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Integrated Compact Electrically Powered and Signaled Actuation Systems

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One of the key challenges in enabling More Electric Aircraft is the development of electrically powered servos that meet or exceed the performance, packaging, weight, and cost of a hydraulic fly-by-wire servo. This paper introduces an innovative Electro-Hydrostatic Actuator that outperforms the existing solutions in terms of mass, size and energy efficiency. The innovative design features hydraulic regeneration when the commanded movement is aligned with the direction of external force. This new feature helps to decrease energy consumption. The high efficiency of the actuator prototype is confirmed by simulation with a verified MATLAB/Simulink model. Simulations also manifest that the proposed actuator has improved phase and gain margins as compared to existing solutions.

I. Introduction

Undesired climate changes drive the desire of reducing carbon footprint in the aerospace industry. One of the viable solutions is creating greener air transport. 'More Electric Aircraft' and 'All-Electric Aircraft' concepts made the paradigm shift toward sustainable aviation operations. Significant efforts are being made to increase the use of electrical power networks for electrically supplied power users as a replacement for conventional hydraulic, pneumatic and mechanical power networks. However, the development of electrical-powered servos that meets or exceeds the performance, packaging and weight of a conventional actuation system is still a challenging problem.

Electro-Hydrostatic Actuator (EHA) is one of the electrical-powered proven solutions replacing the conventional hydraulic servo actuators (HSAs)[1]. The EHA has been tested on NASA's research vehicle, F-18 Systems Research Aircraft (SRA)[2] and also has been implemented on F-35 Joint Strike Fighter. This project INCEPSION (Integrated Compact Electrically Powered & Signalled Actuation Systems) aims to develop and test an ultra-compact electrically signaled and powered hydraulic flight control actuation system, which outweighs the current energy efficiency limitation by decoupling the peak output power from the power drawing from the supply. To analyze actuator performance and develop control system a high-fidelity MATLAB/Simulink model was developed. The performed analysis revealed that proposed design outperforms existing solutions in terms of mass, size, energy-efficiency and has improved phase and gain margins.

The paper organized as follows. Sections II introduces INCEPSION concept; Section III demonstrates analysis of the actuator performance obtained based on the high-fidelity model. Section IV concludes the paper and discusses future steps.

II. Project INCEPSION

A. Overview

The size of the system is only 238 mm (including the jack port) $\times$ 185 mm $\times$ 73 mm with 7.5 kg of weight and its image is shown in Fig. 1 (200 mm for the blue arrow.) The product has only one-quarter the weight of the equivalent

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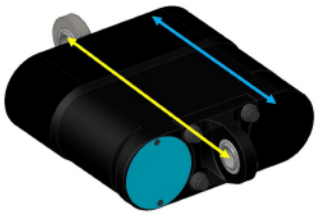


Fig. 1 Product image

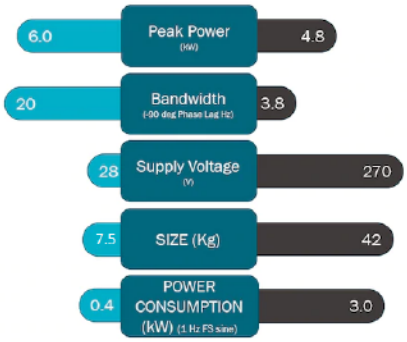


Fig. 2 Targeted design requirement (left) vs. Modern electro-mechanical benchmark (right)[4]

competitor because of its compact design and all elements in the system are housed and connected through a unitary Additive Manufacture (AM) part. Weight saving in aircraft components can be a big impact on fuel consumption of aircraft and emissions. If it is adopted on a civil aircraft, the product can save more than 8 kg per actuator, and with more than 40 such actuators per aircraft total weight savings can be significant (greater than 320kg). This has a noticeable impact on fuel burn and could save more than 60kg fuel per 1000km traveled [3]. The performance comparison chart is shown in Fig. 2. The power consumption is expected to be reduced from 3kW (1Hz Full Stroke sinewave) to 0.4 kW, and supply voltage from 270 V to 28 V. This advanced design also delivers five times of bandwidth of the existing actuator product and the actuator can also provide higher peak power to compensate high loading scenarios, e.g., during gust-alleviation.

To achieve targeted power consumption, INCEPSION adopts a first principles approach to actuation design based on energy use minimization. Fixed-wing aircraft flight control surfaces have a characteristic where the load is relatively constant irrespective of the direction of actuation. That is, the load has little hysteresis beyond the friction of the flight control bearings. Therefore, the net energy required to extend and retract the actuator is net zero. The INCEPSION actuator contains sufficient internal energy storage for full surface control against the maximum spring rate of the surface. The rate of that energy conversion (power) between the internal store and external load has little impact on the power required from the actuator aircraft supply, being a function of internal actuator architecture.

In this way, INCEPSION has two weight benefits. Firstly, the primary power transfer is through fluid which is significantly more compact than the equivalent electrical-powered actuators, EMA, and secondly reducing power supplied to the actuator enables weight savings across the aircraft by downsizing electrical power offtake, conversion, and distribution.

B. Internal Energy Harvest

As said, the internal energy storage mechanism plays a vital role to improve energy efficiency. The mechanism diagram is shown in Fig. 3. To realize the design, the element, Energy Switching Valve (ESV), has a prominent place.

The ESVs connecting with three different fluid channels and the pistons are utilized to rapidly transfer the fluid and the energy between three different fluid channels. The three fluid channels are the service line which connects with the actuator, the accumulator line, and the reservoir line, respectively. All of them can be either sources or sinks depending on the moving direction of the pistons.

Among three fluid channels, a high pressurized accumulator is used as a capacitor by restoring high pressurized fluid when the commanded movement is the same as the direction of external force (see (a) and (d) in Fig. 4). In the two scenarios, the harvesting mechanism is triggered. The fluid in the service line is pressurized by an external load, e.g., aerodynamic load on ailerons. The fluid possessing high potential energy fills the piston chamber through the ESV. Then, the fluid presses the piston stroke toward the bottom position. Next, the ESV switches to the accumulator while the piston stroke reaches the bottom of the piston. Finally, when the stroke goes upward, the pressurized fluid is restored in the accumulator for later usage.

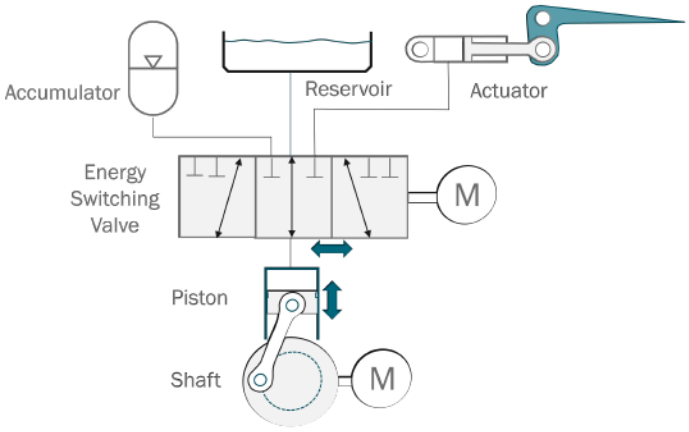


Fig. 3 The design concept

C. Full System Architecture

The system is designed to be operated at a higher bandwidth and be able to transfer the fluid continuously, therefore, 6 of ESVs, and 6 pistons are applied. The simplified full-scale system diagram can be seen in Fig. 5. Also, all the elements used are described in Table. 1. The 6 pistons with the 6 ESVs, and each 2 of the 6 pistons work in the same phase in respect of the stroke position in a piston. Hence, there are three phases in the systems with a 120-degree difference from the others. Each ESV can switch to different channels separately.

The number of operating ESVs can be proportional to the power demand. For instance, in the low energy consumption flight, e.g., level flight, only one or two ESVs need to be operated to compensate for the leakage loss and maintain the control surface in the same position; whereas six ESVs are activated to quickly move the control surface and/or withstand the intensive external aerodynamic load when flying in very gusty weather.

Apart from the elements seen in Fig. 3, two more elements are introduced in the final design, which are Main Control Valve (MCV) and Bootstrap Reservoir. MCV is the essential parts used to decide the direction of the actuator, i.e., extension or retraction. Bootstrap Reservoir, or self-pressurizing reservoirs, offers an "airless" fluid Reservoir and it is pressurized by Primary Accumulator.

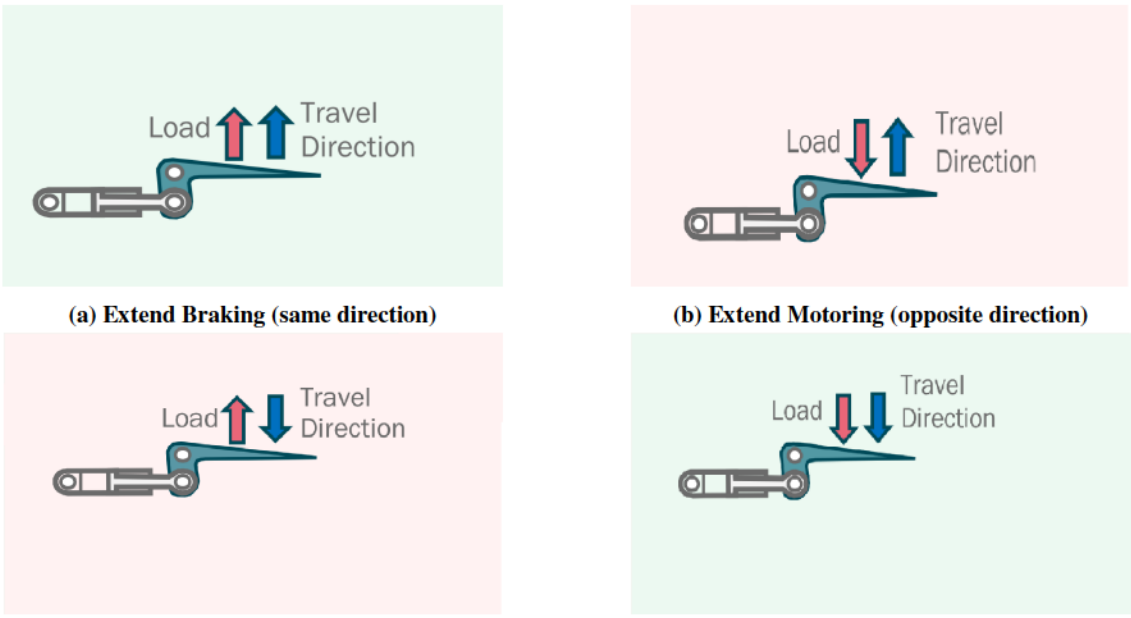
Table 1 The elements used in INCEPSION actuator

Name	Quantity	Elements connecting with
Motor	1	External electrical power, Shaft
Shaft	1	Motor, 6 pistons
Piston	6	Shaft, one ESV
Energy Switching Valve (ESV)	6	Three fluid channels, one piston
Main Control Valve (MCV)	1	Three fluid channels, two Accumulators, Reservoir, Actuator
Primary Accumulator	1	MCV, Reservoir
Actuator	1	MCV, Control Surface (excluded)
Bootstrap Reservoir	1	ESV, MCV, Primary Accumulator

III. Simulation, Control and Design Validation

A. Modeling

To verify actuator characteristics at the preliminary design, to find possible shortcomings of the design and to design the actuator controller, a high-fidelity model of the actuator is developed with MATLAB/Simulink. After developing and verifying the system model, the power loss factors including friction, viscosity, and leakage in the model have been introduced and simulated to find out the most ideal operating states and to design the controller.



(a) Extend Braking (same direction)

(b) Extend Motoring (opposite direction)

(c) Retract Motoring (opposite direction)

(d) Retract Braking (same direction)

Fig. 4 Four Quadrants Approach

B. Simulation and Efficiency Mapping

To design a system with minimum energy consumption, the energy efficiency in different operating conditions is investigated. In the efficiency mapping phase, the speed of the motor from 500 to 3000 RPM, pressure in the pipeline from 4MPa to 28 MPa, and the number of ESV are seen as critical factors to the system's efficiency. To find the power efficiency in different operating conditions the Eq. (1) to Eq. (3) are used. The efficiency is measured at different sets of the constant motor rotating speed. In the open-loop simulation, an adequate external torque maintaining the stable rev of motor speed, the additional mechanical power, needs to be provided to compensate for the power loss. The external torque is measured to fill the Eq. (3)

$$Efficiency(\eta) = \frac{Useful\ Output\ Power}{Total\ Input\ Power} = \frac{Fluid\ Power}{Fluid\ Power\ +\ Mechanical\ Power} \tag{1}$$

$$FluidPower = Pressure \times Flow\ Rate \tag{2}$$

$$MechanicalPower = Torque \times Angular\ Speed \tag{3}$$

The result of efficiency mapping is presented in Fig. 6. The highest efficiency, around 92%, takes place when all 6 ESVs are operating at 28MPa and 500 RPM of the motor speed. Conversely, the system has the lowest efficiency while only one ESV operating at 3000 RPM and pressure in the pipeline is at 4 MPa.

We can see that the efficiency is increasing with the growth of the pressure. On the other hand, the increasing RPM reduces the efficiency, as expected, because more mechanical friction loss per second is involved when angular displacement rises. Also, at the same motor speed and the same pressure condition, the more ESVs are activated, the higher efficiency becomes. This results from the mechanical power loss caused by the 6 pistons and their rolling caps are the identical, regardless of the number of the operating ESVs. Hence, the higher fluid rate increases the proportion of Fluid Power in Eq. (2)

C. Controller for INCEPSION

The system output is controlled by the primary electric motor, MCV or ESVs. Due to the system architecture, the controller is split into three sub-controllers shown in Fig. 7. They are Internal Energy Management System, Energy Supply and Efficiency Management System and Output Surface Controller, respectively. Internal Energy Management System mainly monitors the total stored energy in Primary Accumulator and activates the energy harvest mechanism

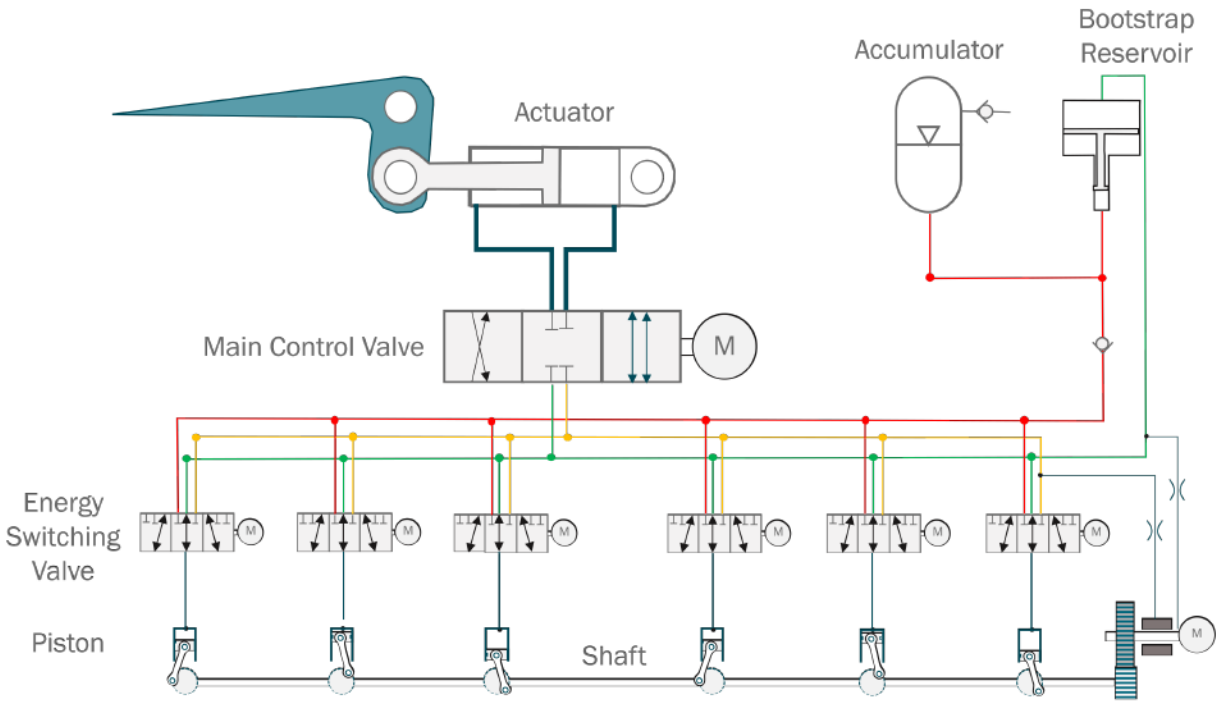


Fig. 5 The full schematic diagram

when conditions permitted; Energy Supply and Efficiency Management System ensures that the motor and shaft maintain sufficient kinetic energy in the shaft and decides the most efficient way to move the jack in the actuator; Output Surface Controller offers the positioning control which is the most important role for the system's performance.

Output Surface Controller determines the number of the piston(s) used to transfer the fluid to or from the reservoir depending on the quadrant status and the flow rate requirement. Basically, at a constant shaft speed, the number of ESV put in operation increases with the rise of the error between command signal and the current actuator position. The diagram showing the logic is in Fig. 8. The number of working ESV is proportionally increase to the the error between the command signal and the current actuator position. A closed loop step test result is displayed in Fig. 9 (The '0' signal for ESV means to connect with reservoir and '1' signal indicates connecting with service line). The system with the controller is also tested with sinusoidal commands in different frequencies to find out its responses in frequency domain. The result can be seen in Fig. 10. The other existing EHA and EMA (Electro-mechanical Actuators) performance from [5] is also presented in the same figure and the comparison shows that INCEPSION can outperform the existing technologies in electrical-powered actuators. INCEPSION only has a 30-degree phase lag at 5Hz while the existing solution has already reached 90-degree. The gain keeps being higher than the EHA over the observed frequency.

IV. Conclusion and Future Work

In summary, the high-efficient and light design are confirmed by the simulation result. It helps us to understand that innovative actuator design can achieve the requirements we set. Also, with the many duplicated sub-systems, such as 6 pistons and 6 ESVs in INCEPSION, the redundancy can be easily implemented in the system for sustainable aerospace.

The next step will be the hardware-in-the-loop test. This revolutionary architecture will be physically verified if the design can reset the paradigm of electronically powered actuators. Besides, two sub-control systems, Internal Energy Management and Energy Supply and Efficiency Management, are mentioned but not developed due to the time constrain. After the two are designed, with the positioning controller, three sub-controllers should be integrated and tested, eventually, work coherently together. This innovative design should be integrated with aircraft to test its reliability and final efficiency improvement.

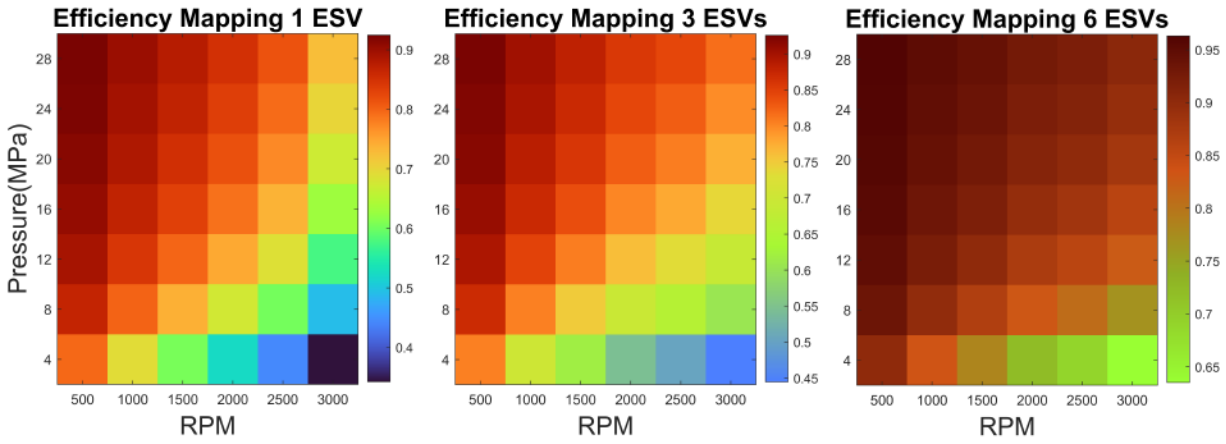


Fig. 6 Efficiency in different operating conditions

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References

[1] Qiao, G., Liu, G., Shi, Z., Wang, Y., Ma, S., and Lim, T. C., "A review of electromechanical actuators for More/All Electric aircraft systems," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, Vol. 232, No. 22, 2018, pp. 4128–4151. https://doi.org/10.1177/0954406217749869.

[2] Navarro, R., *Performance of an electro-hydrostatic actuator on the F-18 systems research aircraft*, NASA, Dryden Flight Research Center, 1997.

[3] Steinegger, R., *Fuel economy for aircraft operation as a function of weight and distance*, ZHAW Zürcher Hochschule, 2017. https://doi.org/10.21256/zhaw-3466.

[4] "Description of INCEPSION," https://domin.co/blogs/news/incepsion-grant-success, 2020. Last retrieved: 11 October 2021.

[5] Cooper, M. A., "Simulating Actuator Energy Ddemands of an Aircraft in Flight," Ph.D. thesis, Cranfield University, 2014.

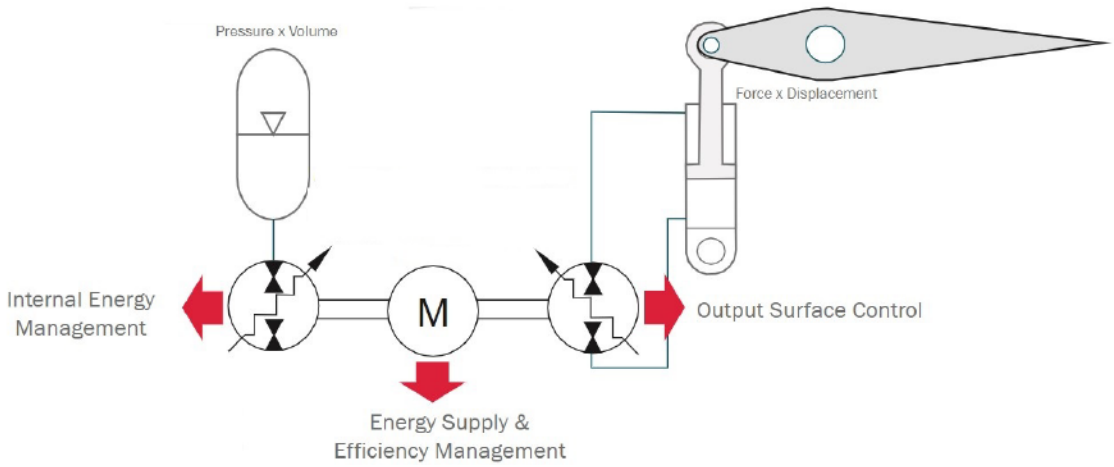


Fig. 7 Controlling tasks allocation

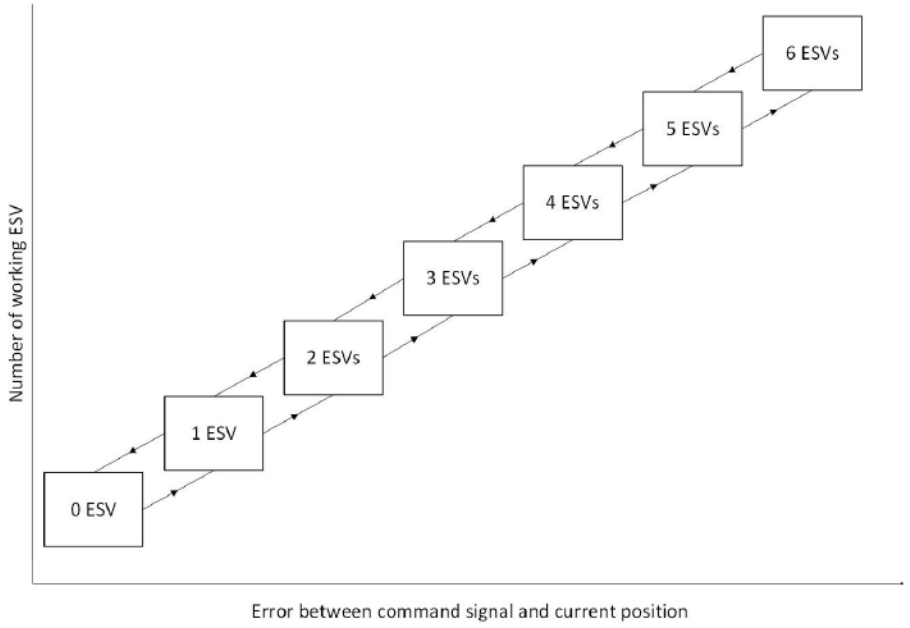


Fig. 8 Positioning controller logic diagram

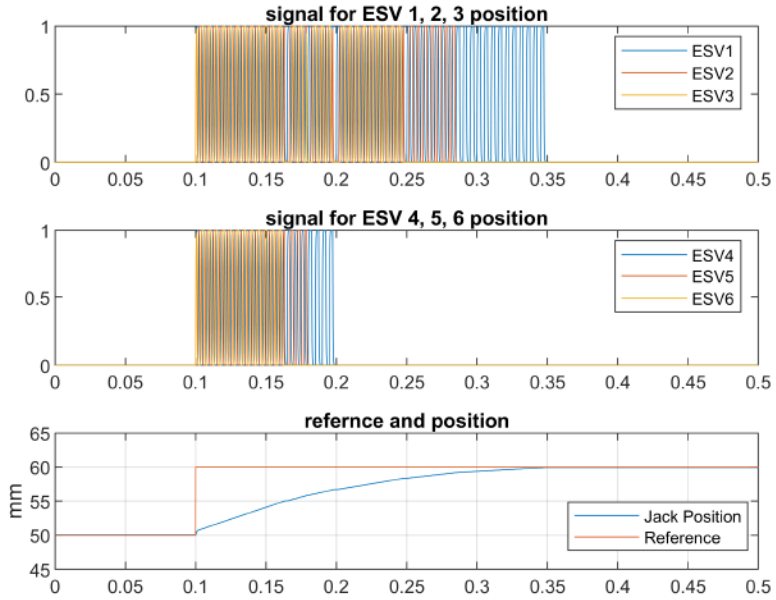


Fig. 9 10mm step response at time = 0.1(s)

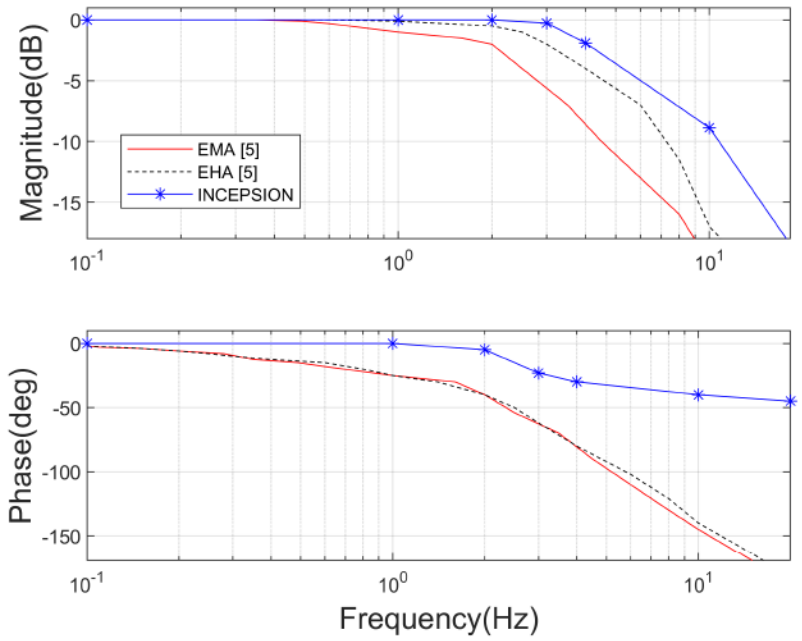


Fig. 10 Performance comparison in frequency domain



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