



AEROSPACE RECOMMENDED PRACTICE

ARP7370™

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General Guidelines for Specifying Motor Requirements for Electromechanical Actuation

RATIONALE

Motors are a key design component of electromechanical actuators (EMAs). As EMAs are being more frequently used for aerospace applications, there is a need for a document providing general guidelines for specifying the motor design requirements. This document meets this need.

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1. SCOPE

This SAE Aerospace Recommended Practice (ARP) provides general guidelines for defining a specification for an electromechanical actuator (EMA) motor.

This document is for permanent magnet brushed and brushless motors.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 1-877-606-7323 (U.S. and Canada only) or 1-724-776-4970 (outside U.S. and Canada), www.sae.org.

AIR6127	Managing Higher Voltages in Aerospace Electrical Systems
ARP5754	Electromechanical Actuators Specification Guide
ARP7490	Recommended Guidelines for the Specifications of Motor Control Electronics for Electrically Powered Actuators
AS22759	Wire, Electrical, Fluoropolymer-Insulated, Copper or Copper Alloy

2.1.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9500, www.astm.org.

ASTM D1868	Standard Test Method for Detection and Measurement of Partial Discharge (Corona) Pulses in Evaluation of Insulation Systems
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2.1.3 Battelle Memorial Institute Publications

Available from Battelle, 505 King Avenue, Columbus, OH 43201, Tel: 1-800-201-2011, www.battelle.org.

MMPDS	Metallic Materials Properties Development and Standardization
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2.1.4 Code of Federal Regulations (CFR) Publications

Copies of these documents are available online at www.ecfr.gov.

14 CFR Part 25	Airworthiness Standards: Transport Category Airplanes
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2.1.5 EASA Publications

Available from European Union Aviation Safety Agency, Konrad-Adenauer-Ufer 3, D-50668 Cologne, Germany, Tel: +49 221 8999 000, www.easa.europa.eu.

CS-25	Certification Specifications for Large Aeroplanes
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2.1.6 European Standard (EN) Publications

Copies of these documents are available online at www.en-standard.eu.

RoHS Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment

2.1.7 RTCA Publications

Available from RTCA, Inc., 1150 18th Street NW, Suite 910, Washington, DC 20036, Tel: 202-833-9339, www.rtca.org.

RTCA DO-160 Environmental conditions and test procedures for airborne equipment

2.1.8 U.S. Government Publications

Copies of these documents are available online at <https://quicksearch.dla.mil>.

AFAPL-TR-75-41 High Voltage Design Guide for Airborne Equipment

AFWAL-TR-82-2057 High Voltage Design Guide: Aircraft

JSC 29129 Electrical Auxiliary Power Unit (EAPU) Corona Design Guideline

NAVSO P-3641 Navy Power Supply Reliability Design & Mfg Guidelines

MIL-HDBK-454 Military Handbook: General Guidelines for Electronic Equipment

MIL-STD-202 Department of Defense Test Method Standard Electronic and Electrical Component Parts

MIL-STD-464 Department of Defense Interface Standard, Electromagnetic Environmental Effects Requirements for Systems

MIL-STD-810 Environmental Engineering Considerations and Laboratory Tests

MIL-STD-961 Military Specification and Associated Documents Preparation of

MIL-STD-7179 Finishes, Coatings, and Sealants for the Protection of Aerospace Weapons Systems

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Recommended Practice.

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 1-877-606-7323 (U.S. and Canada only) or 1-724-776-4970 (outside U.S. and Canada), www.sae.org.

ARP5311 Aerospace-Interface Definition for Mechanical Actuation Subsystems

ARP5724 Recommended Test Requirements for Electromechanical Actuators

2.2.2 ISO Publications

Copies of these documents are available online at www.iso.org/store.

ISO 7137 Environmental Conditions and Test Procedures for Airborne Equipment

2.2.3 U.S. Government Publications

Copies of these documents are available online at <https://quicksearch.dla.mil>.

AFSC DH 1-6 System Safety Design Handbook

MIL-HDBK-470 Department of Defense Handbook: Designing and Developing Maintainable Products and Systems

MIL-STD-461 Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment

MIL-STD-704 Aircraft Electrical Power Characteristics

2.3 Definitions

ARP4386 contains the terminology, nomenclature, and definitions appropriate for use in Actuation and Control Technologies.

The following terms and definitions are in addition to those in ARP4386.

BACK EMF CONSTANT: Back electromotive voltage per unit speed (AC or DC voltage)

EDDY CURRENTS: These are loops of electric current induced within conductors by a changing magnetic field. These currents can occur in the magnetic core of electric machines.

FAILURE: This is any malfunction causing a performance degradation outside the limits as defined in the detailed specification.

LOAD: This is the force applied to the output of a linear actuator or the torque applied to the output of a rotary actuator occurring as a result of the position or movement of the output.

NOTE: Since an EMA may have either linear or rotary outputs, the term load should be used throughout this document to represent either force or torque as applicable to the application.

MOTOR CONSTANT: This is the ratio of the torque over the square root of the input power at ambient temperature.

NOTE: This is usually defined at 80 °F (25 °C) - related to copper losses.

MOTOR TORQUE CONSTANT: This is the electromagnetic torque per unit motor current (AC or DC).

SALIENCY: This is the variation of the inductance at the motor terminal according to the rotor position (for brushless motors only).

SCALAR CONTROL: This is the control method of an AC electrical motor that consists of adjusting input voltage and frequency to control its speed and torque.

FIELD-ORIENTED CONTROL or VECTOR CONTROL: This is the control method of brushless motors with sinusoidal back-EMF (commonly referred to as Permanent Magnet Synchronous Motors, or PMSMs) using a transformation to convert three-phase currents into a rotating reference frame for control of torque and flux.

SIX-STEP or TRAPEZOIDAL COMMUTATION: This is the control method of brushless motors with trapezoidal back-EMF (commonly referred to as Brushless DC motors, or BLDCs), using three discrete Hall effect sensors to switch the phases in a fixed sequence.

FIELD or FLUX WEAKENING: This is a control strategy in field-oriented control that allows extending the speed range of a PMSM by reducing the flux in the machine above a certain speed. The maximum speed achievable without field weakening is known as the base speed.

TORQUE RIPPLE: This is the periodic fluctuation in output torque of an energized motor as it rotates, mainly caused by back EMF harmonics, commutation effects, and cogging torque.

COGGING TORQUE (DETENT TORQUE or NO-CURRENT TORQUE): This is the torque caused by the variation of magnetic reluctance due to slotting. It can be observed when the shaft of an unenergized motor is slowly rotated by hand.

Appendix A presents some supplementary information including several definitions of motor parameters.

2.4 Abbreviations and Acronyms

The abbreviations and acronyms used in this document are defined below.

AC	alternating current
DC	direct current
dV/dt	rate of change of voltage
EMC	electromagnetic compatibility
EMA	electromechanical actuator
Back EMF	back electromotive force
LRU	line replaceable unit
MCE	motor control electronics (the EMA control and monitoring electronics)
MTBF	mean time between failures
PM	permanent magnet
PWM	pulse width modulation
RMS	root mean square
RoHS	Restriction of Hazardous Substances
VAC	volts alternating current
VDC	volts direct current
V _{RMS}	root mean square voltage

3. RECOMMENDED REQUIREMENTS

3.1 General

EMA motors covered by this document should be designed according to a specification. The specification should specify the requirements necessary to satisfy the application. The guidelines contained in this ARP are recommended for use in developing an EMA motor specification.

As a general guideline, each of the requirements set out in the specification should be defined in its own statement and uniquely identified within the specification by an alphanumeric tag relating it to the specifier's requirements database.

Unless otherwise defined, the requirements defined in the specification should be met under all rated operating conditions and during the service life specified.

NOTE 1: This document is limited to design requirement recommendations only.

NOTE 2: U.S. military specifications created using this document as a guideline should use MIL-STD-961 as a guide for the preparation of the specification.

NOTE 3: Appendix A provides supplementary information to assist in developing the technical specification.

NOTE 4: It may be recommended that the Motor Control Electronics (MCE) and motor be designed or selected by the same source as a comprehensive understanding of each component's detailed design is essential for both the MCE supplier and the motor manufacturer to define and predict performance.

3.2 Electromechanical Actuator Motor Description

While much of this ARP is independent of the type of motor selected, there are some sections which are tailored to permanent magnet brushed and brushless motors. A brief discussion on this family of motors is included to provide the context for some of the sections that follow.

It is recommended that the specification includes a brief overview of the purpose, functions, and context of the EMA motor within the wider system and the end application. The EMA general configuration should be defined. It is recommended to include an illustration showing how the motor unit is integrated into the EMA and interfaced with the MCE (refer to ARP7490). The description should not contain any requirements.

The end use of the motor, along with the safety criticality of the end application, should be summarized.

The various states and modes of the EMA motor should be described.

Recommendations for inclusion in the general description are the following but not limited to:

- a. Electrical or mechanical redundancy
- b. The torque and speed limits
- c. Voltage and/or current limits
- d. Built-in sensing needs (speed, position, temperature, etc.)
- e. Sinusoidal or trapezoidal back EMF (brushless motor)

f. Characteristics of the power drive, including, as applicable:

- The type of power bridge
- Scalar or field-oriented control
- PWM or bang-bang control
- Any current limitation
- Field weakening, etc.

g. Mechanical attachments

h. Any surrounding heat sources or sinks

The interfaces to the motor should be briefly described including the mechanical and electrical interface and any built-in sensors. A context diagram is often helpful in summarizing the interfaces and interactions of the system.

3.3 EMA Motor Scope

The required scope of the motor specification should be defined in detail. Several supporting specifications may be included within the main specification.

3.4 Functional Requirements

The detailed specification should define the functions of the motor including:

- The type of motion
- The loads
- The operative modes
- The sensing means

The functions should only focus on the need and required behavior and not define the method of implementation.

3.4.1 Motoring Function

The specification should define the motoring function in terms of the expected operation in terms of speed, position, and torque. The specific speed and load operation point specification is described in 3.5.

3.4.2 Back Drive - Reversibility Function

The specification should define whether the EMA is required to perform a function with a mechanical torque input and without electrical power from the MCE (i.e., the EMA may need to be back-driven when unpowered).

Typical requirements may include:

- a. The level of free-movement torque when the motor wiring is disconnected (cogging, friction, bearing drag), and
- b. The resistive torque that appears when the motor shaft is externally driven with the windings electrically connected, due to back-EMF and induced currents.

3.4.3 Degraded Function

The specification should state any reduced performance functioning that is acceptable under failure conditions or limit exceedance conditions such as overtemperature.

3.4.4 Measurement Function

Where required, any required built-in sensors such as the position, speed, or temperature should be specified. The recommended characteristics of the sensors to be specified are listed in 3.8.

3.5 Motor Performance Specification

To define the motor performance requirements, all relevant operating points in terms of motor speed and torque should be specified.

3.5.1 Operational Point

Below is a summary of such operating points (refer ARP5754 Section 11 for additional details related to these operating points). They should be specified along with their thermal environmental conditions, which can be specific for each operating point (where applicable):

- a. The maximum torque (maximum motor torque, with no movement, or the maximum driving torque, at a specified very low speed, for a short time duration - to be defined). Remark that holding the torque with no movement results in an unbalanced current distribution that is thermally more constraining.
- b. The maximum continuous motor torque (maximum motor torque with no movement, or the maximum driving torque at a specified very low speed, with no time limitation).
- c. The maximum allowable motor torque (maximum allowable output torque should be specified if it is to be limited by the EMA design).
- d. The reversal from stall torque (level of applied load torque at which the EMA begins to move when the load is reduced from a value greater than the stall torque).
- e. The Maximum No Load Rate (maximum speed under no or lightly loaded conditions).
- f. The Maximum Rate Under Load (maximum speed under required loading conditions or the time required to move from one position to another under a given load profile).
- g. The Maximum Allowable Rate (the maximum allowable output speed should be specified if it is to be limited by the electromechanical subsystem design).
- h. The Maximum Acceleration (specify the maximum acceleration under defined load conditions).
- i. The Velocity step response for acceleration (time from activation of the motor to achieve maximum speed under defined load and environmental conditions).
- j. The Frequency response with associated magnitude and load characteristics.

The specified motor output torque for each of the above operating points should include all the associated torque terms as:

- The inertial torque necessary to accelerate or decelerate the load,
- The friction torque,
- The viscous damping load, and
- Any other external load.

It is important to note that the EMA output force or torque, as well as load inertias, have to be transformed to the motor reference frame through the gear ratio as shown in Section A.4.

3.5.2 Thermal Sizing

Thermal management is one of the main aspects of the sizing of a motor. It deals with the capacity of the motor to produce torque and speed from electrical power while generating minimal losses and distributing and rejecting those losses without exceeding the maximum admissible internal temperatures during its mission. The requirement corresponding to this sizing is the thermal duty cycle.

The thermal duty cycle should be specified along with their environmental conditions including thermal exchange possibilities. It consists of describing, over time, the motor operating conditions—speed and torque. In particular, continuous load, start and stop cycles, servo-actuator cycles, frequency response requirements, and/or any cycle that may drive thermal design should be accurately defined with the associated environmental conditions.

The following aspects should be considered in the thermal sizing:

- The insulation class of the wiring and insulation system is related to the admissible temperatures of the materials
- Hot spots on the windings (e.g., end-windings)
- The magnet temperature range, including impact on the performance and the risk of demagnetization
- The maximum skin temperature when appropriate (e.g., explosive atmosphere or any aircraft structural limitation)
- The brushes and rotor heating, especially for the DC brushed motor

3.5.3 Smoothness and Ripple

The allowable motor torque ripple should be specified for those applications that are sensitive to EMA output force/torque ripple. The torque ripple requirement should specify the test conditions that can be implemented in the production environment since the output torque ripple may be highly dependent on:

- The transmission dynamics
- The frequency of the ripple that depends on the number of poles and the motor speed
- The commutation and control method

Another characteristic that affects the smoothness of a motor is the cogging torque, also known as no-current torque or detent torque. It could be specified as well when necessary, e.g., when a drive back-reversibility function (see 3.4.2) is required.

NOTE 1: Slotless motors are available which have reduced torque ripple and cogging torque. However, there are other considerations in terms of torque density.

NOTE 2: In some cases, cogging torque can be required to ensure the irreversibility of the EMA.