A Position Synchronization Control for Dual Redundant Electro-mechanical Actuation in Flight Control System

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Abstract. The paper develops a position synchronization controller for a new active/active dual redundant electro-mechanical actuation system and designs a test platform to validate the performance of the controller. The mathematic models of the position synchronization system are firstly built based on the schematic of the active/active dual redundant electro-mechanical actuation system. The position controller for DEMA and GEMA of is developed based on the velocity and acceleration feed forward and traditional PID theory. A series of motion experiments are carried out to verify the effectiveness of the controller design for active/active dual redundant electro-mechanical actuation system. The experiments results show that the position controllers designed for either DEMA or GEMA are satisfied, the biggest following error is not more than 0.1mm. And the synchronous motion tests show that the PI plus Output Saturation feedback position synchronization control can reduce more than 30 percent synchronous position errors. Furthermore, the tests of position synchronization show that EMA stiffness has a big influence on the synchronous precision. The new position synchronization controller designed based on the accurate system model and actual system parameters can better achieve the position synchronization requirements of the dual redundant EMA system, which makes good sense for redundant systems.

1. Introduction
One hundred years ago, on December 17, 1903, the Wright brothers, Orville and Wilbur, invented and built the world’s first successful aircraft and made the first controlled, powered and sustained heavier-than-air human flight [1]. From then on, human have produced thousands of various aircrafts, which have greatly changed the world. The aircraft is a complex vehicle flying on air and composed by three main parts: airframe, engine and on board systems [2]. The flight control system belongs to this on board systems and is powered by the hydraulic and electric ones. It is divided into primary level and secondary level. It is in charge of controlling the aircraft attitude (the yaw axis by rudders, pitch axis by elevators and roll axis by ailerons) and aerodynamic configuration (the high lift by slats and flaps, trim by trimmable horizontal stabiliser and the air brake spoilers and some special surfaces) by moving the flight control surfaces [3][4].

Due to the maturity and power density of the hydraulic technology, conventional hydraulic power has been widely used to actuate the actuators in the past 50 years. In this technology, the power energy is given to the fluid by increasing its working pressure (now up to 35MPa), and is transmitted by mass transfer (Power-by-Pipes, PbP). This has a good advantage of taking away the heat generated by power losses, however, this induces many engineering constraints and makes the maintenance cost keep high. The current development aim in aviation is to make large commercial aircraft be cheaper,
safer and greener. The more electrical aircraft (MEA) can offer many potential advantage in terms of performance, maintenance, integration, reconfiguration, ease of operation and management of power[5]. Electrical powered (Power-by-Wire, PbW) actuation system is considered by aircraft makers as an important means to achieve the MEA goals. Electro-mechanical actuation (EMA) as one of the most important technology of electrical powered actuation (EPA) system is introduced in the new generation of aircraft in replacement of the conventional PbP actuation [6] and is gradually used widely. In 2011, Boeing not only introduced electro-mechanical actuator (EMA) for spoilers (4 out of 14) for the B787 to fulfil the spoiler actuation function in case of loss of hydraulic power, but also for the THS [7]. Also in 2011, another big aircraft manufacture Airbus introduced EMA for a civil aircraft aileron on the A320 MSN1 F2675. Until June, 2012, the EMA has successfully completed 38 flight cycles and 114 hours without any failure alarm [8]. As electro-hydraulic actuation (EHA) is considered as the transitional form of EPA to EMA, the EMA will be introduced more and more into the primary flight control system.

As a safety critical application, the primary flight control system is strictly required to have a very good performance on statics, dynamics and reliability. For the primary flight control system, redundant actuators are generally employed to drive a common surface; for the secondary flight control system, one actuator with internally redundant arrangements is used for each function [9]. The existing redundant actuation configurations and their properties and applications are Parallel Force/Position Summing, Tandem Force/Position Summing and Speed Summing. The parallel force/position summing configuration is a common choice for the primary flight control system on commercial airliners. But in most cases they operate on active/active mode, the force fighting between actuators in parallel force summing configuration is serious and must be addressed. However, there is no force fighting in the parallel position summing configuration [9] which is suitable for all kinds of actuator. In this research, the redundant actuators composed by two different EMAs are selected to be studied in present research.

This thesis is proposed to address the position synchronization issue of a hybrid electro-mechanical actuation system. The test platform of the system is designed. In section 2, the motion of the redundant system is analysed, and then the nonlinear mathematic model of the system is built. The schematic of the synchronization strategy is given. In section 3, the virtual model of the system is built in the AMESim virtual environment, and the performance of the synchronization strategies is pre-validated in this virtual environment. In Section 4, the experimental design and parameter setup is given. In section 5, a series of motion experiments are carried out. The performance of the controller with and without synchronization strategies are verified by the synchronous motion experiments. The influences of system stiffness of the redundant system are also investigated. The present work is concluded and an outlook over the further improvements and perspectives is provided in Section 6.

2. Modelling and analysis of the synchronous motion system

In order to model the position synchronous configuration, first, models for the two actuators are presented, which will be connected with a model for the control surface structure. The schematic of synchronous motion system is presented in Fig. 1.

![Figure 1. The schematic of synchronous system.](image-url)
The synchronous motion system researched in this paper includes two EMAs which combine PMSM motor driving an inverted planetary roller-screw (PRS). The system is balanced with both EMAs working together as one EMA is driven to extend the other is counter driven to retract. The system is generally in one of three conditions: ACTIVE, when the system is in operation and STAND-BY when the control system is powered-up but the motors are isolated or AUXILIARY when only one EMA is actuating the flight control surface. The two employee are different types of EMA. Depending on the type of drive, linear EMAs can be divided into two types: gear drive and direct drive, shown in the Fig. 2.

![Figure 2. Type of the linear EMA.](image)

The gear drive type of linear EMA comprises a single PMSM motor that drives through a transfer spur gear train, (1:1 ratio gearbox that is incorporated due to the size envelope restrictions). The gearbox is lubricated and sealed for the duration of the proposed trial fit programme. The gear train drives into a planetary roller screw and by earthing the roller screw nut assembly the rotational energy is transferred into linear force acting on the output rod. This structure needs all the separate parts to be under good performance. This can be used in the field without space limit. However, the direct drive EMA eliminates the gear reducer and timing belt. The screw nut is compacted with motor rotor. This design makes the EMA be much smaller and more independent than traditional rotary to linear conversion mechanisms. The linear EMA in the Fig. 3 is an actual product made of Exlar company. Other company like SKF can also produce this kind of EMA.

![Figure 3. Linear actuators with integrated motor.](image)

The reversible planetary roller screw (PRS) is preferred to ball screw in the compact EMA, firstly because the roller screw has higher loading carrying capacities and better stiffness. For another reason, the PRS has a near 15 times greater life time than ball screw, with the same other condition. Though the PRS EMA has many advantages, its structure becomes complicated. There are many work still need to be done, such as system modelling, friction analysis.

2.1. Modeling of the electro-mechanical actuation
As is shown, in the Fig. 4, the model of EMA comprises a nonlinear description of a velocity controlled PMSM, while inner loop is a current controlled loop, and a model of mechanical transmission kinematics including a gear box (or direct drive) and a roller-screw [10-11] actuator, with position and speed controlled in the outer loop.
For the description and vector control of the motor dynamics, current and voltage are transformed from the 3-phase system to the direct and quadratic axis of the rotor by the Park-transformation. The transformation matrix is written as [12-13]:

\[
C_h(\theta) = \begin{bmatrix}
\cos \theta & -\sin \theta & 1 \\
\cos(\theta - 120^\circ) & -\sin(\theta - 120^\circ) & 1 \\
\cos(\theta + 120^\circ) & -\sin(\theta + 120^\circ) & 1
\end{bmatrix}
\]  

(1)

Electromagnetic torque equation of the BLDM can be written as:

\[
T_e = \frac{3}{2}n_p \Psi_r i_q + \frac{3}{2}n_p (L_d - L_q)i_d i_q
\]

(2)

Where \( L_q, L_d \) is the inductance in q-axis or d-axis, \( i_d, i_q \) is the current in q-axis or d-axis, \( n_p \) is the number of pairs of poles \( t \), and \( \Psi_p \) is the magnetic flux of the permanent magnet. Considering the nonlinear friction and external disturbances, the torque balance at motor shaft can be derived as:

\[
T_e + T_f(t) = T_L + J\ddot{\theta}_m + T_m(\omega_m)
\]

(3)

Where \( T_e \) is the motor electrical output torque \([N \cdot m]\), \( T_d \) is total external disturbance \([N \cdot m]\), \( T_L \) is the effective torque on the screw \([N \cdot m]\), \( T_f \) is the nonlinear friction torque \([N \cdot m]\) including static friction torque, Coulomb friction torque and Stribeck effect friction torque, \( J \) is total rotary inertia in motor side \([kg \cdot m^2]\), \( \theta_m \) is motor angular position \([rad]\) and \( \omega_m \) is motor angular velocity \([rad/s]\).

As is known, roller-screw transfers the rotational power into translational form though:

\[
k_{ema} = 2\pi / P_{rs}
\]

(4)

Where \( k_{ema} \) is drive ratio and \( P_{rs} \) is roller-crew lead \([mm]\).

Considering the direction dependent efficiency \( \eta_{ema} \), which represents the efficiency of the gearbox and the roller-screw, and external load force \( F_{ema} \) \([N]\), the torque balance at roller-screw can be derived as:

\[
F_n = m_{ema} \ddot{x}_{ema} + F_{ema}
\]

(5)

Where \( m_{ema} \) is equivalent mass of the roller-screw and surface \([Kg]\) and \( F_n \) is the roller-screw input force, which can be written as:

\[
F_n = \eta_{ema} k_{ema} T_f R
\]

(6)

Where R is gearbox ratio \([dimensionless]\).
The Laplace transformation of upper seven equations is done to get the prototype of EMA, as shown in Fig. 5.

In Fig. 5, it can be found out that the EMA system is structured by two parts. One part is the EMA which is made up of one PMSM and one reducing mechanism roller-screw. The inputs of this part are the reference torque command $T_m$, the rod moving speed $\dot{x}_{ema}$ and acceleration $\ddot{x}_{ema}$. And the output is the force, $F_n$ generated by EMA. Another part is the air surface which can influence the aerodynamic characteristics of airplane, the inputs of this part are the EMA output force $F_n$ and the external load force $F_{ema}$, and the outputs are the air surface moving displacement $x_{ema}$, speed $\dot{x}_{ema}$ and acceleration $\ddot{x}_{ema}$. The joint between rod and the air surface can be looked as rigid, so the displacement, speed and acceleration of rod are equal to the ones of air surface.

2.2. Modeling of control surface structure

The control surface structure is modelled as a mass, representing the surface inertia $J$, and equal attachment stiffness $c_s$ and damping $d_s$ for two EMAs. The inputs are EMAs displacements $x_{ema}$ and $x_{dem}$, as well as the external air loads $F_{air}$. The outputs are the control surface angel $\theta_s$ and the forces acting on the EMAs $F_{gema}$ and $F_{dema}$. The equation is thus derived as:

$$J_s \ddot{\theta}_s = F_{gema} R_{ema} \cos \theta_s + F_{dema} R_{ema} \cos \theta_s - F_{air} R_s$$  \hspace{1cm} (7)
$$F_{gema} = c_s (x_{gema} - x_s) + d_s (\dot{x}_{gema} - \dot{x}_s)$$  \hspace{1cm} (8)
$$F_{dema} = c_s (x_{dem} - x_s) + d_s (\dot{x}_{gema} - \dot{x}_s)$$  \hspace{1cm} (9)

Where $x_{gema} = x_{ema} = R_{ema} \sin \theta_s$, $x_s = R_{ema} \cos \theta_s$.

The equation (7), (8) and (9) show that surface stiffness has an influence on the kinetic characteristic. In fact, the system stiffness bring lots of problems for the redundant system, like force fighting, out of synchronization and limit cycle. The experiments carried out in the next section shows something on this aspect.

2.3. Modeling of synchronous motion system

The controller of the synchronous motion system is realized by IPC, which can be used to simulate the FCC (flight control computer). The outputs range of the force and encoder sensors are +/-10VDC. They are collected by Target Controller. The output range of IPC board are also +/-10VDC, which are calculated by the IPC basing on the synchronous control strategy. The position command is separately sent to GEMA and DMEA controllers. The GEMA and DEMA controller complete the GEMA and DEMA control. The analog output from Target controller includes velocity, position and torque demand. The current and velocity message are sent back to the Target controller, as well as errors and status information. The schematic block of the synchronous motion system is shown in the Fig. 6.
Based on the models of the single channel of EMA and control surface, the dynamic mathematic model of the synchronous motion system of EMAs can be derived. The structure diagram of the synchronous motion system without controller is shown as Fig. 7.

It is shown in the Fig. 7 that there are three parts in this synchronous motion system, EMAS part, Compliance part and control surface part. Based on the different parameter, every EMA has its own controller, the controllers are designed and validated in the following tests. In the compliance part, the compliances between EMA and control surface are assumed as the same, but because of the differences of the structure and mechanical connection of the EMA, the value is different. And this has a big influence on the system synchronization accuracy, which will also be validated in the following test. External variables are target position command $X_r$ and external load $F_{air}$.  

3. Experiment setup
For carrying out the research, a hybrid actuation test bench composed one DEMA and one GEMA is designed and employed. The test bench was built for evaluating the motion behaviors of the two EMAs and placed in the Fluid Power Transmission and Control Research Center of SMEA, BUAA.
Beijing, China, as shown in Fig. 8. The test bench will be used to demonstrate the performance of redundant actuation system in laboratory environment as the level 4 of technology readiness level. The position synchronization control force strategies to be proposed will be validated on this test bench.

3.1. Mechanical Configuration
The test bench includes one DEMA and one GEMA which both combine a PMSM motor driving a planetary roller-screw (PRS). There is a gear box in the GEMA driving screw to do rotary motion, while the DEMA eliminates the gear reducer, the screw nut is compacted with motor rotor, as is shown in Fig. 8 and Fig. 1. One swing mechanism with two joint bearing connecting end is used to connect the two EMAs. This swing iron lump can rotates around the central axis, driven by these two EMAs. The ellipse iron lump is used to the surface, especially the inertia. The stand bar between the EMAs is used for supporting the rotating shaft and tailstock. The EMAs are fixed on the bench by two anchorages, which can simulate the linkage compliance to airframe and their value can be adjusted based on requirements. In addition two force sensors are installed on the rod end of actuators to measure their output forces, and angle sensor is stalled on the rotating shaft. The two EMA are fixed in symmetrical position, one push and one pull to position the load, like the parallel arrangement, the system performances are quite similar. The results got on this test bench can be applied on other parallel arrangement redundant actuation system. Meanwhile, this arrangement can also be used to study the single actuator’s property. In case one actuator is studied, the other one can be force controlled to simulate the air load. The following table summarizes the main properties of test bench:

|            | GEMA       | DEMA       | Load                  |
|------------|------------|------------|-----------------------|
| Stroke     | 200mm      | Stroke     | 200mm                 |
| Max Speed  | 149mm/s    | Max Speed  | 127mm/s               |
| Max Force  | 47KN       | Max Force  | 17KN                  |
| Supply Voltage | 380V/12A | Supply Voltage | 380V/6A               |

3.2. Electric Architecture
The schematic of electric system is presented in Fig. 6. The IPC connected to test platform is not inside the control loop. It is in charge of some offline programming, parameter setting and data collection. The control laws are designed in the Matlab/Simulink simulation environment on IPC, and then downloaded to be executed on the target controller. Meanwhile the experiments results stored in target controller target can be uploaded to IPC. All the data transmission between target controller and IPC is on the basis of TCP/IP protocol. And the data transmission between IPC and controller is on the basis of RS232 protocol.
3.3. System performance Requirements
For the studied active/active position control redundant actuation system, the objective of thesis is designing the position controllers with synchronization for DEMA and GEMA to ensure that the following performances can be obtained:

- Position controller of each EMA performance: position tracking error of each EMA is smaller than 0.5mm;
- Position synchronization controller performance: position synchronization error of the actual position is smaller than 0.5mm;
- Segregation: the cross links between channels should be minimized and limited to ensure the immunity against failure propagation from one channel to another channel;
- Complexity: the strategy needs short computation time and few numbers of sensors.

4. Test result and analysis
4.1. DEMA controller performance
To validate the DEMA controller performance, two groups of experiments have been done. The frequency are 1Hz and 5Hz, and the amplitude utilized decreases from 3mm to 1mm. The schematic of the DEMA controller is shown in the Fig. 9. The velocity and acceleration feed forward, as well as PID are served in the DEMA controller. The proportional, integral and differential gains are 26.87, 296.3 and 0.001, while the velocity and acceleration gains are 0.746 and 0.006.

![Figure 9. The schematic of the DEMA controller.](image)

The sine position tracking performance of the controller obtained from the test is shown in the Fig. 10. In the Fig. 10 above, the position error following the sine target position (3mm, 1Hz) is nearly zero, the result is very good. However, with the frequency increased to 5 Hz, the following error come about, up to 0.1mm. To be sure, this follow error is acceptable, compared to the system synchronization requirements 0.5mm.

![Figure 10. Sine tracking curve of DEMA under different frequency and amplitude.](image)
4.2. GEMA controller performance
To validate the GEMA controller performance, two groups of experiments have been carried out. The sine target position signal is the same as DEMA. Because there are many differences between GEMA and DEMA in the aspect of transmission mode, mechanical and electrical parameters, the different controller gains are chosen in FEMA controller. The proportional, integral and differential gains are 22, 202.8 and 0.002, while the velocity and acceleration gains are 0.6687 and 0.0025. Under the different sine signal, 1mm amplitude and 5Hz frequency, 3mm amplitude and 1Hz frequency, the performance of the FEMA is satisfied, shown in the Fig. 11.

As is shown in the Fig. 11 (below), the actual following error is small that it can only discovered under enlarged view.

4.3. Position synchronization controller performance
The schematic of the position synchronization motion system without synchronization controller is shown in Fig. 12.

Depending on the good control performance of the GEMA and DEMA controllers, the actual position tracking result of the two EMAs, without synchronization controller, are shown in Fig. 13. The 10mm position command is separately given to these two EMAs at the same time. From this plot, it shows that DEMA and GEMA almost move together. The asynchronization obviously happens at the beginning of stretch out and draw back moment. The static synchronization errors around 0mm position are unstable, while 10mm position is relatively constant.
The actual position difference between these two EMAs is shown in the Fig. 14. The biggest synchronization error is nearly 0.03 mm, refer to the red curve in Fig. 14. From the Fig. 14, we discover that the tracking error from the DEMA (blue curve) make a big contribution to the synchronization error, as much as above 90 percent. However, the tracking error from GEMA is so small that nearly can be ignored.

To improve position synchronization accuracy of the active/active redundant EMA system, the synchronization controller is designed. The schematic of the controller is shown in the Fig. 15. Because of the good position tracking performance of GEMA, the controller makes the GEMA as reference position. DEMA, as a slave, synchronize the GEMA position. The position difference between GEMA and GEMA channel is \( \Delta = X_g - X_d \). The difference is used to compensate the position feedback \( \theta_g \) and \( \theta_d \). Then a proportional and integral controller is adopted before the compensation. Avoiding unnecessary and unforeseen overshoot feedback, a saturation output unit is employed, as is shown in the Fig. 15. The \( X_g \) and \( X_d \) are obtained from the surface angle encoder feedback \( \theta_{cs} \). The surface load is set to null.

Figure 13. Position synchronization curve without synchronization controller.

Figure 14. Position synchronization errors without synchronization controller.

Figure 15. Schematic of synchronization controller.
In this strategy, the position controllers designed for DEMA and GEMA in Fig. 9 are involved, so the only parameter to be valued is the proportional and integral gain for the synchronization controller. The synchronization control strategy should not alter the system performance on pursuit, rejection and stability. Theoretically, the larger the gains value, the faster the synchronization controller being synchronized. But the larger gains will worsen the system stability. So finally, a balance value should be selected. For choosing this value, several experiments are run on test bench. In the end, the proportional gain is $1.45 \times 10^{-6}$, and the integral gain is $1.1 \times 10^{-6}/s$. The position synchronization tracking curve gotten with this controller parameters is shown in Fig. 16. The 10mm relative position command is given to these two EMAs at the same time. From the Fig. 16, it shows that two EMA channels output almost the same position. There is no apparent error in Fig. 16. In fact, from the plot in Fig. 17, the biggest synchronization tracking error is 0.02mm. More than 30 percent of the error is reduced, compared with no synchronization controller.

![Figure 16. Synchronization tracking curve with synchronization controller.](image)

![Figure 17. Position tracking errors with synchronization controller.](image)

From the Fig. 14 and Fig. 17, it is easy to find that DEMA has a more tracking error relative to FEMA one. The DEMA deviation is 0.02mm, while GEMA is 0.0025mm, as are shown in the Fig. 17. They are not in the same order of magnitude. The big gap due to different load capacity. It means that FEMA has a bigger stiffness than DMEA. The force output of DEMA have almost no impact on the GEMA’s position tracking. In contrast, the DEMA’s position tracking accuracy is poor, due to the poor stiffness.

### 5. Conclusions and future work

In this paper, two EMA position controllers and a synchronization controller are designed, and an active/active redundant electro-mechanical actuation test system is developed to combine the DEMA and GEMA, realizing synchronous motion. A series of synchronous motion experiments are carried out to verify the effectiveness of the design of test system and the synchronization controller. The single channel motion experiments shows that the PID plus position and velocity feed forward controller is very effective for EMA position control. The biggest position tracking errors is 0.1mm. The good performance of these two controller is a firmer foundation for the synchronization controller design. The synchronous motion experimental results show that the synchronization controller can
achieve synchronous motion control function well, by decrease more than 30 percent synchronization error.

As future works, the EMA controller and synchronization controller will be verified in other electromechanical system, and a new active/active redundant electro-mechanical actuation test system will be employed as an experimental platform for further study on redundant electro-mechanical actuation system. Meanwhile, the attention will be put on the optimization design of system structure and controllers to further improve the active/active redundant electro-mechanical actuation test system performance. Moreover, influence of the stiffness from inner EMA and rod end mechanical connection is worth researching and solving. The appropriate control method should be adopted to achieve the function requirements for the flight control system. With the improvement of the performance active/active redundant electro-mechanical actuation system, this redundant EMA system can be not only expected to be used in the primary flight control system, but also navigation control, to accomplish aim of the more or all electric aircraft and ship.

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