# EMA Health Monitoring: An overview.

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# EMA Health Monitoring: An Overview

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## ABSTRACT

This paper presents an overview of the last decade of work on Electromechanical Actuators (EMA) Health Monitoring (HM) of the industrial cooperation between Liebherr-Aerospace in Lindenberg and the DLR Institute of System Dynamics and Control. The efforts on simulation of damage, (component) testing and development of HM algorithms will be presented.

## KEYWORDS

Bearing, Gear, EMA, Hardware testing, Health Monitoring, Simulation, Damage

## I INTRODUCTION

Within the last decade, Health Monitoring (HM) of Electromechanical Actuators (EMA) has gained interest, although first publications on the HM of high lift systems date back to 1990 (Chan, Southcombe, Trmal, & May, 1990).
At the moment, several (international) research programs like "ACTUATION 2015[1]", "OMAHA[2]", "GENOME-CORAC[3]" and "LuFo V EMA[4]" have identified health monitoring of EMA as an important aspect for the electrification of aircraft. Jamming, estimation of remaining life and preventive maintenance are identified as some of the most important drivers for HM algorithms (Todeschi & Baxerres, 2014).

Classical health monitoring of rotating machines usually relies on vibration analysis using acceleration sensors (Tandon & Choudhury, 1999) and debris analysis (Ebersbach, Peng, & Kessissoglou, 2006). However, by avoiding specialized sensors for HM, it is possible to increase the Mean time between failures (MTBF) of the actuator and save production costs.

This paper focuses on 3 parts:

1. Development of simulation models to represent the behavior of an EMA with damaged components.
2. Extensive testing of components and complete EMA with and without damages to identify the behavior of these components in dynamic systems.
3. Development of HM algorithms for the detection of incipient faults in bearings and gears of electromechanical actuators using on-board sensors needed for the actuator control.

## II SIMULATION AND VERIFICATION OF DAMAGED COMPONENTS

For the development of HM algorithms, the behavior of the actuator in case of incipient faults must be known. Test data with damaged components can only be obtained after the complete development and construction of the actuator. This hinders the optimal design of HM algorithms together with the actuator.
A good example where these problems surface, is the specification of the accuracy of the sensors that are needed for the HM algorithms: Without simulations, it is possible to specify the sensor accuracy only after the first measurements with broken components. As an EMA is a highly integrated

[1] See e.g. http://www.actuation2015.eu
[2] See e.g. http://www.dfki.de/web/research/projects?pid=909
[3] See e.g. http://aerorecherchecorac.com/en/
[4] See e.g. http://www.bmwi.de/DE/Themen/Technologie/schluesseltechnologien,did=232982.html

system, it is not trivial to change sensors after the development and production phase.

Furthermore, the amount of incipient faults that can occur in an actuator is very large. Typical actuators have a two stage gear train that consists of at least six bearings and four gear wheels. Assuming four failure modes per bearing and three per gear wheel, the amount of tests is already 36 for single faults. Considering that for each test, the complete actuator must be disassembled and assembled, the costs and time involved with these tests are very high. If simultaneous faults have to be considered, the testing effort would become immense.

The design of HM algorithms without the possibility to test the actual EMA can be aided by simulations. For such simulations, the effect of faults on the actuator must be known and included in dynamic simulations. These system simulations including faults have proved to be helpful also in the vehicle simulations for the early identification of potential problems (Linden & Tobolár, 2015).

## 2.1 Simulation of damaged components

Models to simulate gear- and bearing damages have been developed to investigate the behaviour of the complete EMA. For this purpose, position dependent friction and stiffness models have been developed for bearings and gears (Figure 1). Using these models it is possible to represent the dynamic response of an actuator with damaged components.

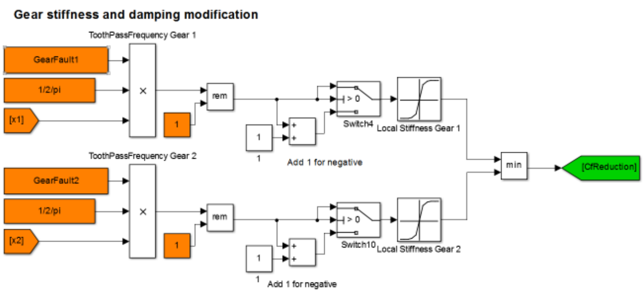


*Figure 1. Position dependent gear stiffness reduction*

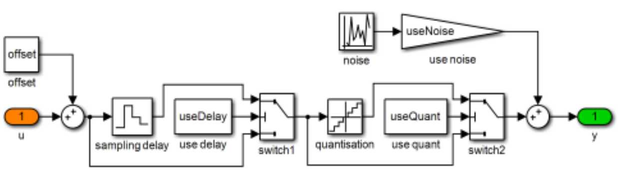


*Figure 2. Sensor modelling*

## 2.2 Sensors simulation

It has been found that sensor accuracy, noise and resolution play a crucial role in the detection of actuator damages. For a complete representation of an actuator, sensor models that include sensor offset, noise, discretisation and delay have been developed (see Figure 2).

## 2.3 Complete system simulation

Using the proposed methods, a model of the EMA including damaged components as well as realistic sensors has been developed. The complete model makes it possible to simulate the behaviour of a damaged actuator with sensor noise. This model allows detailed simulations of actual flight scenarios which are used for the development and assessment of HM algorithms.

It has been found that simulations of damaged EMA are of great value to the designers of HM algorithms. They can be used to better understand scenarios in which many fundamental questions are unanswered. The simulations can give answers to design problems like: “What happens if the gear damping is higher than expected?” or “How large must be the effect of a broken bearing to be detected?”.

Furthermore, such simulations have proven valuable for optimisation of parameters for the HM algorithms. Also real flights can be simulated by including the actuator command and the loading of the actuator. These realistic loading conditions can be used to verify the possibilities and limitations of HM systems.

## 2.4 Experimental investigation of gear and bearing damages

Gear and bearing damages have been investigated using dedicated test rigs for gear testing (Figure 4) and for bearing testing (Figure 5). The gear test rig is presented in detail in a previous publication (Linden, 2014). The goal of these measurements is the validation and further optimization of the models developed in Section 2.1

In Figure 3, a friction measurement of a bearing under load is shown. The friction changes caused by the bearing damage can be clearly observed. These measurements will be used to further optimize the models of damaged bearings. It is planned to extend the models to be dependent on the loading condition and bearing speed.

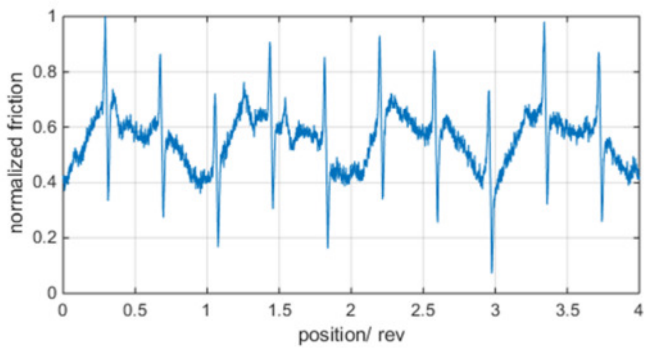


*Figure 3. Normalized friction of a damaged bearing*

The results obtained by the gear testing show good agreement with the used models.

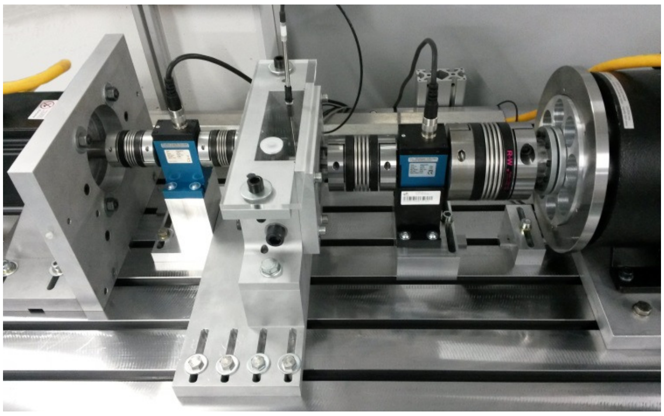

*Figure 4. Gear test rig at DLR-SR for detailed testing of damaged gear wheels*

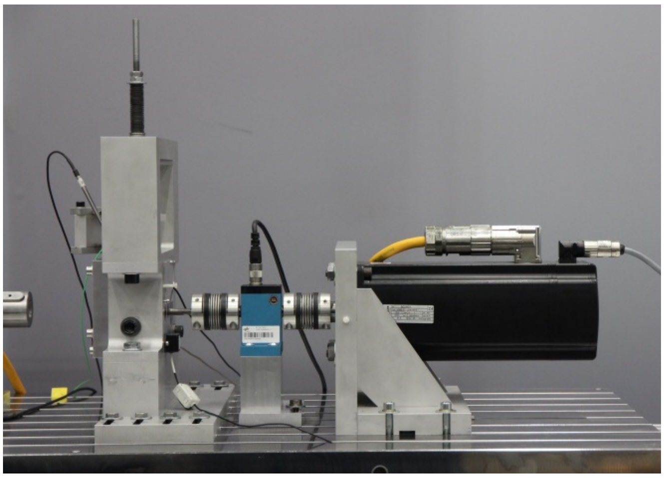

*Figure 5. Bearing test rig at DLR-SR for detailed testing of damaged bearings*

# III HEALTH MONITORING TESTING

The simulation of damaged components and the development of HM algorithms using simulations is a new research topic. However, since no experience is available on the simulation of broken components in an EMA, also tests have been carried out on complete EMA. These tests have delivered valuable insight into the behavior of an EMA with damaged components and will be used to validate the simulations. Figure 6 shows the EMA test rig which can be used for acceptance, performance, endurance and health monitoring tests located in the test lab at Liebherr-Aerospace in Lindenberg / Germany.

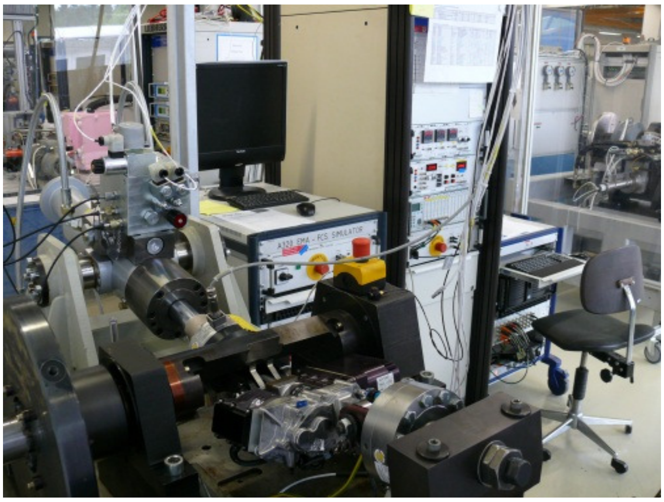

*Figure 6. EMA test rig for Aileron at Liebherr*

Figure 7 shows a simplified schematic of the EMA test rig representing following major components:

(I) Actuator adaption with load cylinder, surface inertia, aircraft kinematic and attachment stiffness
(II) Flight Control Computer (FCC) simulator with position controller
(III) Test rig control & data acquisition
(IV) High frequency data acquisition & DC source

The Liebherr EMA test rig and data acquisition center was designed to ensure that various file formats, generated by the different test rig sub-systems or sensors, can be recorded accurately. Technically, the subsystems consist of the a) mechanic/hydraulic test rig interface and b) electrical sensor and bus signals (analog/digital). The FCC Simulator (II) is linked via a real time fiberglass interface with the Test Rig Control & Data Acquisition (III).

In the development of the test rig, the synchronization of the different acquisition systems proved to be challenging. Care has been taken to synchronize the different data logging systems, implement suitable filters and exclude electromagnetic interference.

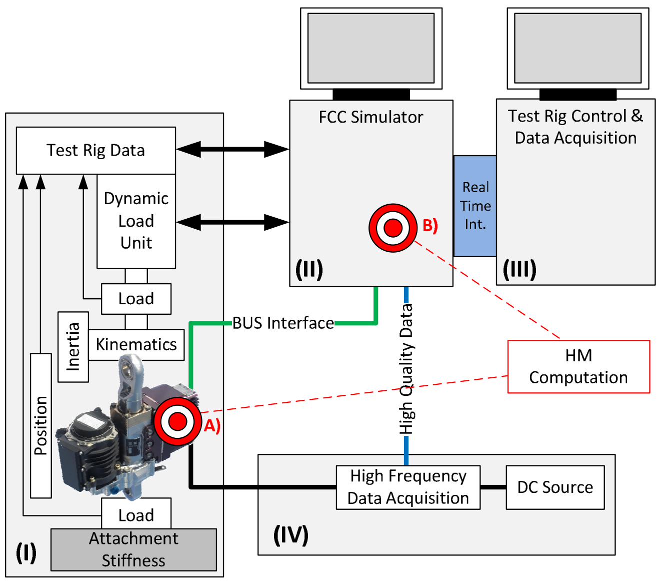


*Figure 7. Schematic overview of the EMA test rig at Liebherr*

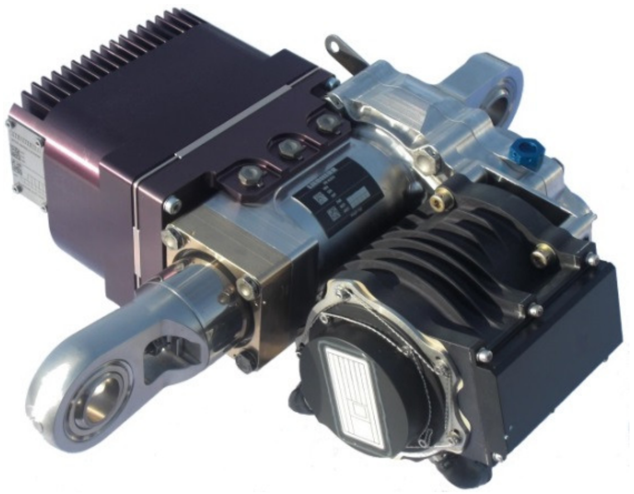

*Figure 8. Aileron EMA used for testing at the test rig shown in Figure 6.*

The investigated EMA (see Figure 8) is designed for the control of an aileron-surface and driven by a permanent synchronous motor with a bell-shaped rotor. This motor is flanged via a two-stage spur gearbox on the shaft of a ball-screw. The key parameters for the tested EMA can be found in Table 1.

*Table 1. Actuator key parameters*

| | |
|---|---|
| **Power Supply** | 270 VDC |
| **Working Stroke** | 38.27 mm |
| **Max. Deflection Rate** | 35 mm/s |
| **Stall Load** | 44.5 kN |
| **Limit Load** | 53.4 kN |
| **Ultimate Load** | 80.1 kN |

Analyzing the FMEA, the components that lead to the highest jamming rates have been identified: The dominant failure mode is an indirect failure mode: the loss of lubrication. This loss of lubrication only leads indirectly to faults: examples are the seizure of a bearing due to the loss of lubricant. The components that have the highest direct failure probability are: 1. Bearings, 2. Ballscrew and 3. Gear.
In the measurement campaign, the focus is set to the bearing and gear faults. The investigations on the ball-screw and on the lubrication will be subject of other investigations. A classical field of application for screws or gearboxes on commercial-aircrafts relates to trim or high-lift tasks. Compared to this, the control of an aileron requires a high dynamic capability combined with a high power density similar to the swashplate control of a helicopter, where at the moment hydraulic actuation is used almost exclusively.
To anticipate the complications encountered during the qualification, preliminary investigations were initiated by risk-mitigation tests and simulations. The tests were performed on an existing EMA used for a very similar serial application and accompanied the whole development-phase. The simulations were performed on standard algebraic and differential equation solver-tools.
The great challenge for components with direct metallic contacts was shown at least during the first qualification attempt of this actuator. The herein described damage were obtained during the risk-mitigation, endurance and fatigue tests.

## 3.1 Ball-Bearing Faults

The axial load of the actuator is held at ball-screw level by two caged thrust-bearings. A small stroke-range combined with high load-cycles is characteristic for aileron applications. This kind of duty-cycles results in visible wear marks on the raceway of the bearings, as well as on the theoretically unloaded cage.

*Figure 9. Wear marks on the thrust bearing surfaces.*

## 3.2 Gearbox Faults

For the risk-mitigation test, artificial damages were applied on the entry-pinion of the gearbox. Three different kinds of gearbox faults were realized on an assembly-press and controlled by high-resolution measurement tools:

- Plastic deformation of one tooth – not depicted
- One crack on one tooth-root
- One broken tooth

In Figure 10, the damaged components are shown. The real challenge was to preserve the reassembly-capability and function of the manipulated components, while the fault is maximized to ensure the best detectability close to the occurring failures. For example, it was impossible to reassemble the pinion with the crack on the tooth-root as the overall deformation was with more than 20 µm too high. Therefore, no measurements could be taken from this pre-damaged gear wheel.

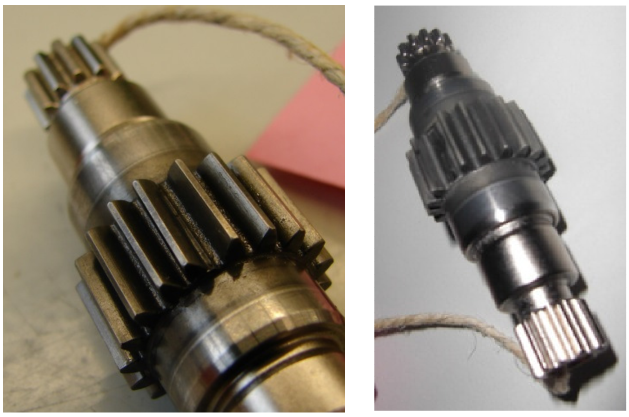

*Figure 10. Damaged gear wheels. Left: Tooth root crack, right: Broken gear tooth*

# IV EMA HEALTH MONITORING

For the detection of faults in an EMA, different HM methods have been developed during the last decade. The focus has been on methods that use only the already available sensors of the actuators to avoid reducing the MTBF by extra sensors, while furthermore keeping the additional costs low. However, to keep track of current methods, acceleration sensors and acoustic emission (AE) sensors have been investigated.

## 4.1 EMA HM Methods

The developed HM algorithms are based on existing EMA sensors without the need for specialized sensors. A model based filtering approach of the noisy sensor data is applied using Kalman filtering. This method has proven to increase the sensitivity of the HM algorithms. Direct assessment of the results by comparing magnitude of the output of the Kalman filtered data to reference values did not lead to good detection rates. Therefore, a combination of signal filtering and a frequency analysis has been applied to further increase the detectability of the faults. Investigation of the specific fault frequencies as well as the eigenfrequencies of the system has proven valuable in the detection of faults in the system.
The latest algorithms are implemented to ensure the feasibility of real-time operation, thus enabling on-line monitoring of the actuators.

## 4.2 EMA gear testing

A healthy actuator, an actuator with a broken gear tooth and an actuator with a plastically deformed gear tooth as specified in Section 3.2 have been tested in a large testing campaign at Liebherr-Aerospace in Lindenberg. The actuator has been loaded at following load-levels: 25%, 50%, 75% and 100% of the maximal compression (Ld) as well as tension load (Lz). At these load levels, a saw-tooth like speed profile has been used with following actuator speeds in both directions: 25%, 50%, 75% and 100% of the actuator speed. Furthermore, the tests have been carried out at room temperature as well as at elevated temperature. Tests with root crack faults will be done at a later stage. Component tests with an artificial tooth crack realized using electrical discharge machining have already been conducted.

# V EMA GEAR TESTING RESULTS

Using the extensive tests presented in Section 4.2, it is possible to show the sensitivity of the developed methods to the different loading conditions and at the same time perform a robustness analysis of the methods.
In Figure 11, the detectability of the gear faults using an acceleration sensor is shown where the amplitude of the detection is the average of first 4 fault harmonics. This method is often seen as the gold standard of HM methods. The results at maximal compressive and tension loading of the actuator for different loading conditions are shown at low and high temperatures. The height of the bars is the increase of the detection amplitude compared to the healthy actuator. The lower magnitude of the modified tooth width (MWG) fault is expected as this is a less severe fault as the broken tooth.
The gear faults can be clearly identified and the detectability of faults is high. This is especially the case for high actuator loads and high motor speeds.

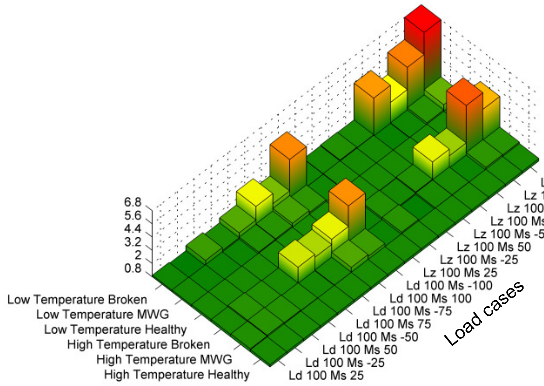


*Figure 11. Detectability of gear faults using an acceleration sensor. The loading condition marked with Ld stand for a compressive load, Lz for tension loads on the actuator. The measurements marked with MWG are the results of the measurements with a plastic deformation of one tooth.*

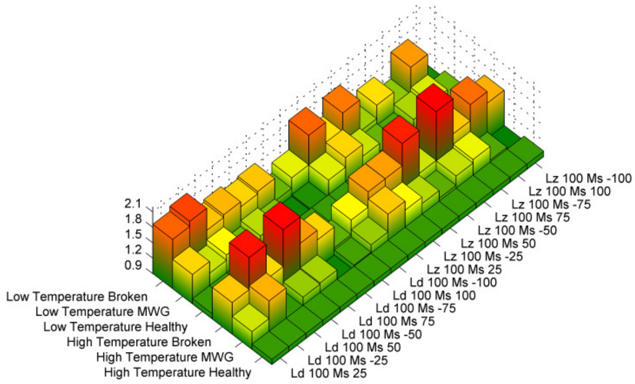


*Figure 12. Detectability of the gear faults using only available sensors on the actuator. The loading condition definition is as described in Figure 11.*

In Figure 12, the results of the tests using the developed HM methods are shown. Note that no extra sensors like acceleration sensors have been used for these results. For most loading conditions, a clear increase of the amplitude can be observed for increasing fault: the plastically deformed tooth yields lower amplitudes than the broken tooth. Furthermore, a compression load (marked by Ld) combined with a negative motor speed as well as a tension load combined with a positive motor speed lead to excellent detectability of the faults.

# VI TECHNOLOGY READINESS LEVEL

According to the European Commission definition of Technology Readiness Levels (TRL) for the Horizon 2020 program, the level of the presented HM algorithms is between 3 “experimental proof of concept” and 4 “technology validated in lab”. All experiments were run on fully functional hardware. However, the measurements have been processed offline for the presented results.
Latest efforts now allow online processing of the results, which would allow for TRL 4.

# VII CONCLUSION

The research of the last decade in the cooperation between Liebherr-Aerospace Lindenberg GmbH and the DLR Institute of System Dynamics and Control has been characterized by testing, the development of the HM algorithms and the modelling of broken components.
The testing of damaged components and complete EMA with damaged components leads to a good understanding of damaged components and the influence on the EMA as a system. Furthermore, the use of simulation models of damaged components has proven to be valuable in the development of HM algorithms.
This knowledge of the EMA systems has led to improved detection methods allowing online monitoring of the actuator and better simulation of damaged components.
The detection of gear faults in incipient and progressed state has been proven possible without the use of extra sensors for HM, thereby reaching TRL 3.

# VIII OUTLOOK

Currently efforts are being made to implement the developed methods on real time hardware. With combined efforts of Liebherr and DLR, a hardware implementation of the algorithms to reach TRL 5 is pursued.
Validation of the HM algorithms and system models is planned using pre-damaged ball bearings that have been extensively characterized in component tests. Simulations of broken components are at the moment used to test the algorithms. Developments using multi-objective optimization methods strive for greater robustness together with increased detection sensitivity. Furthermore the simulations will be used to verify all specified faults in the actuator.
At the moment, also system level effects that influence the performance of the EMA as a whole are investigated like online measurement of play.
As the influence of the effect of Active-Active configurations on HM algorithms is not known, further research is planned to better understand such systems. Moreover, the possibilities of using such Active-Active configuration for active HM are investigated.

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