DESIGN OF A NOVEL CONTROLLER TO INCREASE THE FREQUENCY RESPONSE OF AN AEROSPACE ELECTRO MECHANICAL ACTUATOR

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ABSTRACT

For aerospace applications, motion control systems are known as Electro Mechanical Actuators. Unlike general motion control systems, noise level and speed of response are critical. In Electro Mechanical Actuators there is no trajectory generator. The target position has to be reached at the earliest. There is no luxury of a controlled acceleration and declaration. The common challenge in EMA design of various Aerospace projects is that they generally have poor frequency response, primarily due to phase lag. Phase lag results due to reciprocatory nature of these actuators across a NULL position .Control systems such as Proportional Integral Differential (PID), Pole Placement, Linear Quadratic Regulator (LQR), Linear Quadratic Gaussian are not ideal for this class of actuators since on their own, they cannot solve the primary problem of phase lag .The main theme of this paper is to reduce the phase lag of an Electro Mechanical Actuator (EMA) by a novel concept, “Piecewise Predictive Estimator (PPE)”. The PPE technique in conjunction with an existing controller can increase the frequency response by up to 15% without any adverse effects on noise characteristics of the EMA. Simulation results are obtained from Matlab/Simulink software tool.

Keywords: PID, LQR, PPE, BLDC, EMA
1. INTRODUCTION

In this class of motion control application, noise is a major concern.

![Electro Mechanical Actuator](image)

**Fig.1 Electro Mechanical Actuator**

We have to satisfy two criterion. Step response will show speed of response as well as noise levels. Bodes plot will show the system bandwidth in hertz, primarily limited by the -90 degrees phase lag, as well as giving us phase margin, which should be more than 60 degrees. PID controllers can be either tuned for high gain, high bandwidth, but will result in high noises. LQR controllers by very definition minimize the cost function consisting of state error and effort required. We require speed of response at any cost.

Various sources of process noise are gear or ball screw backlash, BLDC motor cogging, commutation current disturbances, MOSFET switching noise, DC-DC converter noise, Load variations.

Sources of measurement noises are position sensor noise (Potentiometer or LVDT), ADC quantization noise, control circuit’s EMI coupling to sensor feedback path. As mentioned earlier, the two primary objectives for EMA design are low noise and high speed of response (bandwidth).

This paper proposes a unique combination of an existing controller such as a PID or an LQR controller and Piecewise Predictive Estimator (PPE), to achieve these two objectives of low noise and high bandwidth response.

The paper is organized as follows.
1. Modelling of Electromechanical Actuator.
2. Comparison of PID Controller with and without PPE.
3. Comparison of LQR controller with and without PPE.
5. Simulation results (Bode & step response)
2. MODELLING OF ELECTRO MECHANICAL ACTUATOR

The modelling of the Electro Mechanical Actuator [2] is done in stages. By using the mechanical properties and electrical properties and equating with Newton’s and Kirchhoff’s laws, we get the transfer function.

\[ u = \text{input to the plant model (voltage).} \]

Motor Parameters:
- \( J \) = Inertia Constant.
- \( K_t \) = Torque Constant
- \( B \) = Friction Coefficient.
- \( R \) = Motor Resistance
- \( L \) = Motor Inductance
- \( K_p \) = Gain

Parameters
\( (J=0.01, \ K_t=0.01 \text{Nm/A, } L=330 \mu\text{H, } R=0.39 \Omega, \ B=0.1) \).

This can be converted to a continuous state space model using Matlab command \( \text{ss}(\text{tf}) \), or directly by replacing mechanical parameters in the \( A, B, C \) and \( D \) matrices.

\[
\frac{di}{dt} = -\frac{R}{L_a} i_a - \frac{k_a}{L_a} \omega_a + \frac{1}{L_a} u_a
\]  
(1)

Newton 2\textsuperscript{nd} law

\[
\Sigma T = V_e = J \frac{d\omega}{dt}
\]  
(2)

\[
T_e = k_a i_a
\]  
(3)

\[
T_{\text{viscous}} = B \omega
\]  
(4)

\[
\frac{d\omega}{dt} = \frac{1}{J} \left( T_e - T_{\text{viscous}} - T_L \right)
\]  
(5)

\[
\frac{di}{dt} = -\frac{R}{L_a} i_a - \frac{K}{L_a} \omega_a + \frac{1}{L_a} u_a
\]  
(6)

Fig. 2 DC Motor
\[
\frac{d\omega}{dt} = \frac{I}{J} (k_a i_a - B \omega - T_L) \tag{7}
\]
\[
S = \frac{d}{dt}
\]
\[
S \theta_i(s) = \omega_i(s)
\]
\[
\left( S + \frac{R}{L} \right) i_a(s) = -\frac{K}{L_a} \omega(s) + \frac{I}{L_a} V_a(s)
\tag{8}
\]
\[
\left( S + \frac{B}{J} \right) \omega_i(s) = \frac{I}{J} k_a i_a(s) - \frac{I}{J} T_L(s)
\tag{9}
\]
Finally the dynamic equation in state space form
\[
\frac{d}{dt} \begin{bmatrix} i \\ \theta \end{bmatrix} = \begin{bmatrix} \frac{r_a}{L_a} & -\frac{k_a}{J} \\ \frac{k_a}{L_a} & -\frac{B_m}{J} \end{bmatrix} \begin{bmatrix} i \\ \theta \end{bmatrix} + \begin{bmatrix} \frac{I}{L} \\ 0 \end{bmatrix} v \tag{10}
\]

![Fig.3 Simulink Block Diagram of Servo Actuated by DC Motor](image)

3. **CONTROLLER DESIGN**

3.1. PID

A Proportional integral derivative controller is a generic control loop feedback mechanism (controller) and commonly used as feedback controller.

In PID controller, the 'e' denotes to be tracking error which is been sent to the controller. The control signal \( u \) from the controller to the plant to the derivative of the error.

\[
u = k_p e + k_i \int e \, dt + k_D \frac{de}{dt} \tag{11}\]

Parameter of PID controller were choose to accomplish design objectives in terms of fast, non-overshooting transient response and accurate steady state operating small differential gain is required because it stabilizes the system, while integral gain influences fast transient responses. The designer should know the process characteristics, and accordingly must decide on the combination and values of P, I, D parameters to keep [4].
PID controller may not be optimal in many cases since increasing gain will also increase process noise leading to unstability. Designers have attempted to modify PID equations to improve its performance [5] [6].

3.2 LQR Design

LQR family of controllers are very effective for linear systems. LQR controllers are designed to minimize the cost function comprising of state error and input effort [7].

\[
J = \int_0^\infty \left( x^T Q x + R u^2 \right) dt
\]

(12)

\[
J = \int_0^\infty \left( \left( \text{tracking error} \right)^2 Q + \left( \text{input} \right)^2 R \right) dt
\]

(13)

J is cost function to be minimized, R and Q are two matrices of the order of state and input.

Q and R matrices are selected by designers by trial and error. If Q is large, to keep J small, input u has to be big.

If R is large, to keep J small, input u must be small.

And control input u is

\[
u = -R^{-1} B^T P x(t)
\]

(14)

where P is calculated by solving the Ricatti equation

\[
u = PA + A^T P - Q + PBR^{-1} B^T P
\]

(15)

Below figure shows the designed LQR state feedback configuration

\[\text{Fig. 4 Linear Quadratic Regulator Structure}\]
3.3 Piecewise Predictive Estimator (PPE)

The origins of PPE are in numerical calculus. Z transform is the foundation of most signal processing.

\[ Zx_n = x_{n+1} \quad (16) \]

Delta operator is defined as

\[ \Delta x_n = x_{n+1} - x_n \quad (17) \]

Del operator is defined as

\[ \nabla x_n = x_n - x_{n-1} \quad (18) \]

\[ \nabla = \frac{\Delta}{1 + \Delta} \quad (19) \]

\[ x_{n+1} = \frac{1}{(1 - \nabla)x_n} \quad (20) \]

\[ x_{n+2} = \nabla^2 x_n = \nabla(\nabla x_n) \quad (21) \]

If a missile has to track a moving target, it is desirable to be able to make a judicious prediction of future location of the target. Since the target does not follow any continuous function, we can only approximate the target trajectory piecewise, where each piece is continuous within this region. Since Taylor’s series representation is valid for a continuous function, we have,

\[ f(x) = f(0) + f'(0)x + \frac{x^2}{2!} f''(0) + \frac{x^3}{3!} f'''(0) + .. \quad (22) \]

Expanding equation (2) as Taylor’s series, we have

\[ x_{n+1} = (1 + \nabla + \nabla^2 + \nabla^3 + ...)x_n \quad (23) \]

Using equation (23) we can have a finite prediction horizon. Although finite, this prediction can improve the target tracking capability considerably by reducing the phase lag without undue increase in gain. This will serve the dual purpose to reduce the phase lag and to reduce the system noise, since we are not resorting to gain increase. The algorithm of PPE is detailed in Fig. 5. This algorithm remains the same in Simulink’s embedded Matlab function block C code, as well as in C code of Code Composer Studio which is used to compile firmware for Texas Instruments 32 bit DSP[3] TMS32.

![Fig. 5 Simulink Block Diagram of Plant Model with PPE](image-url)
Flow Chart for PPE Embedded Function:

Start

Variables x, y, del, del1, del2, del3, del4

Collect the input(x) from chirp

TRUE

Is empty(x)

FALSE

Estimate the 6 values

Is empty(del)

END

Is empty(del1)

END

Is empty(del2)

END

Is empty(del3)

END

Is empty(del4)

END

Estimate the del values

Estimate the del1 values

Estimate the del2 values

Estimate the del3 values

Estimate the del4 values

Find out del, del1, del2, del3, del4

Calculate Estimated Values using del, del1, del2, del3, del4

Assign the estimated value to output(y)

End

Fig. 6
4. SIMULATION RESULTS

Fig. 7 Frequency Response with PID Controller

Fig. 8 Frequency Response with PID Controller and PPE

Fig. 9 Frequency Response with LQR Controller

Fig. 10 Frequency Response with LQR Controller and PPE

Fig. 11 Step Response with PID Controller

Fig. 12 Step Response with PID Controller and PPE
5. CONCLUSION

Using matlab simulation, it is observed that there is a significant improvement in frequency response due to reduction in phase lag at higher frequencies, from 22Hz without PPE, to 25Hz with PPE, thus meeting our goal. Future work can be done experimentally with improved performances of an electro-mechanical actuator.

REFERENCES