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# NONLINEAR PID CONTROLLER MODIFICATION OF THE ELECTROMECHANICAL ACTUATOR SYSTEM FOR AEROFIN CONTROL WITH A PWM CONTROLLED DC MOTOR

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**Abstract**. *In this paper, we investigate the control of an electromechanical actuator (EMA) system for aerofin control (AFC). The EMA is realized with permanent magnet brush DC motor controlled by constant current driver. Using nonlinear model of the EMA-AFC system that includes nonlinearities of the motor driver, a PID position controller is designed. In this paper we proposed the control algorithm modification in order to improve transient response of the EMA-AFC system. Motivation for this comes from experimental work with EMA-AFC testing system. Presented results show that the transient response and with modified PID controller are considerably better compared to those obtained with conventional PID position controller.*

**Keywords**: *Electromechanical actuator, Aerofin, DC motor, Current motor driver, PWM, PID control.*

## 1. INTRODUCTION

The use of electromechanical actuation is becoming increasingly popular in the aerospace industry as more importance is placed on maintainability. Electromechanical actuators (EMAs) are being used in the actuation of flight critical control surfaces and in thrust vector control. A good understanding of the dynamic properties of these actuators is critical in their successful application [1]. Before EMA are widely accepted by the aerospace community at large for flight-critical actuation, extensive research, development, and testing must be performed [2].

Direct current (DC) motors are used very often in the actuation systems of the aerodynamic surfaces. In previous research we considered an electromechanical actuator system for aerofin control (AFC) driven by permanent magnet brush DC motor. Before utilizing the control task, we were supposed to design the DC motor driver. For this application we

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developed the constant current motor driver. The idea was to pulse width modulate (PWM) the control signal, clipping it to maximum allowed current. Physical realization of such solution is usually simpler and cheaper than the conventional voltage driver.

For the purpose of studying plant's dynamic behavior and control synthesis, a SIMULINK model of the EMA-AFC systems has been developed, taking into account nonlinearities due to mechanical limitation of the fin deflection, limited motor torque and angular velocity, friction in gears and bearings, backlash in gears and crank mechanism, etc. These effects were possible to be studied by developing appropriate simulation model. Also, SIMULINK gave opportunity of efficient modeling of the current motor driver. Using the nonlinear simulation model, a PID controller for EMA-AFC system has been synthesized. Obtained results were validated experimentally using EMA-AFC testing system. It was shown that the model matches the real EMA-AFC system dynamics and it can be used for further investigation.

The purpose of this paper is to investigate improvement of the EMA-AFC system's response. According to simulation and experimental results, we realized that transient response could be improved by nonlinear modification the PID control algorithm.

Aerofin control (AFC) system, considered here, is the control of the missile using four grid fins. The grid fins configuration is presented in the Fig. 1. By deflecting them, moments are generated about the center of mass, which in turn rotate the airframe. The resulting incidence angles generate aerodynamic forces, which accelerate the vehicle in the desired direction [4].

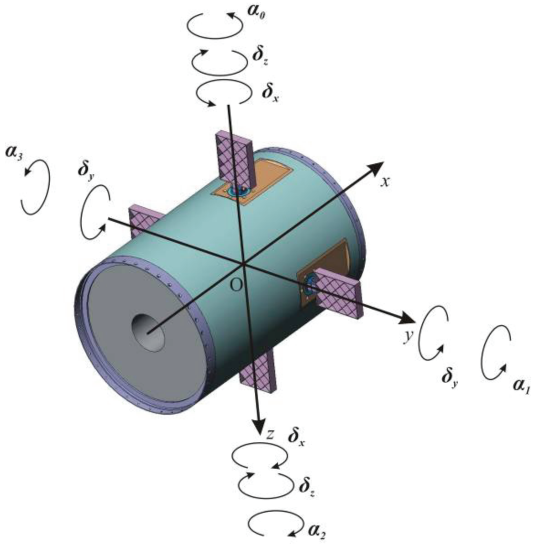

Fig. 1 AFC system

The missile autopilot sends roll, pitch, and yaw commands ($\delta_x$, $\delta_y$, and $\delta_z$) to the AFC system. Before they can be utilized, they have to be separated into individual fin commands, i.e. angles $\alpha_i$, where $i$=0,1,2,3. Each actuator module can convert the reference fin command $\alpha_{ir}$, into an actual surface deflection $\alpha_i$, $i$=0,1,2,3. Each actuator module requires tight, independent position control of the surface deflection, usually less then 10 degrees.

## 2. HARDWARE AND INSTRUMENTATION

Fig. 2 schematically illustrates the AFC testing system.

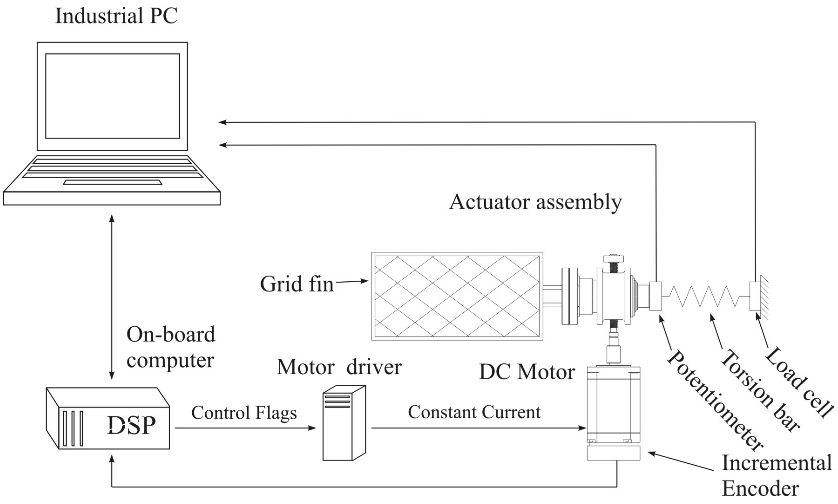

Fig. 2 EMA-AFC testing system

The actuator assembly consists of the Maxon RE 30 permanent magnet brush DC motor with integrated Maxon planetary gearhead GP 32 with a 3.7 to 1 reduction, which drives the screw shaft SRCW 10 x 3R with precision SKF roller nut SH 10 x 3 R. The actuator's assembly output shaft is connected to the roller nut via lever mechanism, driving the grid fin, see Fig. 3.

On the motor rear side, an incremental encoder is mounted and fixed to the rotor shaft. Incremental encoder is Maxon Encoder MR, Type M, with resolution of 256 pulses per revolution. Pulses from the encoder are forwarded to the control computer.

The control computer is an onboard computer (OBC), consisting of two digital signal-processing (DSP) modules based on Analog Devices ADSP-21065L processor. Namely, one DSP module is used for angle measurements, while the other realizes control algorithm. All electrical connections between the DSP modules in the OBC are via motherboard. The OBC is connected with the industrial PC via serial communication, providing bi-directional transfer of set points and acquisition data. Main control loop is performed on 2 KHz sampling rate, while serial communication with PC operates on 500 Hz. The OBC receives autopilot commands, converts them into individual fin angles, and, based on appropriate control algorithm calculates control. Control signal is pulse width modulated, and two flags are forwarded to the motor driver.

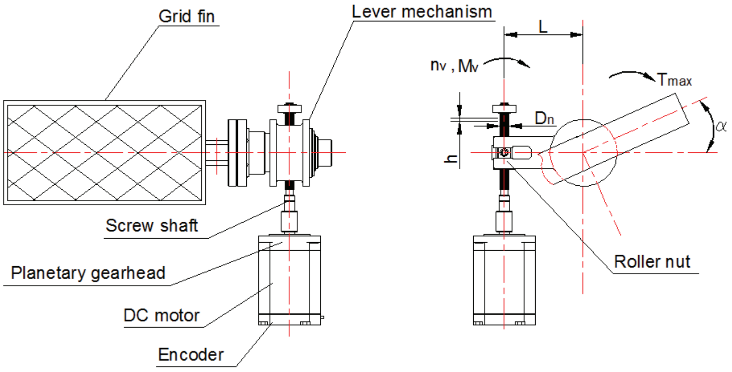

Fig. 3 Actuator assembly

As mentioned before, the motor driver has been designed to be simple and reliable. In order to be controlled, it needs one flag for enabling the current output, and another one for changing the current direction. The output current is adjustable, thus the driver can be used for different motors. Once, when the driver is enabled, the constant current, either positive or negative, supplies the motor, and the motor shaft rotates. The motor shaft is kept around zero by providing duty cycle around 50 percent. Since the maximum current supplies the motor always, both positive and negative, the rotor shaft oscillates around zero. Having in mind the large gear ratio in the actuator assembly, the magnitude of the oscillations is attenuated, and it is negligible compared to the gear backlash.

In order to simulate inertial load, the grid fin has been mounted on the actuator assembly. The calibrated torsion bar is connected to the opposite end of the output shaft, and cantilevered with the load cell to the test bench stand. The torsion bar is designed to produce load torque induced by the aerodynamic force. It has been calibrated to give maximum torque for maximum fin deflection angle, e.g. 10 deg. Actual fin angle deflection is measured by the potentiometer fixed to the output shaft. The industrial PC has acquired the load torque and deflection angle.

## 3. MODELING

Fig. 4 presents nonlinear mathematical model of the EMA-AFC. The model incorporates several nonlinear effects: gear backlash, static friction, motor shaft rate limiter and control current saturation.

Here, only the most important notes necessary for proper understanding of the model are briefly referred to.

Dynamics of the motor torque $T_m$ can be expressed by:

$$\frac{L_A}{R_A}\frac{\mathrm{d}T_m}{\mathrm{d}t}+T_m=\frac{K_M}{R_A}U_m-K_e\omega_m \tag{1}$$

where $R_A$ is armature resistance, :$L_A$ is armature inductance. Ratio $L_A / R_A$ defines motor electrical time constant $\tau_e$. The motor torque constant $K_M$, and motor electrical constant $K_e$ are the same for an ideal motor.

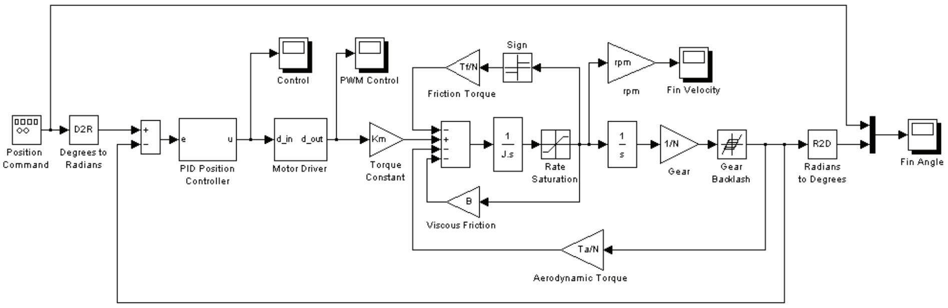

Fig. 4 Simulink block diagram of EMA-AFC system

Equation (1) is simplified in nonlinear model for two reasons. First, electrical time constant $\tau_e$ is very small for this motor. Second, the motor driver is constant current generator, which is indifferent to the induced back electromotor force $K_e\omega_m$, where $\omega_m$ is rotor angular velocity.

Thus, the motor torque becomes:

$$T_m = K_M I_A \tag{2}$$

Dynamics of mechanical part is:

$$J\frac{\mathrm{d}\omega_m}{\mathrm{d}t} = T_m - T_L \tag{3}$$

where $J$ is total moment of inertia and $T_\mathrm{L}$ is load torque.

Namely, the two moments of inertia $J_m$ and $J_L$, are equivalent moments of inertia of the rotating motor components and the actuator assembly moment of inertia, respectively. In almost all cases, the motor inertia will be the most significant one because of the large mechanical advantage of the screw drive system. Reflecting the inertia for each of the rotating components in the actuator assembly to the motor shaft results in:

$$J_L = \frac{J_{fin} + J_{lever}}{N^2 \cdot \eta_g^2} + J_{screw} + J_{pg} \tag{4}$$

where $J_{fin}$ is the fin moment of inertia, $J_{lever}$ is the moment of inertia of the lever in screw drive mechanism, $J_{screw}$ is the screw shaft moment of inertia, $J_{pg}$ is the planetary gearhead moment of inertia, $\eta_g$ is the efficiency of the screw drive system, and $N$ is total gear ratio.

Simulation model includes model of the current motor driver. The continuous control signal from the OBC is sampled on 2 KHz and clipped to the maximum current $I_M$. The clipped current signal is held and forwarded to the motor.

## 4. CONTROLLER DESIGN

### PID Controller

In previous research, there has been performed synthesis of the PID position controller using nonlinear simulation model (4).

$$u(t) = K_P e(t) + K_I \int_0^{\tau} e(\tau)\mathrm{d}\tau + K_D \dot{e}(t) \quad (4)$$

where, $e(t) = \alpha_r(t) - \alpha(t)$, $\alpha_r(t)$ is reference and $\alpha(t)$ is measured fin angle.

Since the current motor driver is inherently nonlinear due to two level current output, it has been impossible to linearize it, i.e. to obtain linearized model of the EMA-AFC system. Hence, in control algorithm synthesis we have been relied on *a priory* knowledge of the plant and extensive simulation.

Design objectives for control synthesis are fast transient response, non-overshooting, and zero steady-state error. It can be accomplished for values $K_p = 1.5$, $K_I = 0.1$, $K_D = 0.1$ of the PID position control algorithm parameters. It was experimentally validated that the model and the real system have same responses, see Fig. 5.

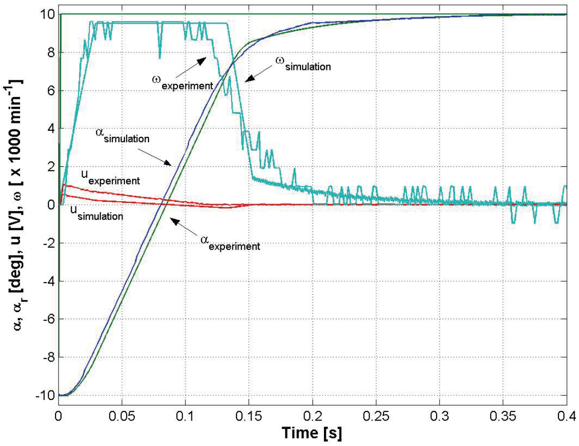

Fig. 5 Experimental and simulation step response

### Modified PID Controller

During the simulation and experimental work with EMA-AFC testing system we have concluded that PID controller works properly when position error is large. If we refer to the square wave response

From Fig. 5 it can be seen that as the output angle approaches to steady-state reference, the response becomes slower. It is expected, because the load torque originated form aerodynamic force works like a spring. One way to overcome this is to schedule the parameters in control algorithm. We propose another approach, i.e. to modify the error signal.

In general, for linear systems, two broad categories of nonlinear PID control are found: those with gains modulated according to the magnitude of the state, and those with gains modulated according to the phase. Besides, nonlinear PID control has a long history and has found two broad classes of application: i) nonlinear systems where nonlinear PID control is used to accommodate the nonlinearity, often to achieve consistent response across a range of conditions; and ii) linear systems, where nonlinear PID control is used to achieve performance not achievable by linear compensation, [5].

The idea is to compress or expand the error signal, which can be mathematically expressed by following equation:

$$e_c(t) = \mathrm{sign}(e(t)) \cdot \sqrt{|\mathrm{e(t)}|} \tag{5}$$

The graphical interpretation is seen in Fig. 6.

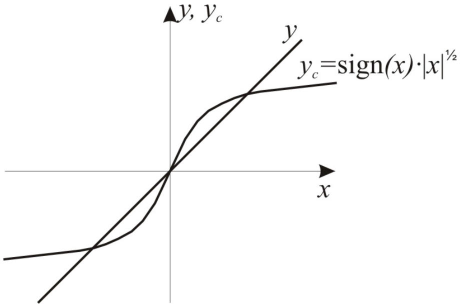

Fig. 6 Comparison of linear and nonlinear gains

The reason that nonlinear controller performs better is that it provides higher gain when error is small and lower gain when error is large. It completely agrees with the intuition obtained from working with practical problems. As a matter of fact, many fuzzy logic controllers and gain scheduling controllers exhibit this kind of characteristics on its error surface. Of course, the fuzzy controller is much more complicated to implement, [6].

Simulation results obtained with PID and modified PID controller are given in. Fig. 7. Presented simulation result has been done for the square wave reference angle with the maximum allowable magnitude of the reference input $|\alpha_{r\max}|$=10 deg .

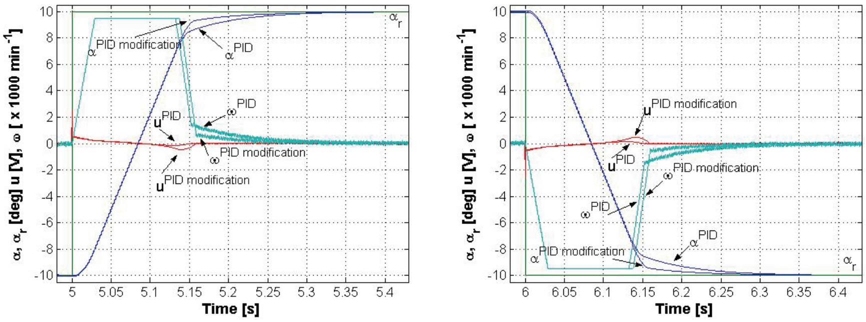

Fig. 7 Square wave response

Parameters for modified PID controller are: $K_\mathrm{p} = 0.8$, $K_\mathrm{i} = 0.1$, $K_\mathrm{d} = 0.1$. It can be seen that response with modified PID controller is improved in terms of rising and settling time.

Simulations have been done for following model coefficients given by mechanical design parameters and motor specifications provided by vendors: $J_{fin} = 1.5\cdot10^{-2}$ kg m$^2$, $J_{lever} = 5\cdot10^{-3}$ kg m$^2$, $J_{pg} = 0.15\cdot10^{-6}$ kg m$^2$, $J_{screw} = 5\cdot10^{-6}$ kg m$^2$, $J_m = 3.33\cdot10^{-6}$ kg m$^2$, $l = 50$ mm, $h = 3$ mm, $N = 395$, $\delta_\mathrm{max} = 10$ deg, $T_{a\mathrm{max}} = 19$ Nm, $T_f = 10$ Nm, $B = 0$, $K_M = 0{,}026$ Nm/A, $R_A = 0{,}611\ \Omega$, $L_A = 1.2\cdot10^{-4}$ H, $I_\mathrm{max} = 6.5$ A, $\omega_\mathrm{max} = 9500$ min$^{-1}$, mechanical time constant of the motor is 3 ms, and gear backlash is 0.2 deg.

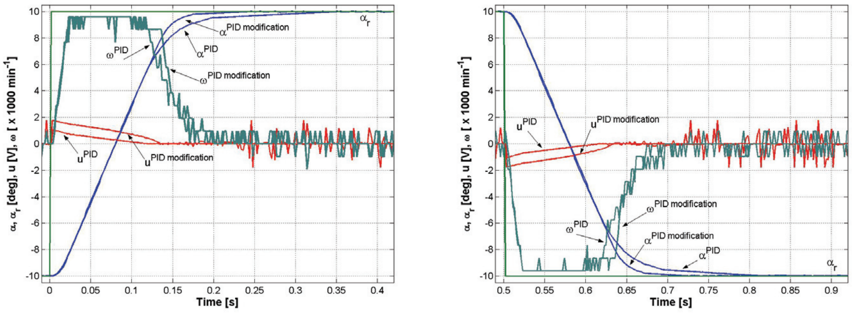

Fig. 8 Experimental square wave response

Experimental results of EMA-AFC system are given in Fig. 8. These results justify this kind of control algorithm modifications because considerably better transient responses have been obtained.

## 5. CONCLUSIONS

Nonlinear model of the electromechanical actuator system for aerofin control that includes nonlinearities of the constant current motor driver is used for syntheses of PID position controller. Being motivated by experimental work with EMA-AFC testing system, we proposed nonlinear modification of the PID controller in order to increase transient response of the EMA-AFC system. Proposed modification was simply to implement improving the response of the system that is proven by simulations and experiments.

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## REFERENCES

1. Schinstock, D. E., Douglas S. A., Haskew, T. A.: Identification of Continuous-Time, Linear, and Nonlinear Models of an Electromechanical Actuator. Journal of Propulsion and Power, Vol. 13, No. 4, p.p. 683-690. 1997.
2. Schinstock, D. E., Douglas S. A., Haskew, T. A.: Modeling and Estimation for Electromechanical Thrust Vector Control of Rocket Engines. Journal of Propulsion and Power, Vol. 14, No. 4, p.p. 440-446. 1999.

3. Schinstock, D. E., Haskew, T. A.: Transient Force Reduction in Electromechanical Actuators for Thrust-Vector Control. Journal of Propulsion and Power, Vol. 17, No. 1, p.p. 65-72. 2001.
4. Zipfel, P. H.: *Modeling and Simulation of Aerospace Vehicle Dynamics,* AIAA, Reston, VA, 2000.
5. Armstrong, B., Neevel, D., Kusik, T.: New Results in NPID Control: Tracking, Integral Control, Friction Compensation and Experimental Results. IEEE Trans. on Control Systems Technology, Vol. 9, No. 2, p.p. 399:406. 2001.
6. Zhiqiang Gao; Yi Huang; Jingqing Han, An alternative paradigm for control system design, *Proceedings of the 40th IEEE Conference on Decision and Control,* Volume 5, p.p. 4578:4585 vol.5, 2001.
7. Åström, K., Hägglund, T.: *PID Controllers: Theory, Design, and Tuning,* Instrument Society of America, Research Triangle Park, NC, 1995.
8. http://www.maxonmotor.com. Maxon Motor AG.
9. Mathematical Model of the Control Surface Servoactuator. *Technical Report*. Military Technical Institute, Serbia & Montenegro. (in Serbian)
10. Unicode products from Texas Instruments, "A Simplified Approach to DC Motor Modeling for Dynamic Stability Analysis", *Application Report SLUA076*. 2000.

# NELINEARNA MODIFIKACIJA PID REGULATORA ELEKTROMEHANIČKOG SISTEMA ZA POKRETANJE UPRAVLJAČKOG KRILA SA ŠIRINSKO MODULISANIM UPRAVLJANJEM MOTORA JEDNOSMERNE STRUJE

**Milan R. Ristanović, Dragan V. Lazić, Ivica Inđin**

*U radu se istražuje upravljanje elektro-mehaničkog sistema za pokretanje upravljačkog krila izvedenog sa motorom jednosmerne struje sa četkicama i permanentnim magnetom. Motor jednosmerne struje je upravljan drajverom konstante struje. Koristeći nelinearni model sistema izvršena je sinteza pozicionog PID upravljačkog algoritma. U radu se predlaže modifikacija upravljačkog algoritma u cilju poboljšanja prelaznog procesa sistema, što je bilo motivisano eksperimentalnim radom na testiranju sistema.. Prikazani rezultati pokazuju da je prelazni process znatno poboljšan sa modifikovanim PID regulatoro.*

Kljucne reci: *Elektruomehanički actuator, Upravljačko krilo, Motor jednosmerne struje, drajver konstante struje, Širinska modulacija, PID.*