Modeling and Identification of Actuator for Flap Deflection

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Abstract:

The electromechanical actuator (EMA) model is presented with the methods for identifying its design parameters. The actuator is a part of the system for flap deployment on the commercial transport airplane. The differential equations with the feedback control describe behaviour of the actuator deflection. There are two concepts of drive system simultaneously considered: a high torque/low speed (HT/LS) and a geared low torque/high speed (LT/HS). For parameter identification in both cases the Maximum Likelihood (ML) method with two minimisation algorithms: linearized Gauss-Newton and Levenberg-Marquardt is applied. Both approaches for each of two design solutions were effective, while tested on hypothetical data.

Keywords: electromechanical actuator, system identification, maximum likelihood method.

1. Introduction

The concept of More Electrical Aircraft MEA, which has been investigated for some time, recently attracts more interest due to trend for "greening" aviation operations. In aircraft control, the electric system will replace the hydraulic one used nowadays, resulting in saving weight and operational costs [1].

In the project NEFS - New Track integrated Electrical Single Flap Drive System, funded by EC under 6 FP the concepts are investigated for replacing conventional hydraulic drive system used for deploying wing flaps of large transport aircraft by individual, distributed electrical drive actuators integrated into each flap track beams [5].

The system performance is tested at the laboratory rig, but the system failures and their influence on aircraft is investigated by simulations. To make the integrated simulations of system and aircraft reliable, the actuator simulation model should reflect behaviour of a real device in a correct way. The required accuracy level of simulation model may be achieved by identification of the system model parameters using data from laboratory tests.

In this paper the actuator model and identification methods are described with some preliminary sample results.

System identification is a process of determining the parameters of mathematical model of the system using data from experiments, sometimes specially planned for the model used. Developed model should describe correctly system behavior to be reliable for further investigation of system dynamics. For assumed structure of the model, the estimation method is selected. The choice of identification algorithm depends on the knowledge about object being identified. Usually computation efficiency and available experimental data are major determinant. The final validation of the identified parameters is based on the experimental data not used for estimation of model parameters [1].

In the paper parameters of electromechanical actuator system nonlinear model are identified using ML method.

2. Actuator model

In the project two concepts of drive systems are considered: a High Torque/Low Speed (HT/LS) and a geared Low Torque/ High Speed (LT/HS).

2.1. The High Torque/ Low Speed concept

In case of HT/LS solution the EMA system contains two drive stations 1 and 2 connected to aircraft flap. Each drive station contains a ball-screw driving the flap connected to common DC motor by U-joint and a gearbox. The motor is controlled by performing assumed function of flap deflection.

The actuator is described by the mechanical equation:

$$J \frac{d\Omega(t)}{dt} = M_n - \left(M_{B1} + M_{TPER1} + M_{TPER2} \right), \quad (1)$$

where: Ω – motor shaft angular velocity, J – inertia moment of rotating parts reduced to the shaft [3].

The torque generated by the motor is calculated as:

$$M_n = k_n I_A, \quad (2)$$

where: k_n – motor constant, I_A – armature current.

The M_{TPER1} and M_{TPER2} are the external torques from station 1 and 2.

Each station contains bevel gear, U-joint and ball-screw.

The M_B is the primary brake torque applied to the motor modelled as:

$$M_B = M_{B\max} - 0,5 M_{Bmax} \left(1 - e^{-K_B \left(\frac{\Omega}{\Omega_{0,5T\max}} \right)} \right), \quad (3)$$

where: κ_B – electromagnetic brake constant coefficient, $M_{B\max}$ – maximal torque value (for $\Omega = 0$), $\Omega_{0,5M_{B\max}}$ – angular velocity value for half a maximal torque $M_{B\max}$.

In bevel gear the motor angular velocity Ω is reduced to Ω_{TP} with reduction ratio i_{TP}:

$$\Omega_{TP}(t) = \frac{\Omega}{i_{TP}} \quad (4)$$

External torque acting on the motor shaft is calculated as the sum of external torque from the U-joint M_{UER}, torque resulting from the losses in bevel-gear M_{TP} and

secondary brake torque M_{B2}, which is equal to zero when the brake is not released:

$$M_{TPER} = \frac{M_{UER}}{i_{TP}} + M_{TP} + M_{B2} \qquad (5)$$

The bevel gear moment due to mechanical energy losses is composed of viscous damping represented by B_{TP} coefficient and Coulomb friction C_{TP} [3]:

$$M_{TP} = B_{TP}\Omega_{TP}(t) + C_{TP}sign(\Omega_{TP}(t)) \qquad (6)$$

The screw is connected to the gear-box by U-joint where the angular rotation is changed:

$$\Omega_U(t) = g_U\Omega_{TP} \qquad (7)$$

where:

$$g_U = \left(\frac{\cos\beta}{1 - \sin^2\beta\cos^2\theta_{TP}}\right), \qquad (8)$$

$$\theta_{TP} = \theta/i_{TP}, \qquad (9)$$

β – angle between the input and output shaft axis,
θ – motor shaft angle of rotation.

The additional moment M_U due energy losses in U-joint is assumed in the same form as for the gear box:

$$M_U = B_U\Omega_U(t) + C_U sign(\Omega_U(t)), \qquad (10)$$

so the U-joint output shaft moment takes the form:

$$M_{UER} = \frac{M_{TSER}}{\cos\beta} + M_U, \qquad (11)$$

In the ball screw the shaft rotation is transferred into nut translation:

$$\frac{dy(t)}{dt} = r \cdot tg\gamma \cdot \Omega_U(t) \qquad (12)$$

where: r – screw rolling radius, γ – nominal lead angle.

External loads F_{ER} from the flap act on the ball-screw. The moment on the screw resulting from external loads is calculated as:

$$M_{ER} = -r \cdot F_{ER1}\sin\gamma\cos\gamma, \qquad (13)$$

where r denotes screw rolling radius and γ stands for nominal lead angle.

The output moment from the ball screw is composed from moment resulting from external loads M_{ER} and additional torque losses in the ball screw M_{TS} modelled analogically to the damping in bevel-gear and U-joint:

$$M_{TSER} = M_{TS} + M_{ER}, \qquad (14)$$

where:

$$M_{TS} = B_{TS}\Omega_U(t) + C_{TS}sign(\Omega_U(t)). \qquad (15)$$

2.2. The Low Torque/ High Speed concept

The LT/HS concept is asymmetric in contrary to the previously described. The motor is controlled by the voltage and form electrical side is modelled in the following form:

$$\dot{I}_A = -\frac{R_A}{L_A}I_A - \frac{k_s}{L_A}\Omega + \frac{U_A}{L_A}, \qquad (16)$$

where: I_A – armature current, U_A – control voltage, k_s – motor magnetic flux coefficient, L_A – inductance of the armature, R_A – resistance of the armature.

The torque generated by the motor is calculated analogically to these in HT/LS solution:

$$M_n = k_n I_A \qquad (17)$$

The whole EMA is described by the inertia moment J of all rotating parts reduced to the motor shaft axis multiplied by angular acceleration of the motor shaft $\dot{\Omega}$ equate to the difference between motor torque and external moment M_{MGER} from all connected devices from station 1 and 2.

$$J\dot{\Omega} = M_n - M_{MGER} \qquad (18)$$

Output moment from the motor is transferred by the shaft which changes it due to the stiffness:

$$M_{ISER} = M_{MGER} + D_{IS} \cdot \grave{e}_{MG}, \qquad (19)$$

where: θ_{MG} – magnetic gearbox output shaft angle of rotation, M_{TPER} – external torque from the bevel gear, D_{IS} – input shaft stiffness coefficient, which is assumed to be zero in the model.

The magnetic gearbox placed just after the motor changes output angular velocity Ω from the motor into Ω_{MG} with reduction ratio i_{MG}. The external torque on the motor shaft is calculated as:

$$M_{MGER} = \frac{M_{ISER}}{i_{MG}} + M_{MG}(\Omega_{MG}) \qquad (20)$$

where: i_{MG} – bevel gear reduction ratio, M_{ISER} – torque on the output shaft, M_{MG} – moment due to losses in the gearbox analogically calculated as in eqs. 6 and 10 :

$$M_{MG} = B_{MG}\Omega_{MG} + C_{MG}sign(\Omega_{MG}). \qquad (21)$$

Magnetic gearbox is connected with the first bevel gear by the input shaft which modifies output moment in a following way:

$$M_{ISER} = M_{TPER2} + D_{IS} \cdot \theta_{MG}, \qquad (22)$$

M_{TPER2} – external torque from the shaft of station 2, D_S – shaft stiffness coefficient, which is assumed as zero in this research.

There are two shafts connected to the output of the first bevel gear. One of them leads to the first ball-screw by the first U-joint and the second shaft which, after one more bevel-gear and U-joint, connects second ball-screw to the system. The first bevel gear reduces angular velocity Ω_{MG} to Ω_{TP1} with ratio i_{BG1} in case of the first station and at the same time but with different ratio i_{BG2} it reduces angular velocity to Ω_{MG2} for the second station:

$$\Omega_{TP1} = \frac{\Omega_{MG}}{i_{BG1}}, \qquad (23)$$

$$\Omega_{MG2} = \frac{\Omega_{MG}}{i_{BG2}} \qquad (24)$$

External torque on the input shaft of the first bevel gear is calculated as the sum of moment coming from the first (M_{UER1}) and second (M_{MG2}) station divided by appropriate reduction ratio, moment of losses in the gearbox M_{TP1} and moment from the brake M_{B2}, which is equal to zero when the brake is not released:

$$M_{TS} = B_{TS}\Omega_U(t) + C_{TS}sign(\Omega_U(t)) \qquad (25)$$

The first station contain U-joint which influence on the angular velocity. These change may be described by coefficient g_U defined as in eq.8 :

$$\Omega_U(t) = g_U\Omega_{TP}. \qquad (26)$$

As the moment due to losses has a form:

$$M_{U1} = B_{U1}\Omega_{U1} + C_{U1}sign(\Omega_{U1}) \qquad (27)$$

the U-joint output shaft moment is calculated as:

$$M_{UER1} = \frac{M_{TSER1}}{\cos\beta_1} + M_{U1}(\Omega_{U1}), \qquad (28)$$

where: β_1 – angle between input/output shaft directions.

The U-joint couple ball-screw with the first bevel-gear. On the ball screw of drive station 1 there are moments resulting from external loads M_{ER1} acing on the flap mounted to the carriage, which is connected to the ball nut and torques due to losses in the ball screw M_{TS1} :

$$M_{TSER1} = M_{TS1} + M_{ER1} \qquad (29)$$

The second shaft, which is connected to the output of the first bevel gear, leads to another bevel gear in which angular velocity as well as the moment are changed into, respectively:

$$\Omega_{TP2} = \frac{\Omega_{MG2}}{i_{TP2}} \qquad (30)$$

$$M_{MG2} = \frac{M_{UER2}}{i_{TP2}} + M_{TP2} + M_{B22}. \qquad (31)$$

From this moment drive transmission in drive station 2 is analogical to these from drive station 1. As the sec-

ond bevel gear is coupled by U-joint with the ball-screw, models of each elements are similar to these from the drive station 1.

The output torque from the U-joint M_{UER2} is calculated analogically to the M_{UER1}. The moment due to losses in the gearbox M_{TP2} is defined in the same way that those from the first bevel gear and magnetic gearbox (eq. 21), while moment from the second brake M_{B22} is equal to zero when the brake is not released.

2.3. Control

The input signal for the system is the required flap deflection angle φ_r (Fig.1).

This signal is transformed into required carriage position y_r which is compared with the position measured by the sensor y_s and changed proportionally into angular velocity of the screw Ω_r command in ACE module using proportional regulator with p_{ACE} coefficient:

$$\Omega_r = p_{ACE}(y_r - y_s), \qquad (32)$$

where:
$$y_s = 0.5\cdot(y_1 + y_2), \qquad (33)$$
y_1, y_2 – carriage position of station 1 and 2 respectively.

The control signal for the motor is calculated in PCE module as:
– in HT/LS concept

$$I_A = \frac{p_{PCE}}{k_n}(\Omega_r - \Omega_s), \qquad (34)$$

– in LT/HS concept

$$U_A = \frac{p_{PCE}}{k_n}(\Omega_r - \Omega_s),$$

where Ω_s stands for measured angular velocity and p_{PCE} is a proportional control coefficient. Appropriate value of the signal should be contained in the boundaries follow from DC motor performance:

$$M_{min} \le p_{PCE}(\Omega_r - \Omega_s) \le M_{max} \qquad (35)$$

As a result in HT/LS solution actuator is described by the state equations:

$$\begin{cases} \dot{\Omega} = \frac{1}{J}\left[M_n - (M_{B1} + M_{TPER1} + M_{TPER2})\right] \\ \dot{y}_1 = r\cdot tg\gamma\cdot\Omega_{U1} \\ \dot{y}_2 = r\cdot tg\gamma\cdot\Omega_{U2} \end{cases}, \qquad (36)$$
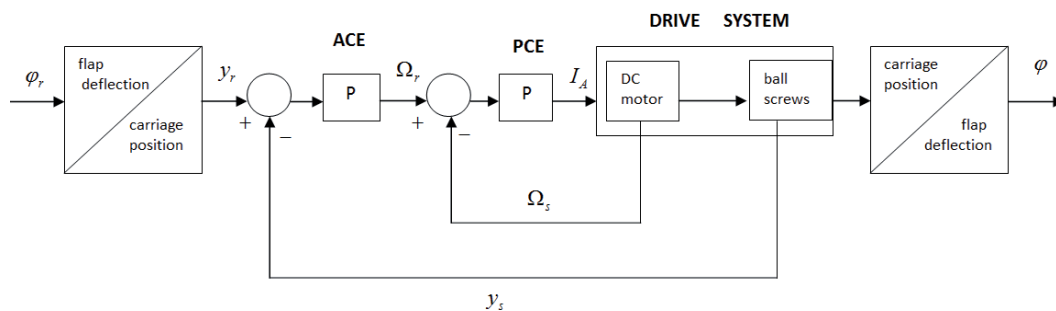

Fig. 1. Electromechanical actuator control system.

where the model states are:

$$x = \begin{bmatrix} \Omega & y_1 & y_2 \end{bmatrix}^T \quad (37)$$

The control equation is:

$$I_A = \frac{p_{PCE}}{k_n}\left(p_{ACE}(y_r - y_s) - \Omega_\sigma\right) \quad (38)$$

While in the LT/HS concept EMA can be described by the fallowing system of equations:

$$\begin{cases} \dot{I}_A = -\dfrac{R_A}{L_A}I_A - \dfrac{k_s}{L_A}\Omega + \dfrac{U_A}{L_A} \\[2mm] \dot{\Omega} = \dfrac{1}{J}\left(M_n - M_{MGER}\right) \\[2mm] \dot{y}_1 = r \cdot tg\gamma \cdot \Omega_{U1} \\[2mm] \dot{y}_2 = r \cdot tg\gamma \cdot \Omega_{U2} \end{cases} \quad (39)$$

where the model states are:

$$x = \begin{bmatrix} I_A & \Omega & y_1 & y_2 \end{bmatrix}^T \quad (40)$$

The control equation is:

$$U_A = \frac{p_{PCE}}{k_n}\left(p_{ACE}(y_r - y_s) - \Omega_s\right) \quad (41)$$

The actuator model is nonlinear with respect to states and is formulated in time domain.

3. Identification methods

The aim of the EMA system identification is to calculate the actual values of mathematical model parameters.

3.1. The Low Torque/ High Speed concept

The output vector of the LT/HS system is formulated as:

$$y = \begin{bmatrix} \Omega & y_1 & y_2 & I_A & \Omega_{TP1} & \Omega_{TP2} & \Omega_{U1} & \Omega_{U2} & M_{ER1} & M_{ER2} \\ M_{TSER1} & M_{TSER2} & M_{UER1} & M_{UER2} & M_{TPER1} & M_{TPER2} & p_{ACE} & p_{PCE} \end{bmatrix}^T$$
$$(42)$$

The observation parameters z are:

$$z = \begin{bmatrix} \Omega_s & y_{1s} & y_{2s} & I_{As} & \Omega_{TP1s} & \Omega_{TP2s} & \Omega_{U1s} & \Omega_{U2s} & M_{ER1s} & M_{ER2s} \\ M_{TSER1s} & M_{TSER2s} & M_{UER1s} & M_{UER2s} & M_{TPER1s} & M_{TPER2s} & p_{ACEs} & p_{PCEs} \end{bmatrix}^T$$
$$(43)$$

where: I_{As} denotes the current passed to the DC motor, Ω_s – angular velocity on the motor output shaft, Ω_{TP1s}, Ω_{TP2s} - angular velocities on the bevel-gears, Ω_{U1s}, Ω_{U2s} – angular velocities on the U-joints. The external torques acting on ball-screws of two stations are M_{ER1s} and M_{ER2s}, while torques before the ball-screws states as M_{TSER1s} and M_{TSER2s}. The torques M_{UER1s} and M_{UER2s} are those before the U-joints, M_{TPER1s}, M_{TPER2s} are moments before the bevel-gears.

The system is observable. The proportional regulators coefficients p_{ACE} and p_{PCE} are taken from regulator adjustment on the test rig.

The estimated parameters are combined in column vector Θ:

$$\Theta = \begin{bmatrix} J & B_{TS1} & C_{TS1} & B_{U1} & C_{U1} & B_{TP1} & C_{TP1} & B_{TS2} \\ C_{TS2} & B_{U2} & C_{U2} & B_{TP2} & C_{TP2} & k_n & p_{ACE} & p_{PCE} \end{bmatrix}^T \quad (44)$$

Considering that in U-joint the β angle reaches maximally 5 degrees, the values of both g_U depending of angle θ_{TS} is close to 1, thus it is assumed that $g_{U1} = g_{U2} = 1$. Parameters β_1, β_2, γ, i_{TP1}, i_{TP2}, r are known from the system design.
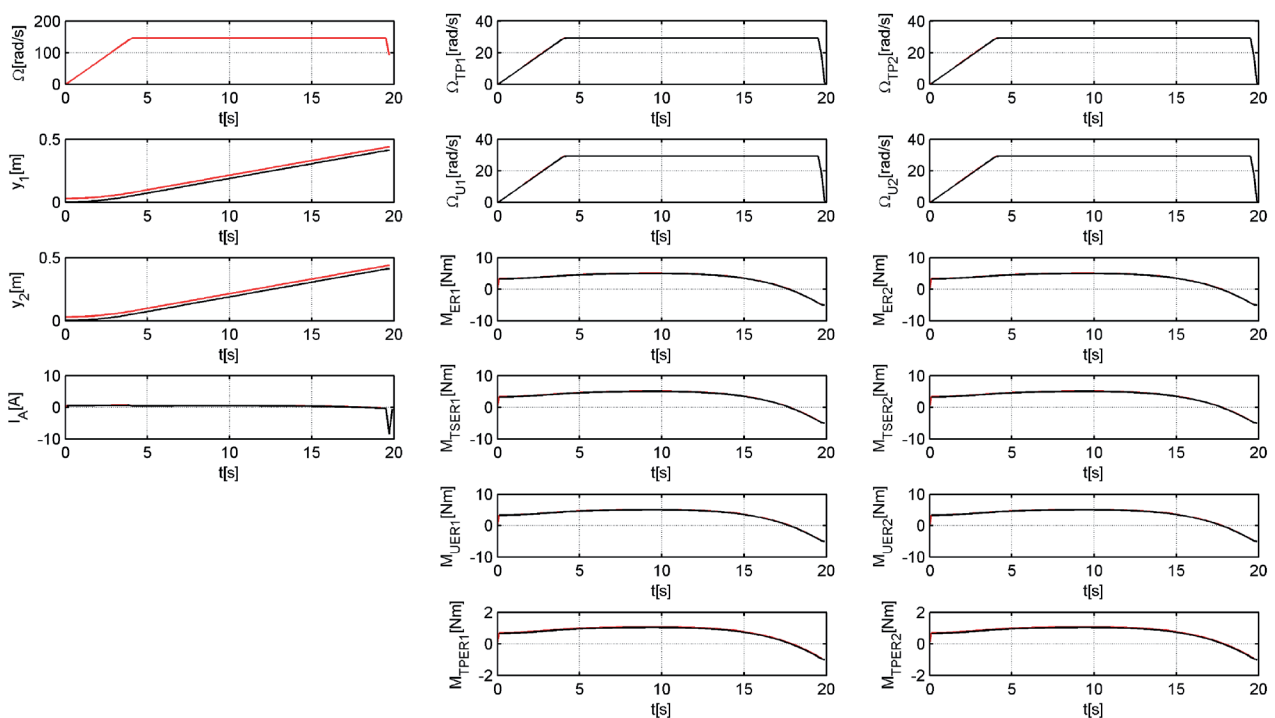

Fig. 2. Comparison of output signals of the HT/LS model with identified parameters using ML_GN algorithm and ML_LM one with outputs considered as measurements.

3.2. The Low Torque/ High Speed concept

In LT/HS solution system there are following outputs:

$$y = \begin{bmatrix} \Omega & y_1 & y_2 & I_A & U_A & \Omega_{MG} & \Omega_{TP1} & \Omega_{MG2} \\ \Omega_{TP2} & \Omega_{U1} & \Omega_{U2} & M_{ER1} & M_{ER2} & M_{TSER1} & M_{TSER2} \\ M_{UER1} & M_{UER2} & M_{MG2} & M_{TPER} & M_{MGER} & p_{ACE} \end{bmatrix} \tag{45}$$

Readouts from sensors creates vector z as :

$$z = \begin{bmatrix} \Omega_s & y_{1s} & y_{2s} & I_{As} & U_{As} & \Omega_{MGs} & \Omega_{TP1s} & \Omega_{MG2s} \\ \Omega_{TP2s} & \Omega_{U1s} & \Omega_{U2s} & M_{ER1s} & M_{ER2s} & M_{TSER1s} & M_{TSER2s} \\ M_{UER1s} & M_{UER2s} & M_{MG2s} & M_{TPERs} & M_{MGERs} & p_{ACEs} \end{bmatrix} \tag{46}$$

The estimated parameters vector Θ is defined:

$$\Theta = \begin{bmatrix} J & B_{TS1} & C_{TS1} & B_{U1} & C_{U1} & B_{TP1} & C_{TP1} \\ B_{TS2} & C_{TS2} & B_{U2} & C_{U2} & B_{TP2} & C_{TP2} & B_{MG} \\ C_{MG} & k_n & R_A & L_A & k_s & p_{ACE} & p_{PCE} \end{bmatrix} \tag{47}$$

The assumption from the previous case concerning g_U is still valid ($g_{U1} = g_{U2} = 1$). System design impose values of such parameters as: $\beta_1, \beta_2, \gamma, i_{BG1}, i_{BG2}, i_{TP2}, i_{MG}, r$.

3.1. Identification algorithm

The Maximum Likelihood (ML) method in time domain with two alternative minimisation methods: linearized Gauss-Newton (ML_GN) and Levenberg-Marquard (ML_LM) was chosen for identification in this research. In both cases, ML estimates are obtained by minimization of the cost function $J(\Theta, R)$, which in case of considered EMA system is assumed as [1], [4]:

$$J(\Theta) = \det(R), \tag{48}$$

where covariance matrix R is defined in the following form:

$$R = \frac{1}{N_{data}} \sum_{k=1}^{N_{data}} \left[z(t_k) - y(t_k) \right] \cdot \left[z(t_k) - y(t_k) \right]^T \tag{49}$$

The ML_GN algorithm with relaxation strategy contains the following steps [2], [4]:
1) Assuming initial values of parameters $\Theta(t_0)$ and states $x(t_0)$.
2) Computation of gradients of cost function with respect to parameters that are identified and gathering them in the matrix G:

$$G_i = \frac{\partial J}{\partial \Theta} . \tag{50}$$

3) Information matrix (Hessian) F evaluation .
4) Solving the following equation with respect to $\Delta\Theta_i$:

$$F_i \cdot \Delta\Theta_i = -G_i . \tag{51}$$

5) Updating parameters:

$$\Theta_{i+1} = \Theta_i + \Delta\Theta_i . \tag{52}$$

6) Checking convergence or maximum iteration number limit

$$\left| \frac{J_i - J_{i-1}}{J_i} \right| < 10^{-5} \tag{53}$$

The same algorithm but with Levenberg-Marquard (ML_LM) method of optimization used for cost function minimization may be applied in the fallowing way [2], [4]:
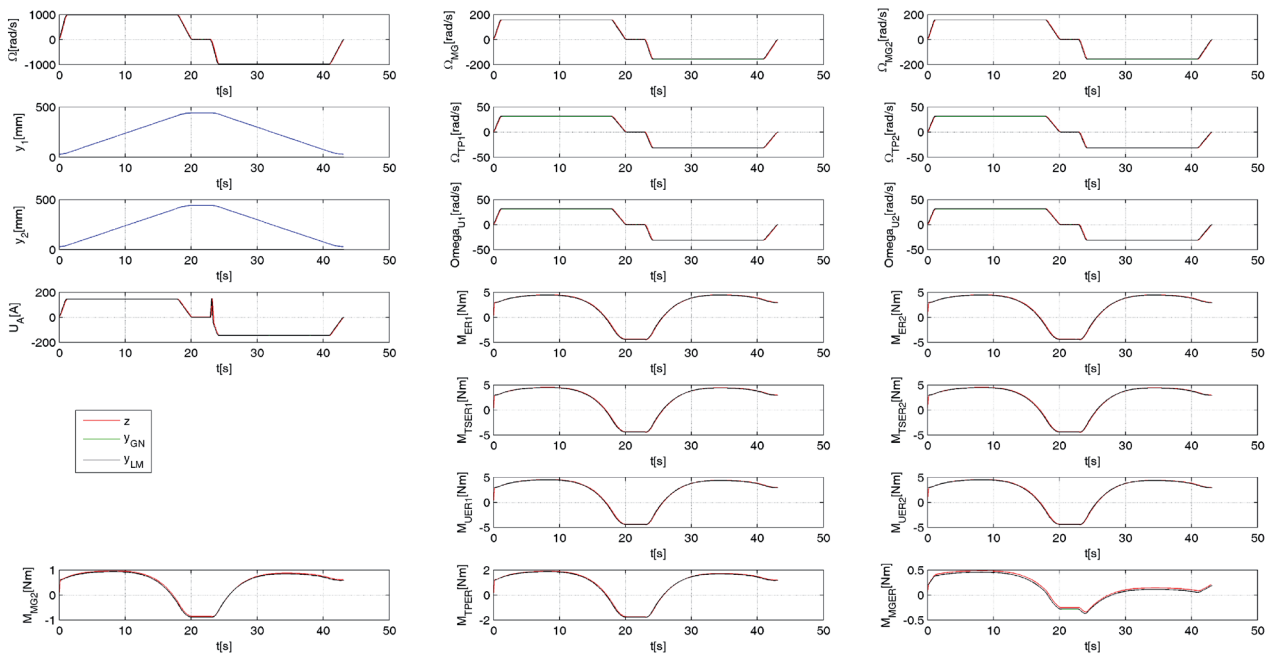

Fig. 3. Comparison of output signals of the LT/HS model with identified parameters using ML_GN algorithm and ML_LM one with outputs considered as measurements.

1) Fallow steps 2-5 from the ML_GN algorithm and compute the cost function $J(\Theta) = \det(R)$, which will be further considered as $J_{i-1}(\Theta)$.

2) Solve the equation:

$$(F + \lambda I) \cdot \Delta\Theta_i = -G \qquad (54)$$

with respect to $\Delta\Theta_i$, for Levenberg-Marquard (LM) parameter $\lambda = \lambda^{i-1}$ and $\lambda = \lambda^{i-1}/v$, where v is a reduction factor $(v > 1)$ and I -the identity matrix.

The LM parameter λ enables to control the update search direction. If $\lambda \to \infty$ the algorithm is reaching steepest- descent variant but while $\lambda \to 0$ it becomes closer to the Gauss-Newton.

3) Update parameters for each of above solution

$$\Delta\Theta_i\left(\lambda^{i-1}\right) \text{ and } \Delta\Theta_i\left(\lambda^{i-1}/v\right).$$

4) Compute respective cost functions

$$J_i\left(\Delta\Theta\left(\lambda^{i-1}\right)\right) \text{ and } J_i\left(\Delta\Theta\left(\lambda^{i-1}/v\right)\right)$$

5) Compare two above cost functions:

$$J_i\left(\Delta\Theta_i\left(\lambda^{i-1}\right)\right) \text{ and } J_i\left(\Delta\Theta_i\left(\lambda^{i-1}/v\right)\right)$$

with the one from previous iteration and choose those which corresponds to the greatest reduction by reaching the smallest value.

6) Select parameters update corresponding to the cost function chosen in previous step.

7) Update parameters vector (Eq. 31).

8) Check convergence or maximum iteration number limit (Eq. 32).

Both identification procedures were implemented in Matlab software environment and applied for the system parameters estimation.

4. Results

Instead of laboratory test data, there were used perturbed by random signal simulation ones to make sure that the algorithms are working correctly and the calculations derived by them are reliable. The results tests of both algorithms for the HT/LS and LT/HS concepts are presented on the Figure 2 and 3 respectively. On each diagram of these figures, the measured output signal is compared to output signals of the model with identified parameters using ML_GN algorithm and ML_LM one.

The results indicates that implementation of both methods leads to accurate parameters and recreates behaviour of EMA system in each configuration (HT/LS and LT/HS) properly.

Currently, the laboratory test are in progress and EMA system will be identified as soon as the data will be available.

5. Conclusions

Two concepts of the EMA system were considered: a High Torque/Low Speed (HT/LS) and a geared Low Torque/ High Speed (LT/HS). Dynamical models describing EMA systems behaviour in both configurations in form of differential equations is developed and Maximum Likelihood method with two alternative optimization algorithms (linearized Gauss-Newton and Levenberg-Marquardt) is implemented in Matlab software environment. As a result the system model parameters are successfully estimated using test data. After laboratory test completion, the experiment data will be used for the system parameters identification and more reliable model for simulation will be obtained.

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