EMADEF: a fully comprehensive analytical tool for the initial design of electro-mechanical servo-actuators for primary flight controls

DELLACASA Andrea[1] JACAZIO Giovanni[2] ZUNINO Alberto[3]

[123]Department of Mechanical and Aerospace Engineering
Politecnico di Torino
10129 Turin, Italy
Email: andrea.dellacasa@polito.it
giovanni.jacazio@polito.it
alberto.zunino@yahoo.it

ABSTRACT

Electro-mechanical servo-actuators (EMAs) are complex systems whose optimization must take into account several different factors: architectural, structural, electrical, performance, control. The optimization process is a complex task since the different issues are normally addressed in sequence and the iteration process is thus rather long. To facilitate this process and reduce the time necessary to define the best design, a new design tool was developed that addresses simultaneously all main characteristics of the EMA: performance, structural, thermal, electrical, control. With this design tool, if a single parameter is changed, for instance the number of teeth of a gear, its effects are immediately reflected into the variations of all characteristics of the EMA (current and voltage of the electric motor, thermal behaviour, stability margins, safety factors and life consumption of the mechanical components). The design tool was developed for an EMA used as a primary flight control actuator providing a controlled linear output in response to the commands received from the flight control computer. Future developments will address different configurations and applications.

This paper describes the structure and the features of this design tools, and shows how it can allow a rapid assessment of all the main characteristics of the EMA, which is instrumental both in facilitating the initial design of an EMA and also to evaluate of the effects of variations of EMAs parameters if, for any reasons (change of requirements, production or procurement issues) these variations could emerge later in the design process.

KEYWORDS

Actuators design, Electro-mechanical actuators, Performance analysis, Structural analysis

I SCOPE

Whenever a new aircraft equipment must be developed, the task of the designer is to define a solution providing an overall optimization of the equipment characteristics. The starting point of the process is the acknowledgment of the requirements established by the Customer in its technical specification and identify which are the most critical issues. It is well known that a design focused on best meeting some requirements may be less effective for other characteristics. A tradeoff analysis is thus typically performed in the initial phase of the design of a new aircraft equipment to assess the relative merits of different design options.

Though this process is in principle straightforward, its implementation is actually complex and time consuming since quite different features must be taken into account:

- Selection of the actuator architecture: direct drive or staged configuration
- Sizing of the actuator components under maximum, limit, ultimate, fatigue and endurance loads
- Actuator performance in steady-state conditions: load/rate capability over the whole range of supply and environmental conditions
- Actuator control and dynamic response: control law definition, accuracy, frequency response, dynamic stiffness, stability margins
- Thermal behaviour

Several engineering tools have been developed for addressing the different issues of the design of electro-mechanical servo-actuators (EMAs); computer codes for stress analysis, performance analysis, thermal analysis are available and offer the possibility of performing very accurate analyses of the different characteristics of the EMA, eventually leading to a final optimal design. However, a critical issue exists during the initial phase of the design process when the EMA configuration and its main

characteristics must be defined, and a tradeoff must be performed among different design options. During this initial design phase, all EMA requirements must be concurrently considered, and the use of dedicated design tools, each addressing an individual characteristic of the actuator, leads to a very time consuming process.

As an example, a variation of the ratio between the speed of the electric motor and that of the actuator output, depending on the amount of the variation, can be obtained by changing the number of the stages of the gear reducer, by simply changing the number of gears teeth, or by changing the ballscrew lead. Whichever the change, there are effects on the sizing of the mechanical components and the relevant stress distribution, on components efficiencies, on the electric motor current and voltage, on the performance limits of the EMA (maximum speed, acceleration), on thermal load of the electric motor, on the EMA dynamic characteristics, which may entail a modification of the control parameters. As a result, the entire assessment of the EMA characteristics when a single parameter is modified takes a long time, and a risk exists that time constraints might prevent a thorough investigation with the possible negative consequence of major modifications being required during the EMA final design.

In order to reduce efforts and time, and facilitate the tradeoff process associated to the initial design phase of an EMA, when fundamental decisions must be taken on its configuration, a design tool was developed which simultaneously addresses all main characteristics of the EMA: performance, structural, thermal, electrical, control. With this design tool, if a single parameter is changed, for instance the number of teeth of a gear, its effects are immediately reflected into the variations of all characteristics of the EMA (current and voltage of the electric motor, thermal behaviour, stability margins, safety factors and life consumption of the mechanical components).

This design tool: Electro-Mechanical Actuators DEsign Framework (EMADEF) thus provides a holistic approach to the EMAs design and it is primarily intended as an instrument for facilitating the initial design of EMAs and for allowing a rapid evaluation of the effects of variations of EMAs parameters if, for any reasons (change of requirements, production or procurement issues) these variations could emerge later in the design process.

II PROGRAM STRUCTURE

EMADEF has been developed with reference to EMAs comprised of the following components (Figure 1):

- Electronic control unit and motor drive, that
  - Receives position command, actuator position, motor speed and current feedback
  - Implements current, speed and position control loops
  - Generates motor controlled currents
  - Dissipates the regeneration energy
- A brushless dc electric motor converting electrical into mechanical power
- A gear reducer consisting of 0 (direct drive) to 4 stages of speed reduction, with each stage made up of parallel axes spur gears with their radial bearings
- A linear actuator converting a high speed rotating input into a low speed translating output; a ballscrew actuator is presently considered, but an option to select between ballscrew and rollerscrew actuators will be introduced as a next development
- A thrust bearing reacting the axial loads and seals preventing moisture ingress into the actuator

A brake is presently not considered in the EMA architecture because most often primary flight control surfaces are driven by two, or three actuators which are not provided by brakes, but have a dissipation device in their electronic control unit to create damping when the EMA is not powered. This allows the active actuators to drive the standby actuators while ensuring that the flight control surface is damped in the aerodynamic wake in case of loss of all the actuators driving that surface.

EMADEF consists of a series of interconnected user friendly spreadsheets that can be grouped into five main blocks as shown in Figure 2.

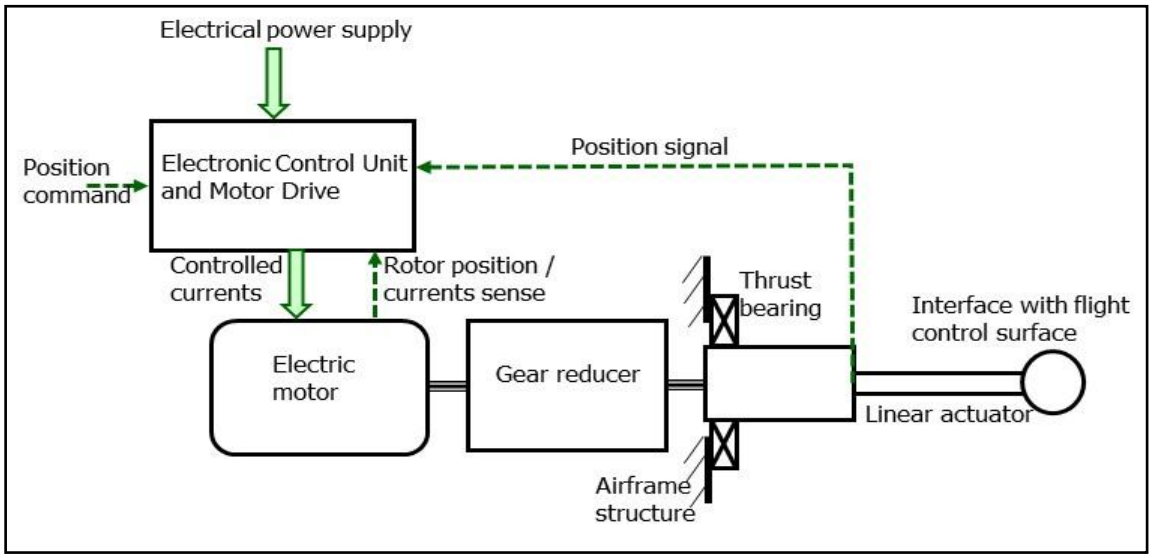

Figure 1. EMA concept diagram

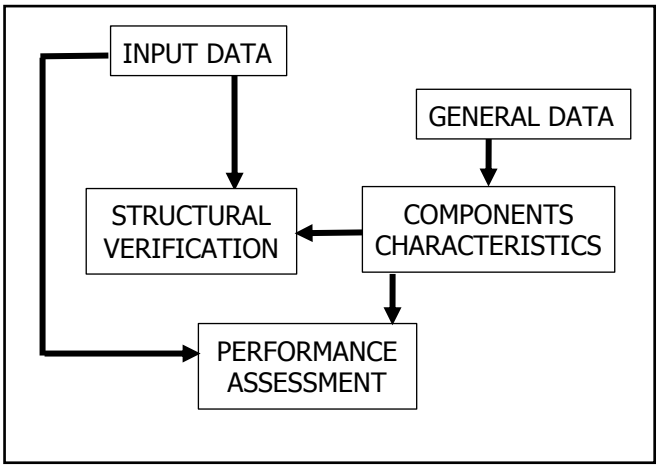

Figure 2. EMADEF organisation

The INPUT DATA block is made up by several spreadsheets containing the EMA requirements and interfaces defined by the relevant specification and the definition of the general architecture of the actuator: direct or staged drive, ballscrew with rotating nut or rotating screw, and number of gear reduction stages in case of staged drive.

The GENERAL DATA block has the purpose of providing a support to the designer for evaluating the performance of the EMA. Data included in this block provide indications for determining the parasitic effects of the mechanical components of the EMA as well as their dependence with the temperature.

The COMPONENTS CHARACTERISTICS block consists of several spreadsheets in which the values of the parameters of each component of the EMA are introduced

The PERFORMANCE ASSESSMENT block contains two sets of spreadsheets. The first set calculates the values of direct and reverse efficiencies, and of the tare losses of the individual components of the actuator (ballscrew, bearings, gears) as a function of the components characteristics and of the environmental conditions. This calculation is based on the information contained in the "General Data" and in the "Components characteristics" blocks. The second set of spreadsheets carries out the evaluation of the performance characteristics of the EMA for the most significant operating conditions: extension and retraction under different operating loads, breakout, different types of duty cycle, limit dynamic conditions, frequency response, dynamic stiffness, stability margins. The performance assessment is made for the entire range of operating temperatures.

The STRUCTURAL VERIFICATION block performs an assessment of the safety factors for the EMA components under maximum operating load, limit load, ultimate load, buckling load, fatigue and endurance.

The structure of each of the above listed blocks is described in the following sections.

III INPUT DATA

This block of spreadsheets contains the summary of the cardinal requirements which are specified by the airframe manufacturer and are fundamental for sizing the EMA. The kinematic requirements include:

- Actuator retracted length
- Actuator travel
- Average lever arm
- Rated extension and retraction speeds

Typically, the actuator performance requirements are specified in terms of linear travel, linear speed and axial load, and such data are thus considered as input data. Actuation time and angular travel are then calculated from the previous data and average lever arm. If angular travel and rate are specified, the spreadsheet can perform the opposite operation and calculate linear travel, speed and axial load starting from the angular values.

The load data are defined as:

- Maximum operating load
- Stall load
- Limit and ultimate loads
- Reversibility load; it is requested in some applications that the EMA be reversible under loads greater than a specified minimum
- Operating cycles; five different types of cycles can be defined which are used to assess the following performance characteristics of the actuator:
  - Ability to respond to the combination of cycle amplitude and frequency without saturation of any quantity (voltage, current)
  - Amount of power converted into heat during the cycle
  - Amount of regeneration power (power flow from external load into electric motor drive) during the cycle
- Fatigue loads
- Endurance loads

The values of the limit and ultimate loads can be either computed automatically by the spreadsheet as a product of the maximum operating load times default values of limit and ultimate load factors, or can be defined by the user (custom values).

The fatigue spectrum data are defined in a table as a sequence of layers in which the user introduces for each layer: minimum and maximum loads, number of cycles and fraction of cycles at normal, high and low temperatures. The spreadsheet then calculates for each layer the mean load and the load ratio (minimum/maximum) which will be used for fatigue calculations taking into account also the scatter factor which is defined by the user in an appropriate cell of the spreadsheet. There is no limit to the maximum number of layers for the fatigue loads table. Figure 3 shows an example of the table defining the fatigue spectrum.

A similar table is available for the endurance spectrum, which contains a column with the definition of the travel for each layer.

IV GENERAL DATA

This block consists of a spreadsheet presenting data allowing an initial assessment of the parasitic effects in the actuator.

It is well known that the overall efficiency of a mechanical drive is affected by power losses resulting from several factors. Under normal operating conditions the main parasitic factors contributing to the reduction of the mechanical efficiency are:

Fatigue spectrum data								
This sheet contains the loads and cycles data for fatigue sizing of the actuator. The user is requsted to input manually the number of fatigue layers. There is no prescribed limit to the number of layers								
High temperature (H.T.)			70	[°C]				
Low temperature (L.T.)			-20	[°C]				
Scatter factor on cycles			5					
Layer	Min load	Max load	Mean load	Load ratio	# of cycles	Fraction @ H.T.	Fraction @ R. T.	Fraction @ L. T.
	F_{min} [N]	F_{max} [N]	F_{mean} [N]	R	n			
1	-40000	80000	20000	-0,50	100	0,50	0,40	0,10
2	-60000	60000	0	-1,00	200	0,50	0,40	0,10
3	-20000	160000	70000	-0,13	500	0,50	0,40	0,10
4	-30000	40000	5000	-0,75	1000	0,50	0,40	0,10
5	-32000	40000	4000	-0,80	1000	0,50	0,40	0,10
6	-40000	48000	4000	-0,83	1000	0,50	0,40	0,10
7	-40000	120000	40000	-0,33	1000	0,50	0,40	0,10
8	-40000	40000	0	-1,00	1000	0,50	0,40	0,10
9	12000	24000	18000	0,50	1000	0,50	0,40	0,10
10	-80000	120000	20000	-0,67	1000	0,50	0,40	0,10

Figure 3. Example of table defining the fatigue spectrum

Table 01-1: Coefficients for mechanical losses								
Parameter	Unit	Actual	C/D	Default	Custom	Typical range		Notes
Radial bearings rolling friction coefficient f_{v1}		0,0015	D	0,0015	0,0020	0,0010	0,0025	

Figure 4. Example of table defining the parameters for parasitic effects calculation

- Sliding friction (proportional to the load)
- Rolling friction (proportional to the load)
- Tare (drag) losses (constant values not dependent on load or speed)
- Speed dependent losses, which on their turn are caused by sliding, rolling and viscous effects

The spreadsheet provides an indication for the following parasitic factors:

- Radial bearings rolling friction coefficient
- Radial bearings tare loss per unit diameter
- Radial bearings speed loss coefficient per unit diameter
- Thrust bearings rolling friction coefficient
- Thrust bearings tare loss per unit diameter
- Thrust bearings speed loss coefficient per unit diameter
- Ball screw rolling friction coefficient
- Ball screw tare loss per unit diameter
- Ball screw speed loss coefficient per unit diameter
- Ball screw seals tare loss per unit diameter
- Sliding friction coefficient
- Gears meshing loss coefficient
- Gears viscous loss coefficient
- Gears shaft seals tare loss per unit diameter

For each of these factors a default value is provided, but the user can either accept this value or introduce a value based on his personal experience by typing it in an appropriate cell as shown in the following Figure 4. Then, by typing either C or D in the C/D column, the actual value taken for the performance calculations will be either the default or the custom one. The same table also reports the typical range of values for that parameter at standard ambient temperature.

A second set of data contained in this spreadsheet is the variation of the parasitic effects with temperature. All mechanical losses tend to increase with decreasing temperature. The increase of the power loss with temperature depends on the specific parasitic effect (drag torque, friction, etc.) and on the actuator design and operation (type of lubrication, sliding speed for the components in relative motion, etc.).

A dedicated table of the spreadsheet provides the increase factors as a function of the temperature, which will be then used in the performance analysis. As for the values of the parasitic effects at standard temperature conditions, default values are suggested for the increase factors at low temperature in case no information is available for the specific actuator under study, but custom values can be used if data relevant to the actuator under study are known.

The default values are calculated as a function of the temperature with mathematical expressions having the following structure:

$$\begin{cases} \gamma = e^{\sum_{i=1}^{7} K_i \cdot (T-40)^i} & T < 0 \\ \gamma = h - i \cdot T & 0 < T < 40 \end{cases} \quad (1)$$

where T is the temperature in [°C]. This expression allows to replicate fairly well the increase of the parasitic effect with lowering temperature. All coefficients a, b, c, etc. are of course different for each physical parameter (friction, tare loss, speed factor, etc.). As an example, the following Figure 5 presents a diagram of the increase factor for the tare losses as a function of the temperature. It must be however strongly emphasized that these factors are only a reference used for the initial assessment of the actuator performance, and that the actual values will depend on the specific application and actuator characteristics.

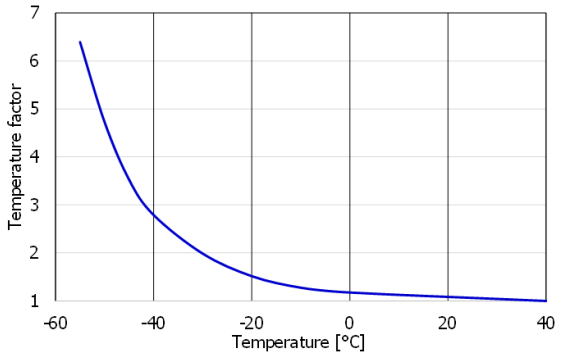

Figure 5. Temperature increase factor for tare losses

V COMPONENTS CHARACTERISTICS

The components characteristics are defined in a group of spreadsheets, each dedicated to a specific component: ballscrew, gear reducer, bearings, electric motor. For each component, the spreadsheet presents the values of the fundamental parameters that are needed for the performance assessment of the EMA and the more detailed parameters that are necessary for the structural verification. In case only the performance analysis has to be carried out, the full program runs anyhow using default data for the undefined parameters. This allows the designer to quickly carry out the initial tradeoff studies more focused onto the performance without the need of fully defining all detailed parameters needed for the structural analysis.

As an example, for the ballscrew the value of the lead is a fundamental parameter since it contributes to the actuator kinematic ratio; the balls pitch circle diameter is also important for determining the ballscrew efficiency, while others parameters are less significant for the performance analysis but are necessary for the structural analysis. The following Figure 6 shows a table with the list of the characteristic parameters of the ballscrew. It must be noted that the user can select some data from a drop-down list. For instance, for the material melting process, the drop-down list offers the following options: air melted, vacuum degassed, electro slag remelted, vacuum remelted. Note that the default value of the ball diameter shown in the table is computed as a function of the other ballscrew parameters.

A similar organisation is used for the definition of the characteristics of the other components. However, the spreadsheet for the gear reducer presents an additional feature relevant to the definition of the number of the stages of the gear reducer, which can be set equal to a value up to four. When the number of stages is changed, the layout of the spreadsheet is automatically modified leaving only the columns relevant to the actual number of stages. This is also reflected in the performance section of the program as it will be outlined later. The following Figure 7 shows the table defining the characteristic parameters of the gear reducer. As for the ballscrew, the user can select from a drop-down list the class of thickness tolerance and the gears material among a list of most commonly used materials for aerospace gears. Similarly, the spreadsheet for the bearings offers the possibility of selecting the bearing in a list of standard size bearings; when the bearing is selected, its characteristics are automatically loaded in the relevant cells of the spreadsheet.

For the electric motor, the electrical, mechanical and thermal data of the motor can be introduced as normally available from the catalogues. However, a feature is introduced which allows to compute the values of the torque constant and of the electrical resistance and inductance if the electric motor is rewound to obtain electric characteristics better suitable for the application under study.

Ball screw data					
Main input data					
Ball pitch circle diameter D_{pw}	37,000	[mm] =	0,0370	[m]	In this section the user is requested to input the main dimensions of the ball screw: these are the minimum data to be used for ball screw rating.
Screw lead P_h	8,009	[mm] =	0,00801	[m]	
Number of loaded turns i	8				
Hole diameter d_i	20	[mm] =	0,0200	[m]	
Material data					
Material hardness	633	[HV]			In this section the user is requested to input the material properties of the ball screw.
Material melting process	Vacuum remelted				
Accuracy class	0, 1, 3 and 5				

Table 03-1: Additional parameters for detailed ball screw dimensioning

Parameter	Unit	Actual	C/D	Default	Custom	Typical range		Notes
Max axial backlash $G4$	[mm]	0,050	D	0,050	0,050			
Profile characteristic z	[mm]	0,250	D	0,250	0,250			
Ball diameter D_w	[mm]	4,762	C	4,755	4,762			must be > 4,705
Ball track profile radius of ballscrew shaft r_s	[mm]	2,476	C	2,476	2,476			
Ball track profile radius of ballnut r_n	[mm]	2,476	C	2,476	2,476			
Ogival offset L	[mm]	0,055	C	0,054	0,055			
Center radius offset H	[mm]	0,078	C	0,078	0,078			
Fillet radius r	[mm]	0,3	C	0,3	0,3			
Ball turns efficiency coefficient		0,86	C	0,86	0,86			
Number of unloaded balls in the recirculation system where balls are recirculated after one turn Z_u		3	D	3	3			

Figure 6. Characteristic parameters of the ballscrew

INPUT DATA

This section contains the input data of the reduction gear stages

Spur gears reduction stages data

This sheet contains the general data of the reductions stages gears

Number of reduction stages				4							
Overall reduction ratio				32,63							
Stage number				**1**	**2**	**3**	**4**	C/D	Default	Custom	Typical range
Number of teeth	Pinion z_1			26	20	22	18	In red if gear is undercut, to avoid undercut incerease z or profile shift coefficient x			
	Gear z_2			50	40	56	60				
Gear reduction ratio				1,92	2,00	2,55	3,33				
Normal module m			[mm]	0,6	0,6	0,6	0,6				
Pressure angle			[°]	20	20	20	20	D	20,0	20,0	18,5	25,0
Profile shift coefficient	Pinion x_1			0	0	0	0				
	Gear x_2			0	0	0	0				
Addendum/module ratio h_a				1	1	1	1	D	1,00	1,00	0,80	1,10
Dedendum/module ratio h_f				1,25	1,25	1,25	1,25	D	1,25	1,25	1,20	1,30
Face width	Pinion b_1		[mm]	3	3	3	3				
	Gear b_2		[mm]	3	3	3	3				
Thickness tolerance	Pinion	Class		DIN 3967 e24	DIN 3967 e24	DIN 3967 e24	DIN 3967 e24	Drop-down menu Lower letter = higher backlash Lower number = tighter tolerance Typical values Case hardened gears: cd25 Nitrided gears: c27, c28			
		Δs_e1	[mm]	-0,03	-0,03	-0,03	-0,03				
		Δs_i1	[mm]	-0,05	-0,05	-0,05	-0,05				
	Gear	Class		DIN 3967 e24	DIN 3967 e24	DIN 3967 e24	DIN 3967 e24				
		Δs_e2	[mm]	-0,03	-0,03	-0,03	-0,03				
		Δs_i2	[mm]	-0,05	-0,05	-0,05	-0,05				
Gear accuracy according ISO 1328-1				6	6	6	6				
Roughness R_z [µm]				6,3	6,3	6,3	6,3				
Material properties											
Material name				42CrMo4	42CrMo4	42CrMo4	42CrMo4				
Material type				Hard tempered	Hard tempered	Hard tempered	Hard tempered				
Elastic modulus E			[MPa]	206000	206000	206000	206000				
Poisson's ratio ν				0,3	0,3	0,3	0,3				
Ultimate strength σ_u			[MPa]	1100	1100	1100	1100				
Limit strength σ_y			[MPa]	900	900	900	900				
Bending fatigue limit stress σ_{Flim}			[MPa]	370	370	370	370				
Pitting fatigue limit stress σ_{Hlim}			[MPa]	1220	1220	1220	1220				
Lubricant properties											
Lubricant viscosity at -40°C ν_{-40}			[mm²/s]	1150				D	1150,0	1150,0	1150,0	1150,0
Lubricant viscosity at 40°C ν_{40}			[mm²/s]	10,3				D	10,3	10,3	10,3	10,3
Lubricant viscosity at 100°C ν_{100}			[mm²/s]	3,1				D	3,1	3,1	3,1	3,1

Figure 7. Characteristic parameters of the gear reducer

VI PERFORMANCE ASSESSMENT

The assessment of the EMA performance is made by a two sets of spreadsheets. A first set of spreadsheets calculates the performance of the individual components of the EMA. For each component the frictional efficiency, the speed dependent losses and the tare losses are computed for different temperatures from +40 °C to -55°C as shown, as an example, in Figure 8. If necessary to evaluate the performance at a specific temperature (for instance -42 °C in place of -40 °C), the value -42 can be typed in place of -40 in the "General Data" sheet and the desired value -42 will show up in place of -40 in all spreadsheets. As shown in Figure 8, the performance characteristics of each component are computed for both running and breakout conditions.

A second set of spreadsheets is used to determine the overall performance of the EMA. The first of these sheets computes the EMA performance moving at the rated speed against the maximum load, and for the reference temperature conditions from +40 °C to -55 °C. In particular, the torque and speed of each EMA component are calculated as well as the motor input voltage, current draw and heat generated in the motor windings. Should the required input voltage exceed the rated input voltage, the corresponding cell is highlighted in red colour to alert of the impossibility to operate at the rated speed against the maximum load. If such condition occurs, the user can adjust the applied load and deployment rate, independently for each temperature, in order to obtain an input voltage lower than the reference value, through two different reducing factors γF and γω respectively applied to the nominal load and to the nominal rate.

The same spreadsheet performs the calculation for three input voltage conditions: nominal, reduced and degraded, thereby offering the user a full picture of the EMA performance with different input voltage available. Furthermore, the spreadsheet also includes the performance calculation for the breakout condition.

The same calculations are performed by other spreadsheets for the following cases:

- No-load
- Custom load (any load in the zero to maximum range for which the user wants to determine the EMA performance)
- Maximum aiding load

Since different actuation speeds may be defined in the extending and retracting directions of the actuator, the user can select in each spreadsheet the direction of motion and the appropriate speed is automatically selected for the calculation and the spreadsheet title is also automatically modified.

In addition to calculating the EMA performance for the previously reported cases, the program also performs the calculation of the EMA behaviour for each of the five operating cycles defined in the input section. This calculation is primarily aimed at determining the following quantities for each cycle:

- Instantaneous electric motor current, voltage and hence electrical power
- Mean value of the electric power converted into heat
- Mean value of the regeneration power
- Steady state temperature increase if the cycle is continuously repeated for a long enough time to reach a thermal equilibrium

The following Figure 9 shows the plots of current and voltage versus the azimuth angle of a single cycle for the case of an EMA subjected to a sinusoidal position command and to a constant load.

The last section of the performance analysis is dedicated to the assessment of the dynamic characteristics. A first sheets firstly computes the dynamic limits of the EMA in which the frequency of a sinusoidal cycle is plotted versus the maximum attainable travel. At low frequencies, the limit is of course determined by the physical maximum travel of the actuator; at intermediate frequencies the limit is normally determined by the maximum voltage, while in the high frequency range the limit is determined by the maximum current. Figure 10 shows the diagram with the dynamic limits for the EMA in an unloaded condition.

The assessment of the dynamic characteristics of the EMA is completed by the analysis of the EMA control loop. The program assumes that the EMA control is performed by three nested control loops: current, speed and position loop.

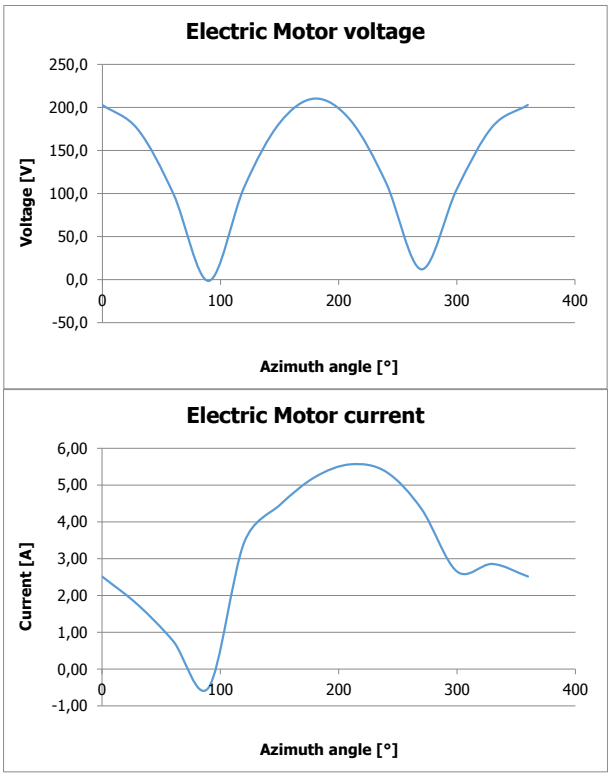

Figure 9. Example of diagram of current and voltage during a sinusoidal cycle

GEAR STAGE #1 PERFORMANCE

This sheet contains the gear stage #1 performance calculation

Gear mesh power loss data

Running		40 [°C]	0 [°C]	-10 [°C]	-20 [°C]	-30 [°C]	-40 [°C]	-45 [°C]	-50 [°C]	-55 [°C]	Working equations
Gears meshing loss coefficient k_{fl}:		0,2500	0,2540	0,2621	0,2691	0,2757	0,2865	0,2963	0,3119	0,3367	$k_{fl} = k_f \cdot \gamma_2$
Direct frictional efficiency η_{ds}:		0,9854	0,9852	0,9847	0,9843	0,9839	0,9833	0,9827	0,9818	0,9803	$\eta_{ds} = 1 - k_{fl}\left(\frac{1}{z_p} + \frac{1}{z_g}\right)$
Reverse frictional efficiency η_{rs}:		0,9852	0,9849	0,9844	0,9840	0,9836	0,9830	0,9824	0,9814	0,9799	$\eta_{rs} = 2 - \frac{1}{\eta_{ds}}$
Pinion viscous coefficient $k_{\omega ps}$:	[Nm/(rad/s)]	7,80E-05	1,35E-04	1,62E-04	1,97E-04	2,51E-04	3,50E-04	4,37E-04	5,74E-04	8,07E-04	$k_{\omega ps} = h_4 \cdot d_p \cdot \gamma_5$
Gear viscous coefficient $k_{\omega gs}$:	[Nm/(rad/s)]	1,50E-04	2,60E-04	3,11E-04	3,79E-04	4,83E-04	6,74E-04	8,41E-04	1,10E-03	1,55E-03	$k_{\omega gs} = h_4 \cdot d_g \cdot \gamma_5$
Breakout		40 [°C]	0 [°C]	-10 [°C]	-20 [°C]	-30 [°C]	-40 [°C]	-45 [°C]	-50 [°C]	-55 [°C]	**Working equations**
Gears meshing loss coefficient k_{fl}:		0,3250	0,3302	0,3407	0,3498	0,3584	0,3724	0,3853	0,4055	0,4377	$k_{fl} = k_f \cdot \gamma_2 \cdot s_f$
Direct frictional efficiency η_{ds}:		0,9810	0,9807	0,9801	0,9795	0,9790	0,9782	0,9775	0,9763	0,9744	$\eta_{ds} = 1 - k_{fl}\left(\frac{1}{z_p} + \frac{1}{z_g}\right)$
Reverse frictional efficiency η_{rs}:		0,9806	0,9803	0,9797	0,9791	0,9786	0,9777	0,9770	0,9757	0,9737	$\eta_{rs} = 2 - \frac{1}{\eta_{ds}}$

Radial bearing power loss data - Pinion shaft

Running		40 [°C]	0 [°C]	-10 [°C]	-20 [°C]	-30 [°C]	-40 [°C]	-45 [°C]	-50 [°C]	-55 [°C]	Working equations
Rolling friction coefficient f_{bs}		0,0015	0,0015	0,0016	0,0016	0,0016	0,0017	0,0017	0,0017	0,0018	$f_{bs} = f_{v1} \cdot \gamma_4$
Bearing speed coefficient $k_{\omega brs}$	[Nm/(rad/s)^{0,6}]	0,0024	0,0040	0,0048	0,0058	0,0070	0,0089	0,0104	0,0123	0,0152	$k_{\omega brs} = h_1 \cdot 0.66 d_{p1} \cdot \gamma_4$
Constant drag torque T_{bp1}	[Nm]	0,0093	0,0109	0,0118	0,0141	0,0184	0,0259	0,0327	0,0438	0,0592	$T_{bp1} = g_1 \cdot 0.66 d_{p1} \cdot \gamma_1$
Breakout		40 [°C]	0 [°C]	-10 [°C]	-20 [°C]	-30 [°C]	-40 [°C]	-45 [°C]	-50 [°C]	-55 [°C]	**Working equations**
Rolling friction coefficient f_{bs}		0,00195	0,00200	0,00202	0,00206	0,00210	0,00216	0,00220	0,00225	0,00231	$f_{bs} = f_{v1} \cdot \gamma_4 \cdot s_f$
Constant drag torque T_{bp1}	[Nm]	0,0139	0,0163	0,0177	0,0211	0,0276	0,0388	0,0490	0,0657	0,0889	$T_{bp1} = g_1 \cdot 0.66 d_{p1} \cdot \gamma_1 \cdot s_t$

Figure 8. Example of performance calculations for individual components: 1st stage gear

Since the current loop has normally a very high bandwidth, it is assumed to be analogue with a simple proportional control law. Should the current control loop be performed by a microprocessor, the recursion rate will be very high and have negligible effect on the overall performance of the EMA. The speed and position loops are assumed to be implemented in a microprocessor and that a PI control is used. For each control loop the program accepts the gains of the control parameters, the sampling time and the computation time of the microprocessor and the properties of the filters in the feedback signals. Based on the EMA characteristics and on the values of the control parameters, the program determines the frequency response for the speed and position control loops, the dynamic stiffness, and the open loop frequency response with the relevant phase and gain stability margins for the speed and position control loops. **Errore. L'origine riferimento non è stata trovata.** shows a case of frequency response for the position control loop.

VII STRUCTURAL VERIFICATION

The last block of spreadsheets is dedicated to the structural analysis of the main components of the EMA. For each component, the safety factors are determined for the following loading conditions:

- Maximum operating load
- Limit load
- Ultimate load
- Fatigue loads
- Endurance loads

Moreover, for the ballscrew, the buckling load and the relative safety factor are determined. For the gears, the stress analysis is performed for both bending and surface (pitting) stresses. As a result of the stress analysis, the cells containing the safety factors change colour as a function of the value of the safety factor:

- Red color for safety factor less than 1
- Yellow color for safety factor between 1 and 1.2
- Green color for safety factor greater than 1.2

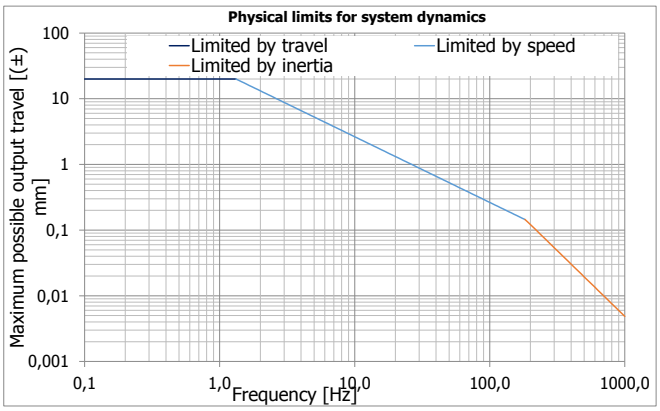

Figure 10. Dynamic limits for the EMA

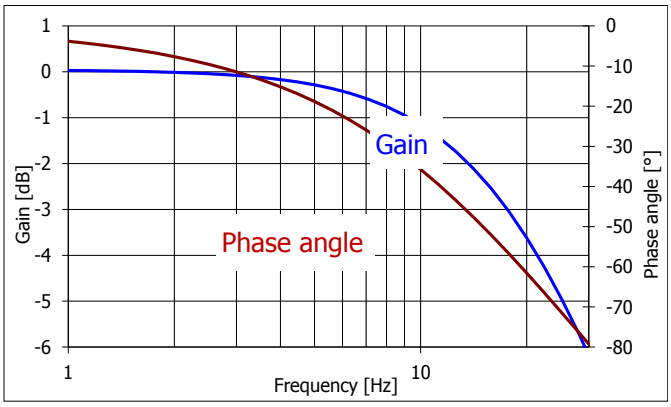

Figure 11. Example of frequency response for the EMA position control loop

Static axial load rating calculation			Working equations
Conformity factor of ballscrew shaft f_{rs}		0,520	$f_{rs} = \frac{r_s}{D_w}$
Reciprocal curvature radii:			
$\rho_{11} = \rho_{21}$	[1/mm]	0,420	$\rho_{11} = \rho_{21} = \frac{2}{D_w}$
ρ_{12}	[1/mm]	-0,404	$\rho_{12} = \frac{-1}{f_{rs} \cdot D_w}$
ρ_{22}	[1/mm]	0,049	$\rho_{22} = \frac{\cos\alpha}{\frac{D_{pw}}{2} - \cos\alpha \cdot \frac{D_w}{2}}$
Characteristic of basic static axial load rating k_0		66,991	$k_0 = \frac{27.74}{D_w \cdot \sqrt{(\rho_{11} + \rho_{12}) \cdot (\rho_{21} + \rho_{22})}}$
Basic static axial load rating C_{0a}	[N]	180907	$C_{0a} = k_0 \cdot Z_l \cdot i \cdot \sin\alpha \cdot Dw^2 \cdot \cos\varphi$
Correction for surface hardness f_{h0}		0,907	$f_{h0} = \left(\frac{Actual\ Hardness\ HV10}{654}\right)^3$
Accuracy factor f_{ac}		1,0	Class: 0, 1, 3 and 5 / 7 / 10; f_{ac}: 1 / 0,9 / 0,7
Static axial load rating C_{0am}	[N]	164034	$C_{0am} = C_{0a} \cdot f_{h0} \cdot f_{ac}$

Figure 12. Example of presentation of the equations used for the calculations

The calculation of the stresses in the mechanical components are performed according to the applicable ISO standards, and the appropriate stress concentration factors are taken into account based on the components geometry.

CONCLUSION

EMADEF is a program developed to provide a tool to the designer of an electro-mechanical servo-actuator for rapidly assessing all the main characteristics of the actuator and simultaneously evaluate the effect of the variation of a single parameter on all the characteristics of the servo-actuator: steady-state and dynamic performance over the entire range of loads and temperatures, controllability, structural behaviour against static, fatigue and endurance loads, electrical characteristics and thermal behaviour. This can be of particular benefit to the designer in the initial phase of the development of an EMA when a tradeoff analysis is typically performed among different solutions to identify the one which optimizes the overall EMA design.

It is worthwhile to note that all the mathematical relationships used for the calculations are clearly described in boxes near the cells where the calculations are performed, which helps the user to clearly understand the physical bases for the computation of all variables. As an example, the following figure shows a section of the static axial load rating of the ballscrew.

EMADEF presently addresses EMAs with a ballscrew, but work is under way to address EMAs with rollerscrews. Future developments of EMADEF will consider architectures with epicyclic gear reducers and also architectures with rotary outputs.

REFERENCES

ISO 3408-5:2006 *Ball screws -- Part 5: Static and dynamic axial load ratings and operational life*

ISO 6336-5:2016 *Calculation of load capacity of spur and helical gears -- Part 5: Strength and quality of materials*

AKNOWLEDGEMENTS

This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement CSJU – GAM REG 2014-2015.