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Multi-level virtual prototyping of electromechanical actuation system for more electric aircraft

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Power-by-wire

Abstract Electromechanical actuators (EMAs) are becoming increasingly attractive in the field of more electric aircraft because of their outstanding benefits, which include reduced fuel burn and maintenance cost, enhanced system flexibility, and improved management of fault detection and isolation. However, electromechanical actuation raises specific issues when being used for safety-critical aerospace applications like flight controls: huge reflected inertia to load, jamming-type failure, and increase of backlash with service due to wear and local dissipation of heat losses for thermal balance. This study proposes an incremental approach for virtual prototyping of EMAs. It is driven by a model-based system engineering process in order to enable simulation-aided design. Best practices supported by Bond graph formalism are suggested to develop a model's structure efficiently and to make the model ready for use (or extension) by addressing the above mentioned issues. Physical effects are progressively introduced, and the realism of lumped-parameter models is increased step-by-step. In particular, multi-level component models are architected to ensure continuity between engineering activities. The models are implemented in the AMESim simulation environment, and simulation responses are given to illustrate how they can be used for preliminary sizing, control design, thermal balance verification, and faults to failure analysis. The proposed best practices intend to provide engineers with fast, reusable, and efficient means to assess performance virtually and enhance maturity, performance, and robustness.

1. Introduction

Anthropogenic CO_2 emissions into the atmosphere have been increased considerably by civil aviation given the rapid growth in the air traffic market in recent years.[1] The aircraft industry has faced economic and environmental issues.[2] Recently, more electric aircraft[3] (MEA) and all electric aircraft[4,5] have received significant interest for developing safer, lower-cost,

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Nomenclature

B	flux density
C	torque
E	magneto-motive force
F	force
f	frequency
H	flux coercivity
I, i	current
l	lead of screw
J	inertia moment
K, k	parameter/constant
L	inductance
M	mass
n	number
U	source voltage
V	PWM voltage
v	velocity
R	resistance
P	power
$\dot{S}$	entropy flow
T	temperature
X, x	translational position
α	duty cycle signal
β	gyrator parameter of motor
δ	motor torque angle
ε	temperature factor
θ	angular position
η	power drive electronic efficiency
ρ	duty cycle of "on-off"
λ	cogging factor
ω	angular velocity
ψ	magnetic flux

Subscripts

0, 1	initial, operating/realistic
A, B, C	motor three phases
c	contact
cd	conduction
cg	cogging
co	copper
d	direct axis current of motor
dd	DC drop
de	power drive electronic modulated voltage
dm	damping
e	elastic
ed	eddy current
ex	external
em	electromagnetic
f, ff, fm	friction, friction fault, friction in motor
fp	free-play
h	housing
hy	hysteresis
is	inductance storage
j	inertia
jm	jamming
k	stiffness or compliance
L	load
lim	limitation
m	motor
n	nominal/rated
nr	nut screw relative
ns	nut-screw
on	on-state
off	off-state
p	pole of motor
q	quadrature axis
ir	iron
R	electrical component resistance
r	relative
s	supply
sc	screw
sw	switching
t	rod
th	threshold
vc	viscous coefficient
w	winding
η	efficiency

and greener technologies for next-generation air transportation.[6,7] With the constant investment in aviation, power-by-wire[8] (PbW) technology eliminates heavy and bulky hydraulic pipes and the pipe vibration issue. Thus, conventional centralized hydraulic, pneumatic, and mechanical networks will be nearly exclusively replaced by an electric power network, which can provide significant advantages in ease of power management, integration, and maintenance, as well as reductions of environmental pollution and fuel burn.[9] As shown in Fig. 1, PbW is introduced step by step into flight controls, landing gears, and engines as the key contribution to MEA, where signal and power are transmitted by electric wires.

However, the maturity of PbW technology is lagging. In fact, the real challenge in implementing PbW in MEA is to develop compact, reliable, and electrically powered actuators with the same function to replace conventional hydraulic servo actuators (HSAs).[10,11] To date, only two categories of PbW actuators, namely, electro-hydrostatic actuators (EHAs)[12] and electromechanical actuators (EMAs),[13] have been developed. These actuators may exhibit architectural changes, e.g., an electric backup hydraulic actuator[14] (EBHA) and an electric backup mechanical actuator[15] (EBMA). PbW actuators have already entered into service in the latest commercial airplane programs.[16] In Airbus A380/A400M/A350, an EHA serves as a backup actuator for primary and secondary flight controls. In Boeing B787, an EMA is partly placed on the front line for secondary flight controls and landing gear braking.[17–19]

Compared with an EHA, an EMA completely eliminates the use of hydraulic circuits, thereby increasing its economic, competitive, and environmental advantages. Significant improvements in the performance and maturity of electric motors (EMs), as well as their power drive electronics (PDE) and control, make EMAs more and more attractive.[20,21] However, a mature EMA for extensive safety critical applications,[22] particularly for primary flight control, still lacks a historical

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