LUBFORLIFE: MORE RELIABLE AND COST COMPETITIVE VTOL ELECTRO-MECHANICAL EQUIPMENT, FROM MULTIDISCIPLINARY SIZING TO TRIBOLOGY IMPACTS TO LOWER COST OF OPERATION.

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Abstract

Re-lubrication of Electro-mechanical actuators (EMA) is synonymous with aircraft downtime, mobilising resources, increased aircraft operating costs and higher risk of fault conditions caused by human error.

With the challenging task of eliminating re-lubrication during the entire electro-mechanical actuator operating life, UMBRAGROUP is leading a Research & Technology (R&T) project, called LubForLife, in collaboration with academics and industrial partners.

This R&T project seeks to achieve more realistic results by addressing the needs of a real flight-control actuator based upon requirements set with one of the major airframer who is closely associated with the project and milestones.

In this paper, UMBRAGROUP lists all the key design aspects identified as drivers for a ball screw based EMA and focuses, then, on some main aspects linked to tribology, architecture and configuration, laying the foundations for the definition of a new standard for electromechanical actuators with no maintenance tasks or very limited ones.

1. GENERAL

For almost 50 years UMBRAGROUP has defined new standards in the production of ball screws from its experience in the design and manufacture of ball screws and from its global MRO services.

In parallel, UMBRAGROUP started investing in “equipment engineering” know-how more than 20 years ago, which led to the optimised integration of different techno-bricks of electromechanical actuation.

Among several other electromechanical actuators in service, UMBRAGROUP designed and now manufactures the 1st safety critical extension and retraction landing gear electric actuators suite for ~~a~~ commercial helicopter certified by EASA.

The LubForLife project is financed by the Italian Ministry of Education, Universities and Research and it is covering partially the UMBRAGROUP investment on the wider activity of reducing the total Life cost of its actuators. UMBRAGROUP also received the support of Airbus Group with mentoring activities to define realistic conditions for the envisioned actuator (size, profile of mission, …) and with guidance and coaching during the development.

The challenging goal of the project is to design, develop, manufacture and test in real-life conditions a maintenance-free actuator. Of course, only the feedback from the field and the in-service experience will lead to the manufacture of a mature product; nevertheless, the study and the progress made are considered a strong baseline for the future applications.

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2. LUBFORLIFE R&T

2.1. Project Overview

The objective of the project is to integrate innovative components and technologies in an EMA, for VTOL, aircraft and UAVs flight controls, that do not require re-lubrication for the entire operating life, reducing maintenance cost and also reducing opportunity for fault conditions caused by human error. The output of the R&D project is to build a "scale 1" actuator in order to perform some representative tests such as wear tests and tests used to validate the analyses and the predictive models.

The project is divided in 11 different work packages:

- lubricant selection,
- actuator architecture,
- sealing system and materials,
- actuator and lubricant diagnostic,
- electric motor,
- methodological process configuration,
- test method for the screening of component and assemblies
- design and manufacturing of the demonstrators
- environmental and endurance tests
- test results validation and feedback to the design

Depending on the content of each Work Package, the target has been:

- to increase specialized knowledge/ to set new standards on the topics in which UMBRAGROUP is already recognized as a point of reference by the market (e.g. ball screws, bearings and more generally "rolling" parts);
- to expand the knowledge on other "bricks" in order to increase UMBRAGROUP system integrator competencies.

2.2. Topic manager: UMBRAGROUP S.p.A.

UMBRAGROUP is a world leader in supplying ball screws for safety critical applications, as Tier 1 and Tier 2 for all the major players in the aviation. UMBRAGROUP is indeed single supplier for Boeing as Tier 1 and Tier 2 depending on the applications, Tier 1 for Airbus Helicopters, Tier 2 for Airbus Commercial Aircraft, Tier 1 of Dassault and Leonardo.
As long-time ball screw supplier, UMBRAGROUP understands that the re-lubrication policy is one of the main drivers for the total life cycle cost of the equipment in this field and consequently a driver for system integrators, aircraft manufacturers and flight companies.

UMBRAGROUP operates one of the largest worldwide MRO stations in central Italy and one in the United States. It has established a strong collaboration network with many other stations all over the world and has collected data from in-service for decades.

The focus on total life cycle cost is an important prerequisite in designing UMBRAGROUP's electromechanical actuation system. When UMBRAGROUP started to integrate the different technologies, such other mechanical parts/sub-assemblies (bearings, gears / pinions, …) and electric parts (electric motors and brakes), the area of study was enlarged from the lubrication topic to all the other work packages of LubForLife projects mentioned in paragraph above.

2.3. Partners

Obviously, this ambitious research program cannot be conducted within UMBRAGROUP alone, since it requires academic skills and specific knowledge and it is therefore conducted, under UMBRAROUP leadership, with the following associated partners:

- UNIAQ - University of Aquila
- E.M.S. - Electro Motor Solutions S.r.l.
- EnginSoft

3. STATE OF ART & BACKGROUND OF BALL SCREW BASED ACTUATORS

3.1. Material selection and RETEX

UMBRAGROUP was the first to introduce corrosion-resistant steel CRES for aerospace ball screw *(commercially known as Cronidur ® 30)* with no in-service issues for almost 30 years on Boeing 777 flap ball screws. Since then, Cronidur ® 30 ball screw has become the standard in the High Lift System, Horizontal Stabilizer Trim Actuator (HSTA), electric thrust-reverse actuation system (eTRAS), electric brake and it was possible for UMBRAGROUP to cumulate a Return of Experience (RETEX) of Millions of Flight Hours.

The choice of this innovative material met the following two main needs:

- the requirement of having a corrosion-resistant steel for exposed components;
- the issues of having surface treatments (i.e. cadmium and chrome plating) in terms of functional aspects (durability, required maintenance, reliability, …) and impact on the environment.

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The results of comparative endurance tests in dry conditions have shown conspicuous advantages with the previous standard i.e. chrome plated SAE 9310. In particular, the backlash evolution is significantly decreased, while keeping, as a consequence, the efficiency at a constant value for a number of cycles five (5) time larger than previous standard material and reaching the same value of efficiency only after a number of cycles seven (7) times higher.

See graph below.

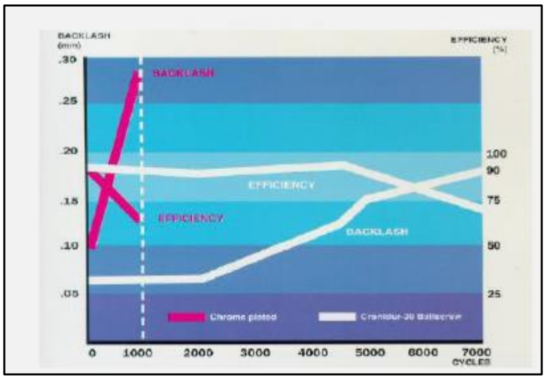

Figure 1 – Results of comparative endurance tests in dry conditions

Moreover, results of comparative salt spray tests per ASTM B 117, after 500 hours, highlighted a much better behaviour against corrosion using Cronidur ® 30.

Finally, the advantages that allowed Cronidur ® 30 to become the new standard for ball screws are: a) superior performance in terms of corrosion resistance and, b) rolling contact fatigue resistance and wear resistance. It is then possible to obtain, through the Induction hardening processes, a local hardening for the screw shaft and ball nut threads and flanges while keeping a lower hardness and, consequently, a higher toughness in the core sections of the components.

3.2. Best practices on ball screw design and rolling elements

UMBRAGROUP has improved its design criteria starting from International Organization for Standardization (ISO) norms, ISO 3408, being able to optimize the Hertzian contact pressures thanks to proprietary software developed and thanks to the use of Finite Element Analyses that allows the calculation of punctual load on each ball.

In addition to that, UMBRAGROUP has been able to optimize the trajectories of recirculating systems leading to a smoother path with respect to standard applications.

This has been confirmed by the evidence of a wide range of tests performed in UMBRAGROUP test laboratories - functional tests in different conditions, structural and vibration tests, environmental tests - and, again, return of experience from the field. These data closed the loop regarding the improved methodologies developed by UMBRAGROUP.

The alternate filling configuration is also considered a key driver allowing a reduction of wear with equal or even higher allowable contact pressure on each ball. The configuration consists of having alternate balls with two different sizes: the load is obviously carried by the bigger balls only, while the smaller ones help the cinematic mechanics allowing pure rolling instead of sliding.

In static conditions, an alternate configuration minimizes the pulsating load effect, reducing pitting and plastic deformation, leading also to a better performance in respect to “false brinelling”.

The benefits of the alternate configuration mentioned above are improved even more by adopting, as loaded balls, the ceramic balls that reduce furtherly friction and wear. In terms of corrosion resistance, ~~then~~, the configuration is completely corrosion-resistant and avoids the use of similar materials, which, even not being a mandatory requirement is not recommended due to the potential micro-welding that may occur locally in the points of contact between the balls and the balls’ races.

Figure 2 – HSTA Ball screw assembly

4. LUBRICANT SELECTION AND TRIBOLOGY CONSIDERATIONS

4.1. General

During the project, even in the initial phases, UMBRAGRUOP and its partners identified some key factors, linked between them as described below.

The first key factor considered is the lubricant selection and all tribology related considerations based on that. This relevant key factor is strictly

linked to the architecture and design criteria of the rolling elements.
The architecture selection, together with the design criteria of the rolling elements, indeed, prevents or facilitates the presence of particles, both external and internal due to wear of the components. Refer to the dedicated chapter for further details about Architecture and Design Criteria.

The purpose within the LubForLife project has been to identify "long life" lubricants for aeronautical use.
Currently, the standard in aerospace application for ball screws is the use of greases. Oil is used for some applications. Solid lubricant is more confined in R&D projects or specific conditions (e.g. Space application).
The use of oil in particular has been prevented by the architecture of actuation systems and installation condition of the ball screws: for example, in standard flap application where ball screws are quite exposed.
Moreover, the lubricant should not have a high viscosity at lower temperature (i.e. -54°C) because this would cause a high resisting torque and, consequently, it affects badly the motor sizing.

The goal of the LubForLife project is that the lubricant must allow the actuator to complete its service life with the lubricant applied on the first assembly without any substitution or maintenance task.
Therefore, all the rotating mechanical parts, especially, ball screw and ball nut, bearings and gears (if any) must not require re-lubrication for the entire operating life.

4.2. Lubricant selection

The activity has followed three main points:

- research on the state-of-the-art of lubricants;
- definition of lubricant requirements for the application;
- survey of lubricant suppliers.

Between all the products available currently on the market, seven (7) potential synthetic candidates have been identified as types of lubricant suitable for the application.

The main characteristics of selected lubricants for tests are oil and greases with, as base oil: PFPE, ESTER, PAO; and as a thickener: PFTE, COmplex Lithium Soap, Lithium.

Then, between them, the selection criteria for the lubricants to be tested has been based on the results of the following:

- the calculation of the viscosity ratio;
- the performance test results (torque) at different temperatures.

The viscosity ratio (k) is an indicator of the integrity of the lubricant at the various temperatures and speeds and to ensure a correct lubrication regime it must be in the range from 1 to 4. This is referred to operating conditions and not storage conditions.
The calculation of the viscosity ratio (k) for bearing and ball screw lubrication has been then performed taking into account the following inputs:

- average bearing diameter
- nominal ball screw diameter
- rotational speed

and

- temperature: 40 °C, 70 °C, 100°C

The picture below shows the calculation results for one of the selected greases: each color represents a case study function of the listed-above parameters.

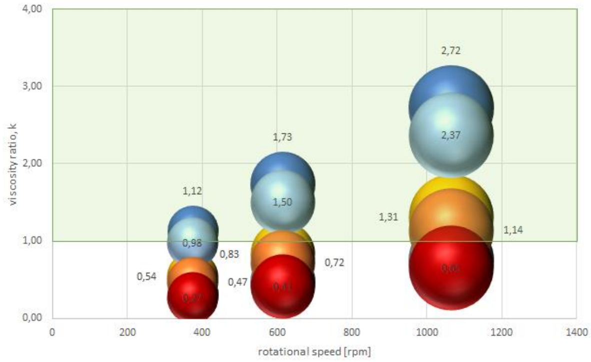

Figure 3 - Calculation of the viscosity ratio - Grease#1

Regarding Temperature torque test, a complete experimental characterization of torque produced by lubricants at different temperatures (70°C, RT, -30°C and -54°C) has been performed.

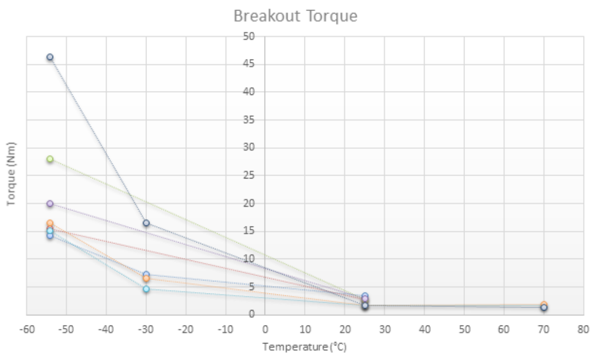

Figure 4 – Breakout Torque for different lubricants

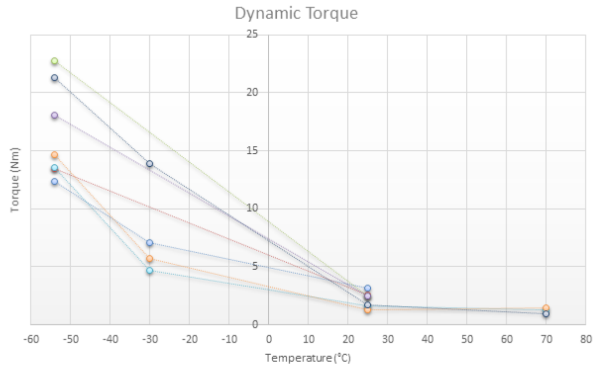

Figure 5 – Dynamic Torque for different lubricants

The test has been performed in a climatic chamber at a stabilized temperature.
Ten (10) cycles of extension/retraction at 100 rpm speed have been performed and the torque required to initiate motion (breakout torque, see Figure 4) and and to sustain motion (dynamic torque, see

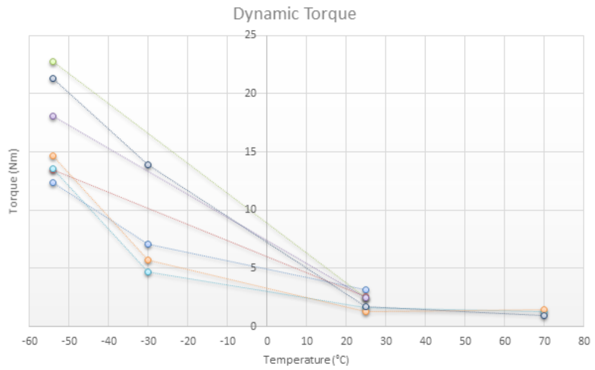

Figure 5) have been recorded.
This test, combined with the mentioned-above theoretical calculation of the viscosity ratio, allowed to discard two (2) lubricants from the selection.

4.3. Tests on lubricants

Within the project, an Endurance test for the characterization of lubricants in terms of duration/life has been performed. This test has been supported by a Wear Debris Analysis, that allowed to measure the wear debris concentration after 50,000 endurance cycles, in particular considering:

- Total particles
- Cutting particles (due to abrasive wear)
- Sliding particles (due to adhesive wear)
- Fatigue particles (due to fatigue on the surface)
- NonMetallic Particles

An aging test for the evaluation of the aging lubricant resistance under accelerated conditions has been also performed: in particular, it has been done a characterization of lubricating properties such as additive aging Extreme Pressure (EP) Test and a Wear Preventive (WP) Test, based on the following test standards: ASTM D2783 for oils / ASTM D2596 for greases and ASTM D4172 for oils / ASTM D2266 for greases.

Finally, taking into account all the test results, an accelerated comparative test, at ball screw assembly level, has been then performed considering two (2) greases and the following two PVD coatings previously selected in another LubForLife work package and available on the market:

- DLC Diamond-Like-Coating, which is a PA-CVD (Plasma Assisted-Chemical Vapor Deposition)
- WC/C Tungsten Carbide/Carbon based multi-layered amorphous coating, which is a PE-CVD (Plasma Enhanced Chemical Vapor Deposition)

In the selected ball screw configurations, the coatings have been applied in order not to remove the traditional lubricant, but with the aim of reducing surface roughness and increasing surface hardness preventing sliding effect on rolling elements and improving the behavior in poor lubrication conditions.

Preliminary test results confirmed that the coatings provide some initial beneficial effects, nevertheless, that a specific coating, possibly to be used as solid lubricant *(e.g. liner on ball bearings)*, has to be specifically developed based on the application and operating conditions (e.g. shocks, small movements).

5. ARCHITECTURE AND DESIGN CRITERIA

5.1. General

Between all the parameters analysed one the most influential has been identified in the actuator architecture. This, as said, influences the lubricant behaviour and prevents the contamination from external agents (i.e. water, dust, A/C fluids) and internal (i.e. components' wear). Moreover, the architecture determines the exposure to high temperature that facilitates the oxidation and, in case of use of grease as lubricant, the separation of the oil from the grease.

The factors for definition of the architecture can be grouped as follow:

- motor torque transmission: direct drive, geared;
- sealing concept: sealed, hermetic, intermediate;
- materials: stainless, standard;
- motor configuration: axial flux, radial flux, magnetic geared

- antirotation: balls' bushings, elliptical;
- sensors: RVDT, LVDT.

A total of seventy-two (72) configurations have been analysed.
The screening process of selection of the actuator was followed using two steps:

- Concept screening, for a qualitative selection of the identified configurations;
- Concept scoring, analysing, through a quantitative scoring, the remaining configurations.

5.2. Sealing Concept

The sealing system has been selected after a screening process that took in consideration different design factors and, obviously, the material compatibility with lubricant and A/C fluids. In particular, for the sealing concept the following parameters have been considered: weight, envelope, sealing efficiency, reliability and durability. In addition, cost - intended as costs of the components/sealing system and the cost of all the working operations needed for the proper installation and functioning of the sealing system - has been taken into account.

The selected sealing system is composed of:

1. Wear Ring
2. Dynamic Seal
3. Scraper

The baseline for the LubForLife actuator is Glass fiber reinforced polyamide for the wear ring, Polyurethane elastomer of the Dynamic Seal and Polyurethabe elastomer for the Scraper.

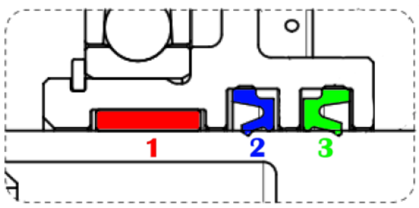

Figure 6 – selected sealing system

It is necessary to mention that currently none of the potential seal suppliers can currently guarantee a useful life higher than 15 years. This is based on 10 years of standard duration plus 5 years of extension depending on operating conditions. A further extension could be taken in consideration once accelerated endurance test results will be available.

5.3. Motor design

A surface Permanent Magnets (PM) machine with concentrated windings has been designed; the goal was to define a direct drive syncronous Machine focusing on the key points of performance, reliability, envelope, torque density, simplicity, reliability, integration with the other parts and efficiency. For this specific application, the 24 stator slots and 22 rotor poles single layer fractional slot motor topology has been selected. The alternate winding configuration is easier to manufacture since there is 1 coil slide per slot and provides higher self-inductance and lower mutual inductance hence better fault-tolerance and flux-weakening capability.

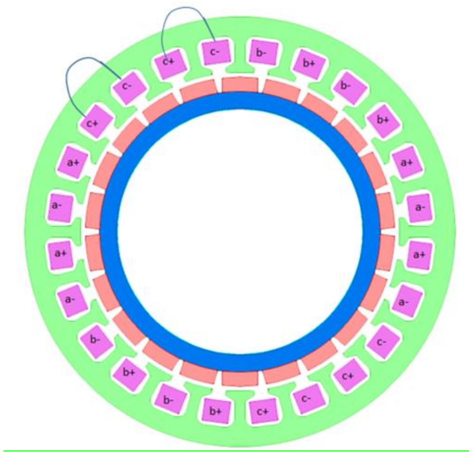

Figure 7 –winding motor layout

Moreover, a motor with double layer winding may suffer from lower overload torque capability with respect to single layer solution due to higher magnetic saturation of the stator tooth tip in the double layer winding machine.

The design is based on the principle of independence between the motor phases, from the point of view of electrical, magnetic and thermal interactions, so that fault conditions in one phase do not affect the operation of the others.

The main motor dimensions have been calculated by means of a prioprietary softwares and Finite Element Analyses.

The preliminary design has been used to have a first and approximate performance result, thanks to optimization procedure and final design refining by a finite element analysis, the optimal configuration for the application was defined.

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5.4. Other main design features selection

For the other main design features, the selection process has been based on the following key parameters:

- for sensors: envelope (of the sensors and consequent envelope due to the different design solution) and measurement accuracy;
- for anti-rotation device: weight and envelope, efficiency, reliability, durability and resistance to wear;
- for materials: resistance to wear and to corrosion. Regarding the resistance to corrosion these has been evaluated jointly with the sealing system.

For all the features, recurring cost is considered a driver being both a relevant contributor of the life cycle cost of the system and a further indicator of maturity and feasibility of the solution.

5.5. Architecture selection

5.5.1. Baseline

From the total number of initial configurations, eight (8) designs have been selected and, then, a further selection has been done for defining the "baseline", taking into account globally performance, envelope, weight and power consumption.

The baseline configuration selected in LubForLife is:

Motor	Sealing concept	Antirotation	Materials	Sensors
Radial Flux	Sealed	Balls Bushings	Stainless	LVDT

The baseline configuration is a "direct drive" fully-sealed meaning that there are no gears between the electric motor and the ball screw assembly, which transforms the input torque in an output linear force.

The selected configuration foresees an internal anti-rotation through a ball bushing. An output rod linked to the ball screw assembly is the mechanical output that allows to keep protected the ball screw thread.

There are no gears for reducing speed and increasing the torque, consequently the radial envelope and the weight are higher with respect to a geared configuration under the same output force.

Nevertheless, the biggest advantage of the direct drive configuration is that, having no gears, the wear is significantly reduced and the presence of detrimental metallic particles too is significantly reduced.

It has been demonstrated, once again also within LubForLife project, that the direct drive configuration is intrinsically more reliable than an equivalent geared solution.

5.5.2. Innovative alternative architecture

In parallel to the course of LubForLife project, UMBRAGROUP has developed a patented solution for a transmission torque without using gears and having only ball screws in the design.

As stated, Direct Drive Actuators have the advantages of a low number of components and deep integration leading to high reliability, lowering wear. Nevertheless, the electric motor has to be sized to generate a torque directly linked to the ball screw lead. Since the ball screw lead is driven by the applied load to accommodate the right ball size, the electric motor is usually working with high torque and low speed requirement or, in some cases, the required envelope risks to be increased.

Indeed, the applied load in a standard linear actuator is entirely borne by one ball screw that leads to a large ball size (and so to a large lead) and consequently to a high motor torque requirement.

Linear actuators with high ratio gear boxes are generally adopting sliding friction devices (i.e.: worm gear, harmonic drive, etc) generating wear and so having shorter life-time. For this reason, this kind of solution has not even been considered in first screening configuration within LubForLife project.

Instead, UMBRAGROUP's patented design consists of an actuator sub-assembly based on ball screw technology.

In particular, the core of the actuator is a roto-translating screw that is a differential ball screw that allows to reduce drastically the torque motor (increasing its speed, under the same power). The torque is no longer linked to the physical lead but to an equivalent lead that can be chosen by the design and the definition of the differential ball screw and its ratio.

Adopting the UMBRAGROUP's patented solution, a wide range of transmission torque is possible. In this specific case, considering the envelope of the LubForLife project, the torque ratio is 1:2.

5.5.3. Conclusions on architecture selection

Within the LubForLife project at least three (3) different actuators are planned to be tested through a HALT test campaign.

Among the three actuators to be tested, also the alternative solution described in this paper has been manufactured and will be tested.

Figure 8 – one of the LubForLife actuator configuration

6. METHODOLOGICAL PROCESS FOR EMA DEVELOPMENT

A Digital Twin model has been developed to simulate the behaviour of the actuator in order to predict wear and constantly monitoring the remaining life.

Generally speaking, a Digital Twin is a virtual representation of physical asset, that could be a multi-physic complex system. It can be considered a connected virtual replica of an in-service physical asset. Within LubForLife project, the Digital Twin, being a multi-domain and multi-physic system model, enables the prediction of system response, the monitoring of phenomena to which the system is subjected and the evaluation of operational parameters, such as performances, and, as said, the remaining useful life.

The input data of the Digital Twin and the related output will be constantly monitored during the test that will be performed on the actuators. The Digital Twin model will be validated during LubForLife test campaign.

Once validated, it will also provide support to the design process, allowing the optimization of the different design features.

The methodology exploited during the implementation consisted of the following five (5) steps:

1. conceptualization of the whole system: system engineering team defined physical field of the phenomenon in order to create a logical process replicating the reality. In this first phase, the system has been conceptualized from an electromagnetic and thermal point of view in order to evaluate and characterize the system temperature increment due to power winding loss of brushless motor. The power loss of the electromagnetic motor, that drives the ball screw actuator, was evaluated based on input values of torque and rotational speed (extracted through sensors embedded in the physical system). The temperature changes have been evaluated on the basis of power winding loss and boundary conditions (such as external temperature and convection coefficient);
2. definition and implementation of detailed numerical models used for the accurate and reliable solution of the involved physical phenomena;
3. implementation of ROM (Reduced Order Models) in order to reduce the computational effort from the detailed numerical models;
4. Integration of analytical, numerical and reduced order models into a multi-physic system model able to replicate the behavior and the response of physical asset;
5. Calibration of the system model on the basis of comparison with results from full numerical models.

The input variables of the here reported system model are:

- Torque needed at actuator level and provided by the brushless motor;
- Shaft rotational speed corresponding to the speed of rotor that is converted into stator translational speed;
- Flight altitude at which the system is working (for calculating the external temperature)
- Flight speed (for evaluating the forced convection)

Other parameters have been defined in the model as constants (such as the geometrical parameters). The monitored outputs are the average temperature of the whole system and of the brushless permanent magnets as shown in Figure 9.

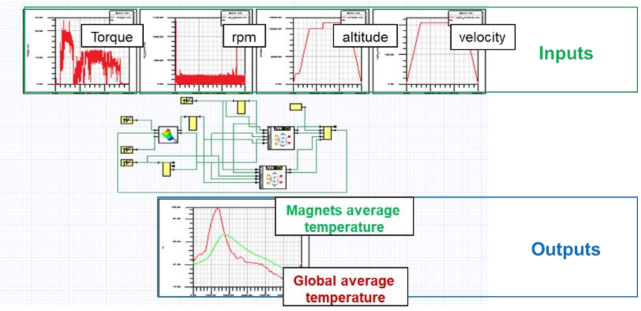

Figure 9 – Electromechanical actuator system model

This system model, enables the real-time and on-demand evaluation of results. The predicted output temperatures are then used for the evaluation of lubricant viscosity through analytical models, for monitoring wear conditions (especially on the contact surfaces between balls and screw shaft threads) and for forecasting the useful residual life and the health state of the system.

7. CONCLUSIONS

Within LubForLife project, UMBRAGROUP and its partners have identified and then analysed the main factors for developing a solution that does not require any maintenance task or, at least, will allow to increase the lubrication intervals.
These factors are strictly interlaced and may affect each other: lubricant selection and sealing systems are indeed relevant items, nevertheless, the architecture definition and design criteria of sub-systems and components may be the real differentiators due to the impact of internal debris on the whole system.

The completion of HALT test campaign will allow further information to be considered in conjunction with the preliminary evidences of the study.

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