Virtual Performance Evaluation for Electro-mechanical Actuators considering Parameter Uncertainties

KREITZ Tobias, ARRIOLA David, THIELECKE Frank
Hamburg University of Technology
Institute of Aircraft Systems Engineering
Nesspriël 5, 21129 Hamburg, Germany
Phone +49 (0)40 42878 8202
Email: tobias.kreitz@tuhh.de

ABSTRACT
The transition from state-of-the-art hydraulic actuation to new electro-mechanical technologies poses a great challenge to both airframers and suppliers for the implementation of appropriate test campaigns during the certification process. Transient effects such as electric motor overheating and inertial loads, previously not present or irrelevant for hydraulic actuators, now have to be taken into account. By implementing a concept for virtual testing of electro-mechanical actuators, the classical development process is enhanced by an integrated, model-based approach. This provides the opportunity for an early execution of performance evaluations to assess the requirements and identify errors before a real prototype has emerged. The use of dedicated, test-driven models allows conducting extensive parameter studies for uncertainty analysis. These concepts are illustrated with a case study of a short-range aircraft’s elevator electro-mechanical actuator.

KEYWORDS
Electro-mechanical actuators, parameter uncertainties, virtual performance evaluation, virtual testing

I INTRODUCTION
The concept of all-electric aircraft gains always more relevance among aircraft manufacturers in sight of the goals in terms of CO₂ emissions reduction dictated by the European vision for aviation Flightpath 2050. Novel electrical power system architectures enable the use of electricity as the primary source of power. This leads to a simplification of the distribution networks of non-propulsive power systems by eliminating hydraulic lines. The underlying motivation for this technological evolution is the reduction of weight (at aircraft level) and maintenance costs associated with hydraulic systems. A key element to be able to make this step is the use of electro-mechanical actuators (EMA) for primary and secondary flight controls.

EMAs for flight control applications typically consist of a set of actuator control electronics (ACE) driving a permanent magnet brushless motor whose fast rotational output is transformed into a slower rotational or translational motion by a mechanical transmission (Fig. 1).

![Figure 1. Linear electro-mechanical actuator](image)

The intrinsic physical relationships among EMA components and the lack of experience in testing these devices poses a great challenge for defining all possible test scenarios to which the actuators can be exposed during flight. Before conducting costly system qualification tests, it is convenient to test virtually all possible scenarios and identify test procedures that can cover the maximum number of scenarios with the minimum number of tests. This could reduce qualification costs and guarantee the performance of an actuator under all scenarios.

In the next chapter the general approach for virtual testing will be explained, followed by a description of the EMA system under test and its corresponding model. Subsequently, the setup of several test-cases will be shown along with the analysis of the results obtained from a series of simulation runs. Additionally, the fulfillment of applicable requirements will be evaluated.
II VIRTUAL TESTING APPROACH

The development of new aircraft systems is a challenging process due to the high complexity and the multidisciplinary nature. Figure 2 shows how model-based and virtual methods can enhance the common V-Model of the well-known development process [VDI 04]. Simulation models are used to support the system development during decomposition and definition as well as in the integration and verification phase.

Figure 2. Enhanced model-based development process

Model-based approaches have long been an accepted part of the design and optimization process for complex system architectures. In this regard simulation studies enable the evaluation and validation of architectures with respect to overall design criteria and functional requirements. The concept of virtual integration extends this approach to the right branch of the V-model (Fig. 2), and offers the possibility to perform virtual tests for the assessment of performance related requirements [GRY 12]. Especially in early development phases virtual integration can enable the identification of inaccurate specifications, which are usually found during real integration tests. Due to the avoidance of faults and a better system understanding virtual integration enables the reduction of development time and costs [THI 11]. This benefit has already been shown in other research projects, e.g. in the scope of high lift systems and costs [THI 11]. This benefit has already been shown in other research projects, e.g. in the scope of high lift systems.

Virtual integration in this paper means the combination of all individual item models to an overall dynamic model of the considered actuation system. Based on the definition given in [KRE 13], virtual testing is to be understood as the actual execution of various simulation runs and the evaluation of results with respect to the determination of specific system characteristics to demonstrate compliance with selected system requirements. The main purpose of virtual testing is thus the reduction of physical experimental effort on system level. This assumes that the different models of the individual items have been previously validated using results from separate hardware test benches. The implementation of virtual testing may be divided into various steps, which are shown in Figure 3. The physical models of all involved system components are collected in a model library. This library includes models for the simulation of electro-mechanical actuator items as well as the actual test infrastructure. The concept of virtual testing aims at investigating the interaction of all modules involved. A challenge is therefore to combine the generic item models to a numerically stable overall system simulation.

The test cases are derived from the requirements specified for the object under test. It must be noted that all physical effects that are relevant for a specific test have to be taken into account during the modeling process.

Figure 3. Overview of the virtual testing approach

The execution of the overall system model with the test sequences previously defined can be done fully automated. Therefore the component parameters are loaded, which were obtained during the detailed design and model validation phase. Finally the test object is evaluated with respect to the defined requirements. Subsequently, the test results are processed and visualized.

III HINGELINE EMA SYSTEM MODEL

The modeling methods employed along the different phases of the system development process depend on the goals to be achieved in each individual phase. In the virtual testing phase, it is necessary to create models that resemble both the topology and the behavior of the real system. This however can have an impact on simulation time since the number of necessary elements to be modeled and the incurring nonlinearities increase significantly. Since virtual testing is performed primarily at system-level, it is assumed that the characteristics of each individual system component are known and all their parameters have been measured experimentally. This aids the creation of detailed models with the use of experimental data for parameters that are usually unknown during the design phase like frictional losses. A model of a hingeline electro-mechanical actuator for elevator control was created under these considerations in MATLAB/SIMULINK/SIMSCAPE. Similar to other a-causal modeling languages, Simscape offers the possibility of modeling multi-domain systems upon the principle of power transfer among components. Through interaction with Simulink, hybrid models can be created. This implies modelling the physical system or plant using Simscape components, while carrying out the controller design and signal generation in Simulink.
Figure 4 illustrates this modelling approach on the elevator’s hingeline EMA model used for virtual testing in this investigation.

![Physical model in SIMSCAPE](image)

**Figure 4. Hingeline EMA model**

The model can be broken down into three main parts: the actuator control electronics, the permanent magnet synchronous motor (PMSM), and the mechanical transmission. In the following these parts will be described in detail.

**Actuator Control Electronics**

It is relevant to test virtually not only the electromechanical components of an EMA but also the drive electronics. This has a twofold advantage. The signals that would be transferred in real control electronics can be monitored, while also permitting a more realistic failure modeling. The individual elements of the cascade control loop are modelled in Simulink starting with the outer position loop up to the pulse width modulation (PWM). Position control is performed with a proportional controller that outputs an angular speed demand. The torque demand resulting from the inner angular speed control loop is transformed into a current demand using Park’s transformation. Within the *stator currents synthesizer* this current signal is converted to a three-phase current demand which is handed over to the PI current controller. The controller outputs the error between current demand and current feedback from the motor as three-phase voltage signals which build up the reference signals $V_{a,b,c}^*$ for the PWM.

Between the PWM and the three-phase inverter a transformation from signal-based to physical modelling occurs. The IGBTs are Simscape physical models whose gate voltage signals are generated by the signal-based PWM. Each phase of the electric motor is connected to an inverter leg as would be done in real hardware, enabling monitoring of all motor terminals.

**Permanent Magnet Synchronous Motor**

Modelling the PMSM physically, allows creating a model in the a-b-c frame [KRI 10] with relative simplicity. The a-b-c currents are thus not transformed to the rotor reference frame within the model. Similar to the ACE, this enables the monitoring of “real” signals with no significant penalty on simulation time. In a first attempt to test the entire EMA system virtually, only frictional and copper losses were modeled for the PMSM. Applying a high-frequency instantaneous voltage at 5-10 kHz to the motor phases poses already a great challenge for the simulation’s integrator in terms of nonlinear behavior.

**Mechanical Transmission**

The mechanical transmission consists of a high reduction ratio gearbox, in this case a Harmonic Drive, performing speed reduction. An output lever of length $l_f$ transmits the driving torque to a parallel linkage that translates rotary motion into translational motion as shown in Figure 5. The attachment of the parallel linkage to the control surface is also at a radius $l_m$ from the hingeline. With this topology no reduction ratio is achieved through the linkage mechanism, therefore the gearbox output moment is equal to the control surface hinge moment or to one half of it if two actuators are driving the control surface.

![Parallel linkage](image)

**Figure 5. Hingeline EMA mechanical transmission**

**3.1 Source of Parameter Uncertainties**

The large temperature variations encountered during a flight mission are the most important influence factor for changes in almost every parameter of an EMA. According to the RTCA/DO-160-F the required operating temperature range for flight control actuators under applicable environmental conditions is between -55°C and 70°C. If the influence of temperature on some component parameters is unknown (due to the lack of experimental data), this influence must be represented in the form of uncertainty as it could have a large impact on system performance. Parameters such as masses, inertias, stiffness, and damping are not considered to be uncertain.

Electric motor parameters are particularly sensitive to temperature variations. High temperatures make the copper windings yield a higher resistance $R$ therefore more current is required to reach the same performance as with the specified temperature of $T_0 = 20°C$. As a result, the motor torque constant $k_t$ decreases. Temperature related changes of $R$ can also be theoretically determined with [AME 88]:

$$R_{\text{phase}} = R_{\text{phase}0}\left[1 + \alpha_{\text{R}}(T - T_0)\right]$$  \hspace{1cm} (1)
where the temperature coefficient for copper at 20°C is \( \alpha_{20} = 3.93 \cdot 10^{-3}/\text{K} \). Similarly, the motor inductance \( L \) is temperature dependent. Without experimental data available, a relationship to quantify its variation would require knowledge about the motor’s permeability, magnetic saturation, and hysteresis. These characteristics are not easily accessible, they are however reflected in the torque constant \( k_t \) whose temperature dependence is easier to obtain. In [PIE 05] an experimental identification of \( k_t \) is performed for a PMSM with similar torque-speed characteristics to those possibly used in aircraft flight controls. \( k_t \) was found to vary in a range of ±20% with large temperature changes. Meanwhile \( L \) varied about ±10%.

Viscous friction is also strongly influenced by temperature. Its variation as a function of temperature can either be modeled or determined experimentally. This is the case for all bearings in an actuator where the lubricant tends to crystallize at low temperatures leading to a higher dynamic viscosity \( \mu \) [SHI 06]. The bulk variation of viscous friction in a high reduction ratio gearbox subjected to large temperature changes can be approximated as \( 0.2 \cdot d_{v,\text{tot}} < d_{v,\text{tot}} < 5 \cdot d_{v,\text{tot}} \) [COC 09].

A further source of uncertainty is wear in the mechanical components. This effect is difficult to model and only lifetime tests could provide values to quantify it. Wear can however be represented in terms of backlash. End-of-life backlash values provided by component manufacturers can be considered as worst-case scenarios.

**IV TEST-CASE DESCRIPTION**

Verification of performance and functional requirements is the prime objective of the virtual testing approach developed herein. Requirements concerning the geometric and physical characteristics of an actuator can be verified with the help of virtual prototypes or with the integration of real hardware. In addition, the only environmental condition considered for virtual testing is the change in temperature. Further tests such as humidity, vibrations, waterproofness, and magnetic effects are out of the scope.

Moreover, the verification of duty cycle requirements through virtual testing seems to be very challenging. It is certainly possible to model the degradation of EMA components as done in [MOR 12]; however, the complexity of the models employed increases significantly leading to very long simulations. A further option is to utilize meta-models containing real degradation data for each component. According to [SAE 13] performance tests are usually conducted for all actuator test categories applicable for EMA’s:

- unit integration tests,
- acceptance tests and qualification tests.

Those tests are designed to evaluate the overall EMA performance and are based on the specific requirements for the given application. Each requirement is assigned to a single test case.

Test cases are generally used to stimulate the interface of a system under test [GRY 13]. In the scope of virtual testing the system under test is defined to be the overall system model. For this reason, the interface consists of the commanded actuator position or deflection rate and the load profile at the rod end. Within this study, four test cases were investigated. These are based on the test methods described in [SAE 13] and will be explained at this point in further detail:

1. **No load/ Loaded speed**
   A series of appropriate combinations of speed step commands and constant external loads is applied to the actuator.
2. **Positioning accuracy**
   A series of different position steps from neutral position to full stroke and vice versa is commanded to the actuator while applying a constant external load.
3. **Frequency response**
   A constant external load is applied to the actuator while commanding a sinusoidal position input of specified amplitude with increasing frequency.
4. **Maximum holding load**
   The actuator is commanded to a specified position. Subsequently the external load is gradually increased until the actuator starts moving.

As an additional benefit, during all test activities the electrical power demand of the actuator will be measured to evaluate if the related requirement (Maximum power consumption) will be met. The described test cases are not meant to be all inclusive; they only cover a small set of performance requirements. Since the approach of virtual testing is rather generic and not test case dependent, it is quite simple to define further tests. The actual values commanded to the system under test strongly depend on the specified requirements, the given application and the actuator capabilities in terms of maximum stroke, speed, etc.

As already explained in the previous chapter, the actuation system is subjected to widely varying environmental conditions during a flight mission, causing large parametric uncertainties. To cover the impact of those effects on the system performance, extensive parameter studies were conducted. Therefore the motor electrical properties, viscous friction characteristics in the motor and the harmonic drive gear box as well as the overall transmission backlash were varied, using uncertainty intervals based on the considerations taken in [COC 09]. The test cases are then executed with the most relevant parameter combinations. This approach leads to several hundred simulation runs per test case. To limit the computational effort, the uncertain parameters are only varied in discrete steps. The boundaries for all parametric uncertainties considered during this study are summarized in Table 1.

**Table 1. Parametric uncertainties of the system**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor winding resistance</td>
<td>70</td>
<td>150</td>
</tr>
<tr>
<td>Motor inductance</td>
<td>90</td>
<td>110</td>
</tr>
<tr>
<td>Motor viscous friction</td>
<td>20</td>
<td>500</td>
</tr>
<tr>
<td>Viscous friction gearbox</td>
<td>20</td>
<td>500</td>
</tr>
<tr>
<td>Transmission backlash</td>
<td>100</td>
<td>300</td>
</tr>
</tbody>
</table>
The overall test case generation and execution process is shown in Figure 6. The test case to be performed is selected first. The nominal values for all system parameters as well as the specified requirements data are provided to the test generator.

Next, the corresponding input time series for the actuator position or speed and the external load are calculated. The system model is subsequently executed with those input data while changing the uncertainty parameter set after each simulation run. During the simulation all relevant system properties are measured and stored for further analysis. The requirements form a so-called test oracle which describes the desired system performance in a graphical representation. This is in the end used to assess the system performance for the selected test case with respect to top level requirements and system specifications. Finally, the evaluation data has to be processed and concentrated in order to visualize the results in a compact way.

**V APPLICATION EXAMPLE**

The previously illustrated method for virtual performance evaluation should be clarified here using the system architecture described in Section 3. The nominal values used to parameterize the system model are summarized in Table 2 [COC 09]. During the simulation runs the parameters affected by uncertainties were modified within the boundaries shown in Table 1.

<table>
<thead>
<tr>
<th>Table 2. EMA nominal values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameter</strong></td>
</tr>
<tr>
<td>Control Electronics</td>
</tr>
<tr>
<td>Power supply voltage</td>
</tr>
<tr>
<td>PWM carrier frequency</td>
</tr>
<tr>
<td>Motor</td>
</tr>
<tr>
<td>Motor inductance</td>
</tr>
<tr>
<td>Motor winding resistance</td>
</tr>
<tr>
<td>Number of poles</td>
</tr>
<tr>
<td>Back-EMF constant</td>
</tr>
<tr>
<td>Rotor inertia</td>
</tr>
<tr>
<td>Motor shaft stiffness</td>
</tr>
<tr>
<td>Motor shaft damping</td>
</tr>
<tr>
<td>Motor viscous friction</td>
</tr>
<tr>
<td>Transmission</td>
</tr>
<tr>
<td>Input shaft inertia</td>
</tr>
<tr>
<td>Output shaft inertia</td>
</tr>
<tr>
<td>Gearbox ratio</td>
</tr>
<tr>
<td>Viscous friction (gearbox)</td>
</tr>
<tr>
<td>Transmission backlash angle</td>
</tr>
<tr>
<td>Transmission shaft stiffness</td>
</tr>
<tr>
<td>Transmission shaft damping</td>
</tr>
<tr>
<td>Lever arm length</td>
</tr>
</tbody>
</table>

A list of requirements for both linear and rotary electrical actuation systems is provided in [AIR 12]. The numerical values used within this study are fictional and have been adapted for the system under consideration. Table 3 lists all important requirement limits to be evaluated. All values are normalized to the maximum actuator stroke, the maximum deflection rate and the maximum operating load respectively.

<table>
<thead>
<tr>
<th>Table 3. Requirements capture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirement</td>
</tr>
<tr>
<td>No load speed</td>
</tr>
<tr>
<td>Loaded speed</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Overall position error</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Frequency response</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Maximum holding load</td>
</tr>
<tr>
<td>Max. power demand</td>
</tr>
</tbody>
</table>

In order to prove the potential of the virtual performance evaluation approach the system under test was analyzed using the test cases described in chapter 4. The considered actuation system is composed of industrial off-the-shelf parts and is not designed for the specific aircraft application. Therefore the actuator might not meet some of the desired performance characteristics, which is actually not the prime subject of this study.

The results obtained for all four test cases are reported in the following paragraphs and it is worthy to remark that the provided simulation parameters have been kept unchanged during all the performed simulations, with the exception of the aforementioned uncertain parameters. The calculations were done on a parallel computing cluster composed of 25 individual MATLAB workers. In total, more than 2500 simulation runs were performed with an overall duration above 40 hours. After all simulations are completed the data is processed in order to visualize the results in a compact way.

**5.1 Test Case N° 1: No load / Loaded speed**

The first test case consists of three consecutive speed step commands to 100%, 51% and 6% of the maximum motor speed. The first step is performed without any external load, whilst for the second and third step an antagonist load of
40% or 100% of the maximum operating load is applied. The full results for this test case are shown in Figure 11 in the appendix. The requirements to be met are represented by a red bordered box. The system passes the requirements check when simulated with the nominal parameter set.

5.2 Test Case No. 2: Positioning accuracy

During this test, the actuator is subject to different position step commands in both directions from neutral position to full stroke. In addition, step commands from fully retracted to fully extended position and vice versa are performed. Throughout the whole test a 40% antagonist load is applied to the actuator.

In Figure 8, a detail for the first step command is shown. Even if the influence of the parameter variations is clearly visible during the transition phase, the system is under any circumstances capable to attain the demanded positioning accuracy. Figure 12 in the appendix depicts the complete results for test case 2. Due to the very restrictive time limits, which are an assumption made for this study, the system violates the performance requirements several times. This again results from high friction for some of the simulated parameter sets.

5.3 Test Case No. 3: Frequency Response

The goal of the third test case is to determine the position frequency response of the actuation system. For this reason a sinusoidal position command of 20% amplitude within a frequency band from 0.5 Hz up to 2 Hz is applied to the object under test. No external load acts on the rod end of the actuator. The results are processed to obtain the gain and the phase shift.

In Figure 9 the bode plot for the described test case is shown. The influence of parameter uncertainties on the amplitude ratio and phase lag is negligible. The actuator rests within the demanded requirement limits for any parameter combination.

5.4 Test Case No. 4: Maximum holding load

For the fourth test case a constant position command to zero position is applied to the system. The external load is slowly increased until the actuator starts moving.

In Figure 10 the corresponding maximum holding load is shown for a random set of parameter samples. The influence of parameter uncertainties is small but noticeable. The overall actuation system seems to be quite over-dimensioned, since the maximum holding load is about 159% of the maximum operating load.

5.5 Additional Analysis: Max. power consumption

During all the above mentioned test scenarios the motor input power demand was measured. The maximum power consumption was found to be 2.81 kW for test case no. 2 while simulating with high friction parameters. This power...
demand value is outside the specified allowable power consumption. Presumably this is due to the high motor inertia and again a result of the over-dimensioned system design.

CONCLUSION

In this article, a concept for the virtual assessment of performance related requirements for electro-mechanical actuators is presented. The approach represents an extension to the classical V-model for system design and is divided into four sub-steps, which are explained in detail on the example of a short range aircraft’s elevator actuation system. In a first step, a model library is implemented containing all the relevant physical models for the system under test. The goal of the second step is to build a complete system simulation of the virtual test bed. To this end, all sub-models are interconnected to form an integrated model, which thus represents the real test rig. The third step includes the actual implementation of the virtual test runs. Generic test cases are defined in order to assess the overall system requirements. In a last step, the test results are processed and evaluated. Since each physical system is subjected to considerable parameter uncertainties stemming from varying environmental conditions, extensive studies are conducted in order to evaluate the influence of such uncertainties on the system dynamic behavior. The simulation results shown prove the effectiveness of the virtual testing approach to analyze the system performance.

REFERENCES


Thielecke, F. et al. (2011), Modellbasierte Entwicklung zum Nachweis neuer Technologien für Hochauftriebssysteme, Deutscher Luft- und Raumfahrtkongress, Bremen, Germany, DGLR, 2011


AKNOWLEDGEMENTS

The research leading to these results has received funding from the European Union’s Seventh Framework Program (FP7-284915) for ACTUATION 2015 under grant agreement no. 284915. The authors would like to thank the project coordination team for authorizing the publication of this work.
APPENDIX

Figure 11. Full results for test case n° 1

Figure 12. Full results for test case n° 2