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INDUSTRIAL ENGINEERING – ROBOTICS SERIES

Aerospace Actuators 1

Needs, Reliability and Hydraulic Power Solutions

Jean-Charles Maré

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Introduction

This book is the first of three volumes that cover the topic of aerospace actuators following a system-based approach. The first volume provides general information on actuators and their reliability, and focuses on hydraulically supplied actuators. The second volume addresses more electrical actuators (electro-hydraulic, electro-hydrostatic and electromechanical) and their signal flows (Signal-by-Wire) as well as their power flows (Power-by-Wire). The third volume illustrates the concepts introduced in the two previous volumes by showcasing various examples of applications of actuation in aerospace (flight controls, landing gear and engines) as well as different types of aircraft (commercial, military or business aircraft, helicopters, convertibles and space launchers).

In order to successfully develop a system perspective in this book series, a top-down approach (from the requirements to the solution) has to be carefully combined with a bottom-up approach (from the technological maturity to the solution). The main guiding idea is, therefore, to focus on requirements and architecture (functional then conceptual) while revealing restrictions imposed by technology on concept implementation, in particular, with regard to functions and phenomena induced by technological choices. Indeed, in practice, solutions are designed according to the functional aspects that have to be implemented and combined. Subsequently, performance is assessed while taking into consideration technological shortcomings[1] such as magnetic hysteresis, winding inductance, mechanical

1 Depending on the application, it is possible for the same physical phenomenon in a technological component to either be harnessed to perform a specific function or to appear as a technological defect that threatens functional performance.

clearance or even hydraulic resistance of pipes. Architectural aspects are generally poorly documented in bibliographies compared to design and technological aspects. However, this does not mean that design and technology are of little importance. Quite the contrary, they too are essential aspects. Indeed, it very often turns out that, as of a given date, technology becomes the limiting factor for the industrial relevance of a project in terms of performance, reliability and cost. Similarly, the accuracy of mathematical models and the computing power they require often restrict safety margin improvement and design optimization.

Design, modeling and technological aspects are generally well documented in bibliographies but the architectural feature, both functional and conceptual, is usually rarely addressed. The difficulty, therefore, lies in formalizing architectures and concepts. The use of mathematical models and technology description is only resorted to when they are necessary for comprehension and technology selection in this volume. The "architecture"-oriented system approach highlights the required functionalities and interdependencies between system components. This approach shows more promise for improving global performance than the "component"-oriented approach. This is because a globally optimal system is hardly ever obtained by simply combining components that are each individually optimal. In commercial aeronautics, developing such an approach is made even more difficult by the organization of design offices: they are often divided up according to aircraft partitioning, and, therefore, often according to "trades". This partitioning was standardized for the first time by the Air Transport Association more than 50 years ago [A4A 14]. Nevertheless, a cross-cutting view has been increasingly encouraged by setting up plateaus, by promoting system expert positions and by the emergence of initial training in systems engineering covering both power and signal aspects.

In this first volume, emphasis is put on hydraulic power actuators. This choice can come as a surprise in this day and age where "more" electrical solutions and even "all" electrical solutions are almost always put forward. However, this choice is justified by several important considerations:

– Hydraulic technology is used extensively for actuating purposes on all aircraft, including the newer ones. The lifespan of a commercial aircraft is typically about 30 years and its marketing life also frequently extends beyond 30 years. New aircraft models of the 2010s should therefore typically still be flying in 2070.

– The maturation of more or all electrical solutions assessed in the laboratory can take more than a decade before reaching a stage satisfactory enough that the new technology can be implemented on aircraft. For instance, the electro-hydrostatic actuators that were implemented on Airbus A380 in 2007 had begun being developed in the mid-1980s.

– It is important to think in terms of requirements and performance rather than restrict choices to a given technological solution. In this regard, a more or all electrical solution should not be an end in itself; it should only be a means of providing safer, greener, cheaper and faster[2] services.

The progressive or complete removal of hydraulics teaching in engineering degrees contributes to a loss of initial skills for engineers. These two established facts advocate for a capitalization effort of knowledge that is prone to disappear.

Following the emphasis put on the system approach, requirements and architectures, this book develops an approach that is complementary to other existing publications on the topic. These constitute a significant source of information. Consequently, the following books should be recommended to broaden the scope of this series:

– generally speaking, for all aircraft systems, [CRA 99, DAN 15, MOI 01, ROS 00, SAU 09, WIL 01] and [WIL 08];

– for all aerospace actuating purposes, [RAY 93] and [SCH 98];

– for aerospace hydraulics, [GRE 85, JEP 85] and [NEE 91];

– for general hydraulics, [BLA 60, FAI 81, FAY 91, GUI 92, MAR 80, MER 67] and [VIE 80].

The present volume consists of seven chapters. Chapter 1 provides an overview of aerospace actuators with an emphasis on requirements and applications. Chapter 2 addresses reliability, that can heavily impact architecture choices in very early development stages. The following chapters focus on actuators supplied by hydraulic power sources. These chapters successively review the energy carrier function, the hydraulic fluid as well as its conditioning, power conversion, control and management; and finally actuators and hydraulic systems integration.

2 Concerning commercial aeronautics, it seems that the fast aspect is no longer one of the main goals because given the current state of technology, this aspect heavily impacts the other three (safety, environmental friendliness and cost).

Notations and Acronyms

Notations

Symbols

a	Weibull parameter	–
A	Availability	–
b	Weibull parameter	–
B	Bulk modulus	Pa
c	Speed of sound	m/s
C	Torque/Control port	N m/-
C_h	Hydraulic capacitance	m^3/Pa
C_p	Specific heat at constant pressure	J/kg/°C
C_q	Flow coefficient	–
d	Diameter	m
E	Energy	J
F	Force	N
f	Friction factor	–
$f(u)$	Density of probability	–
$F(u)$	Probability of failure	–
g	Gravitational constant	m/s^2
$h(u)$	Failure rate	depends
I	Electrical current	A
I_h	Hydraulic inertia	kg/m^4

J	Moment of inertia	kg m^2
k	Gain	depends
K	Mechanical stiffness	N/m
l	Length	m
L	Inductance	H
M	Mass	kg
n	Number of elements	–
N	Number of items in service	–
p	Lead	m
$\mathcal{P}$	Power	W
P	Pressure	Pa
Q	Volume flow rate	m^3/s
$R(u)$	Probability of success (or, in short, reliability)	–
R	Electrical resistance	Ω
s	Orifice cross-sectional area	m^2
S	Area	m^2
t	Time	s
u	Service quantity	depends
U	Electrical voltage	V
v	Linear velocity	m/s
V	Volume	m^3
V_0	Displacement	m^3/rad
x	Position	m
y	Position/opening	m
z	Vertical position	m
Δ	Difference	–
ε	Control error	depends
η	Efficiency	–
λ	Constant failure rate	/FH
μ	Dynamic viscosity	Pl
θ	Angular position	rad

Θ	Temperature	°C
ρ	Specific density	kg/m^3
τ	Time constant	s
ω	Angular velocity	rad/s
ω	Angular frequency	rad/s
ξ	Pressure drop coefficient	–

Subscripts

0	Initial, reference, no-load
a	Apparent
b	By-pass
c	Load/kinetic
C	Coulomb
d	Valve/metering/drain/difference
DC	Detection–correction
e	Elastic
em	Electromagnetic
f	Leakage
g	Gravity
h	Hydraulic
hc	Hydro-kinetic
hm	Hydro-mechanical
hs	Hydro-static
l	Laminar or linear
m	Mechanical/mean
M	Maximum
n	Rated
o	Orifice
p	Position/pilot
P	Supply/parallel
q	Quadratic/thermal
r	Reflected/response/feedback

R	Return
s	Structure
S	Series
t	Turbulent
u	Controlled
v	Volumetric
VM	Majority voting
x	Position
$\propto$	Asymptotic

Superscripts

$*$	Setpoint
$-$	Per mass unit

Acronyms

ACMP	Alternative Current Motor Pump
ADP	Air Driven Pump
CSMG	Constant Speed Motor Generator
EBHA	Electric Backup Hydraulic Actuator
EBMA	Electric Backup Mechanical Actuator
ECAM	Electronic Centralized Aircraft Monitor
EDP	Engine Driven Pump
EHA	Electro-Hydrostatic Actuator
EMA	Electro-Mechanical Actuator
EMP	Electro-Mechanical Pump
FbW	Fly-by-Wire
FH	Flight Hour
HMA	Hydro-Mechanical Actuator
HSA	Hydraulic Servo Actuator
HSMU	Hydraulic System Monitoring Unit
LEHGS	Local Electric Hydraulic Generation System

MEPU	Monofuel Emergency Power Unit
MLA	Maneuver Load Alleviation
MRHS	Main Rotor Hydraulic Subassembly
MTBF	Mean Time Between Failure
MTOW	Maximum Take-Off Weight
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
PbW	Power-by-Wire
PCU	Power Control Unit
PoD	Power-on-Demand
PTU	Power Transfer Unit
PWM	Pulse Width Modulation
SbW	Signal-by-Wire
SPGG	Solid Propellant Gas Generator
RAT	Ram Air Turbine
THS	Trim Horizontal Stabilizer
TVC	Thrust Vector Control

Contents

1

General Considerations

1.1. Power transmission in aircraft

1.1.1. *Needs and requirements for secondary power and power flows*

On an aircraft, a distinction is made between primary power, which is used to ensure lift and airborne movement, and secondary power, which is used to power systems (flight controls, avionics, landing gear, air conditioning, etc.). Although much less significant than primary power, secondary power is nevertheless non negligible, as shown in Table 1.1.

Actuation (flight controls and landing gear)	Instantaneous power: 50–350 kW
Cabin lighting	15 kW permanently
Galley	120–140 kW intermittently (warming oven)
	90 kW permanently (cooling)
In-flight entertainment	50–60 kW permanently
Cockpit avionics	16 kW
Cabin air conditioning	190–300 kW

Table 1.1. *Secondary power requirements for a large commercial aircraft [COM 05]*

Power is generally conveyed from sources to users by redundant networks in electrical, hydraulic and pneumatic form. For a typical 300 seat aircraft, these networks are estimated to respectively transmit a power of 230 kVA, 230 kW and 1.2 MW.

Figure 1.1 illustrates the complexity of secondary power networks for a single-aisle aircraft of the Airbus A230 type [LIS 09]. On this diagram, power flows from power generators situated on the inner ring, through distribution networks located around the intermediate ring, to power users gathered on the third ring. The outer ring depicts the surrounding air which is considered here as being equivalent to a thermal power source. Power flows are depicted by colored arrows whose colors indicate the nature of the power involved.

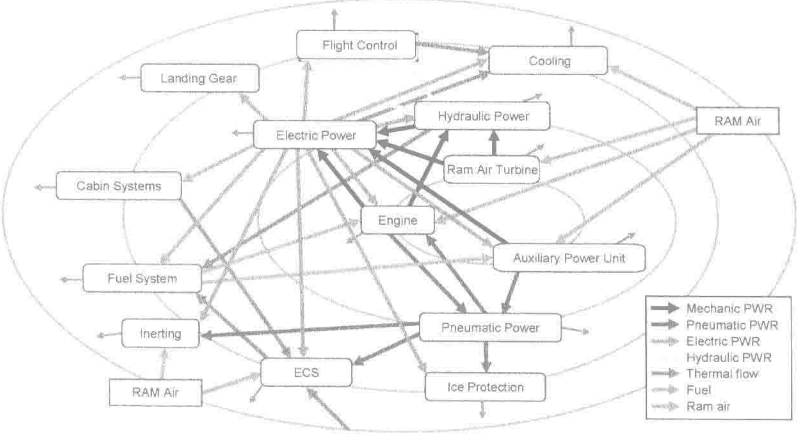

Figure 1.1. *Secondary power flows for an Airbus A230 type single-aisle aircraft [LIS 08]. For a color version of the figure, see www.iste.co.uk/mare/aerospace1.zip*

1.1.2. *Actuation functions*

A function can be defined as the act of transforming matter, energy or data in time, shape or space [MEI 98]. In practice, the perspective from which a function is viewed depends on the engineering task at hand. For instance, for the purpose of power scaling, the actuation function can be viewed as the transformation of power received at the source into power transmitted to the load; this transformation takes place both in shape (e.g. hydraulics toward translational mechanics) and in space (aspect of power transmission from point A to point B). In contrast, when designing flight controls, the actuation function is considered as the act of converting a signal (e.g. an electrical command for positioning a load) into another signal (current position of the load).