Force Fight in Parallel-Redundant Electro-Mechanical Actuation Systems

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Abstract

In parallel-redundant actuation systems operating in active/active mode a position offset between the actuator outputs can lead to excessive forces and torsion of the primary flight control surface. The key drivers leading to a substantial force fight in systems involving two nominally identical electro-mechanical actuators (EMAs) were identified using a detailed nonlinear system model. While in hybrid configurations involving an EMA and a hydraulic actuator, dissimilar dynamics are the main source for a force fight, in the system at hand parameter deviations from the nominal state are crucial. A worst case study is performed to quantify the maximum resulting force fight paying special attention to wear causing increased gear backlash and friction, sensor uncertainties and signal delays. Moreover Monte Carlo simulations give insight in the likelihood of the event of excessive force fight assuming Gaussian and uniform distributions of the identified key parameters. It is concluded that active compensation measures are compulsory to avoid parasitic forces and to ensure a good load sharing. Differences to purely hydraulic configurations are pointed out.

Introduction

In the context of increased electrification of primary and secondary flight control, EMAs have a great potential in terms of overall system weight, maintainability and reliability. Conventional hydraulic aileron actuation systems of large civil aircraft are usually operated in a parallel-redundant active/standby configuration. However, in passive mode EMAs show an increased inertia and breakaway forces due to multi-stage gear ratios, which makes the transition to an active/active configuration necessary. In this operation mode, a position offset between the actuator rods must be substantially reduced in order to ensure an equivalent load share on both EMAs. A strong inequality results in a parasitic, safety-critical force on the control surface which can be limited by an active force fight compensation as proposed in (4). In hybrid actuator configurations consisting of hydraulic and electro-mechanical actuators, dissimilar system dynamics dominate the originating force fight as further investigated in (1) and (2). However they are theoretically nonexistent if identical ideal actuators are used. In practice however, dissimilar dynamics and position offsets can be caused by asymmetric wear, measurement uncertainties, manufacturing tolerances, environmental influences, and asynchronous data transfer and processing. According to (3) an opposing servo-valve offset is the key force fight driver in hydraulic actuation systems. In the present study potential sources in systems consisting of electro-mechanical actuators are identified, parameterized and evaluated in order to assess the need and in perspective, the architecture of compensation measures. In worst case simulations the relevant parameters are systematically varied and the maximum force fight is quantified based on selected load and position profiles. In addition, the expected force fight is stochastically evaluated by Monte Carlo simulations. The simulations were performed on a detailed nonlinear model representing the total system allowing the systematic variation of a large set of parameters.

System description

The investigated system consists of two linear EMAs from the manufacturer Liebherr Aerospace GmbH in a parallel-redundant configuration actuating an aileron via the kinematics of an Airbus A320. The interaction between wing structure, EMAs and control surface can be modelled according to the free-body diagram in Fig. 1 (neglecting damping). It can be shown that there is a proportional relationship between the actuator output position offset Δx and the force fight ΔF:

$$\Delta F = \frac{k_L}{1+\frac{k_L}{k_h}} * \Delta x$$

Stiff junctions are thus, even though desirable for a precise position control of the aileron, disadvantageous in terms of force fight.
The EMA itself is composed of a permanent-magnet synchronous motor whose output shaft is actuating a

two-stage gearbox followed by a roller screw converting rotary into linear movement.

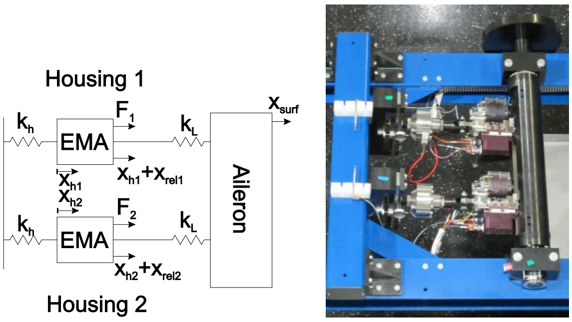

Fig. 1: Aileron actuation in a free-body diagram and its realisation on a test rig

It is position-controlled in a conventional cascade control according to Fig. 2. In the simulations on hand an active force fight compensation was intentionally *not* implemented yet in order to evaluate the need and structure of such a system first.

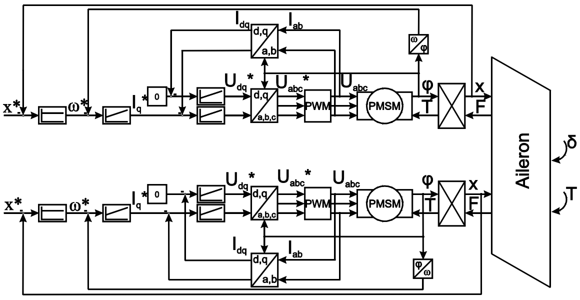

Fig. 2: Control architecture of the total system

To provoke a strong force fight the control surface was driven from maximum negative deflection to maximum positive deflection and in reverse. While in the worst case simulations a maximum opposing hinge moment was applied on the aileron, the Monte Carlo simulations were realized with a constant average air load.

Identification of key parameters

In a first step, variations of structured uncertainties and disturbances were quantized in close cooperation with the manufacturer of the investigated EMA. A set of 22 evaluated parameters was narrowed down to 4 key parameters causing a substantial force fight:

- An opposing LVDT offset between inboard and outboard EMA leads to a permanent position offset and consequently to a static force fight
- A permanent asynchronism in the position reference value of the Electronic Control Units caused by delayed signals of *one* Elevator Aileron Computer (ELAC) induces a dynamic force fight during acceleration and braking phases
- Increased gear and roller screw backlash of *one* EMA causes force fight peaks during direction changes
- Increased friction of *one* EMA causes similar force fight peaks

Thus in contrast to servo-hydraulic actuators the dynamic force fight peaks introduced by the gear stages have a decisive influence.
Deviations of motor constants have little influence due to the robust cascade control ensuring a good disturbance rejection.

Worst case and Monte Carlo study

In order to quantify a maximum possible force fight, the simulations were executed under systematically permuted key parameters to obtain the worst case parameter combination listed in Table 1. It results in a slightly degraded dynamic behaviour of EMA 1.

	LVDT offset	**ELAC Signal delay**	**Backlash**	**Friction**
EMA 1	Min	Max	Max	Max
EMA 2	Max	Min	Min	Min

Table 1: Worst case parameter combination

The predicted force fight under worst case conditions made up 33.9% of the maximum combined operating load of both EMAs underlining the need for an active compensation even with nominally identical actuators.

For the Monte Carlo study the key parameters were varied according to their probability assuming a Gaussian distribution of sensor offsets and uniform distributions for signal delays, backlash and friction.
The predicted average force fight made up 11.5% of the maximum operating load with a standard deviation of 4.2%.

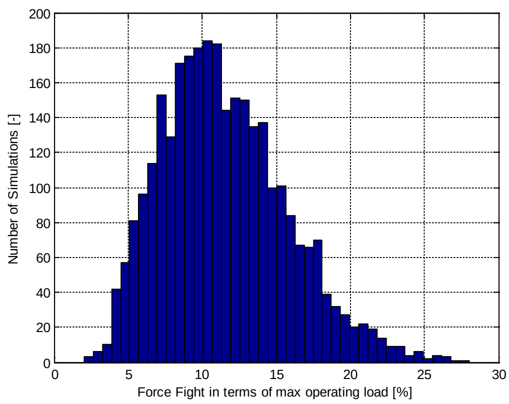

Fig. 2: Histogram of the predicted force fight under stochastically varied key parameters

Conclusions

The objective of the present study was to identify the main parameter deviations that contribute to a substantial force fight in a parallel-redundant electro-mechanical actuation system and quantify the influence. By means of nonlinear simulations including a large set of uncertain parameters four key drivers were identified and their impact evaluated.

Worst case and Monte Carlo studies have shown that active force fight compensation measures are crucial not only in hybrid active/active configurations but also in purely electro-mechanically actuated flight control surfaces. Special attention should be paid to increased gear backlash and friction that induce high force fight peaks on the control surface.

References

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