EHA reaches 70$^{\circ}C$ as the highest temperature. In each simulation, the hottest node is the motor, the coolest node is the accumulator.

The transmission ratio from motor shaft to cylinder varies when pump displacement changes. So the percentage of two kinds motor losses can be controlled in EHA-VPVM. Since the motor produces the most heat, EHA-VPVM controller tries to make the motor total losses smallest when EHA works in a relatively stable state. When aircraft surface requests fast response, the controller will put dynamic performance at first place. Then, the EHA-VPVM can maintain a much lower motor temperature than EHA-FPVM.

5 CONCLUSION

This paper presents the thermal modeling and simulation of EHA prototype based on C919X aileron with AMESim. Thermal characteristics when operating whole flight envelope is achieved. Thermal characteristics differences between EHA-VPVM and EHA-FPVM are obtained due to the dual-variable structure of the EHA prototype. Simulation results show that the thermal properties of two kinds of EHA meet operating requirements of the aircraft. Thermal characteristics of EHA-VPVM is more outstanding attribute to flexible control mode and optimization control algorithm of heating.

But some parts of the thermal model are simplified and some important parameters are difficult to obtain so that empirical coefficients are used to instead of the actual parameters. More accurate modelling with the aid of experiment is on the way. In addition, EHAs are modeled with the method of lumped parameter. Distributed parameter modelling is necessary in order to predict the accurate thermal characteristics of EHA.

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NOMENCLATURE

EHA	electro-hydrostatic-actuator
COMAC	Commercial Aircraft Corporation of China, Ltd.
EHA-VPVM	EHA with variable pump and variable motor
EHA-FPVM	EHA with fixed pump and variable motor
EHA-VPFM	EHA with variable pump and fixed motor
BLDCM	Brushless DC Motor
LVDT	Linear Variable Differential Transformer