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REVIEW ARTICLE

Modelling and simulation of flight control electromechanical actuators with special focus on model architecting, multidisciplinary effects and power flows

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Abstract In the aerospace field, electromechanical actuators are increasingly being implemented in place of conventional hydraulic actuators. For safety-critical embedded actuation applications like flight controls, the use of electromechanical actuators introduces specific issues related to thermal balance, reflected inertia, parasitic motion due to compliance and response to failure. Unfortunately, the physical effects governing the actuator behaviour are multidisciplinary, coupled and nonlinear. Although numerous multi-domain and system-level simulation packages are now available on the market, these effects are rarely addressed as a whole because of a lack of scientific approaches for model architecting, multi-purpose incremental modelling and judicious model implementation. In this publication, virtual prototyping of electromechanical actuators is addressed using the Bond-Graph formalism. New approaches are proposed to enable incremental modelling, thermal balance analysis, response to free-run or jamming faults, impact of compliance on parasitic motion, and influence of temperature. A special focus is placed on friction and compliance of the mechanical transmission with fault injection and temperature dependence. Aileron actuation is used to highlight the proposals for control design, energy consumption and thermal analysis, power network pollution analysis and fault response.

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1. Introduction

In recent years, increases in fuel costs, a focus on reduced carbon footprint and the emergence of new competitors have driven the aerospace industry to take steps towards creating greener, safer and cheaper air transport.[1] The concepts based on extended use of electricity in "More Electric Aircraft" (MEA) and "All Electric Aircraft" (AEA) have logically defined the technological shift towards greening aviation operations.[2,3] Currently, numerous research activities strive to widen the use of electrical power networks for electrically supplied power users (Power-by-Wire or PbW) as a replacement of conventional hydraulic, pneumatic and mechanical power networks.[4] At the same time, PbW actuators have become sufficiently mature to be introduced in the latest commercial programmes:

– Electro-hydrostatic actuators (EHAs) as backup actuators for primary and secondary flight controls in the Airbus A380/A400M/A350.
– Electromechanical actuators (EMAs) as frontline actuators for several secondary flight controls and landing gear braking in the Boeing B787.

Although they remove central hydraulic power distribution, EHAs still use hydraulics locally to maintain the major advantages of conventional actuators with regard to secondary functions (e.g. back-driving, overload protection, and damping) and in response to failure (i.e. easy hydraulic declutch and extremely low risk of jamming). EMAs, however, remove both central and local hydraulic circuits by transmitting motor power to the load through mechanical reducers (e.g. gearbox, nut-screw). Nevertheless, EMAs are not yet sufficiently mature to replace conventional hydraulic servo-actuators (HSA) in normal mode for safety-critical functions such as flight controls. Several technical challenges still need to be overcome: weight and size constraints for integration, voltage spikes and current transients affecting the pollution and stability of electrical networks, heat rejection for actuator thermal balance, reduced reflected inertia for dynamic performance, increased service life and fault tolerance or resistance (e.g. for jamming or free-run) for safety.[5,6]

A model-based and simulation-driven approach can unquestionably provide engineers with efficient means to address all these critical issues as a whole. In particular, it facilitates and accelerates the assessment of innovative architectures and concepts,[7,8] and their technological embodiments. Introducing all or more electrical actuation raises new challenges:

(a) Heat rejection - the temperature of motor windings and power electronics is a key element affecting service life and reliability. Thus, thermal balance is an important issue in PbW actuators. Unlike in HSAs, where the energy losses is taken away by fluid returning to the reservoir, the heat in PbW actuators has to be dissipated locally into surroundings or a heat sink. Simulation of lumped parameter models can provide a detailed view of the temperature and heat flow fields.[9,10] Unfortunately, these methods are too time-consuming for modelling and simulation at the system-level. In addition, they cannot be used in the early design phases because they are too detailed and require numerous parameters that are not yet known. The heat generated in EMAs comes from a multiplicity of sources: electronic (switching and conduction losses), electrical (copper losses), magnetic (iron losses) and mechanical (friction losses). Accurately quantifying this heat during a reference flight cycle helps determine the operating temperature of the actuator components.

(b) Response to failure - safety-critical functions like primary flight controls must have extremely low failure rates (e.g. 10^{-9} per flight hour). This is achieved through installation of multiple channels for redundancy. However, each channel must have fail-safes to enable the remaining channels to operate correctly. This requirement introduces another challenge in EMAs, where jamming and free-run faults of mechanical components are considered. In HSAs, a fail-safe response to failure (free, damped or frozen) is easily obtained at low mass and low cost by resorting to bypass valves, restrictors, pilot operated check valves or isolation valves. Unfortunately, it is no longer possible to transpose the needs in the hydraulic domain to EMAs where clutches, brakes, dampers and torque limiters may be required. Virtual prototyping at the system-level therefore becomes a focus, not only to support conceptual design but also to verify control and reconfiguration strategies.

(c) Electrical pollution: the power control of electrical machines (e.g. actuator motor) is based on high frequency on/off switching (e.g. 8–16 kHz) of power semi-conductors through pulse width modulation (PWM). Although power is controlled with very low energy losses, it generates high transients in the electrical supply bus and can affect the stability of the electrical network. Moreover, regenerative currents need to be managed properly under aiding-load conditions. This is another reason why model-based systems engineering (MBSE) of PbW actuators calls for more realistic models.

All these considerations support developing high fidelity models with a transverse view of the physical domains involved in EMAs. These models have to be properly structured in order to support the MBSE development process and the associated engineering needs: they must be energy balanced, replaceable and incremental. This paper reports research that has contributed to this goal. It makes wide use of the Bond-Graph methodology for graphical and qualitative modelling. Bond-Graph modelling[11,12] explicitly displays multidisciplinary energy transfers, and the structure and calculation scheme for simulations. Incidentally, it facilitates the design of a model structure that enables incremental or even decremental modelling. In the following sections, the models are developed at a system-level to support various major engineering tasks such as control design, component sizing, thermal management, power budget and network stability for flight control EMAs. Their main contribution concerns model decomposition versus EMA architecture from a multidisciplinary point of view and with special consideration of power flows and response to failure.

Section 2 describes the EMA under study, focusing on power and signal architecture, coupled physical effects and