THE APPLICATION OF CONFIDENCE INTERVAL IN THE EVALUATION OF ELECTRIC ACTUATION DUTY CYCLE

David E. Blanding, Matthew R. Sexton, Matthew Segal, Jason Grow
The Boeing Company

Keywords: *Actuation, Motor, Duty, Intervals, MEA*

Abstract

Electric actuators will soon become the dominant flight control system for the More Electric Aircraft (MEA), replacing the traditional centralized hydraulically controlled system. For decades, electric actuation has been used on aircraft secondary flight control and utility systems. With recent advancement in motor and power electronics technology and the desire to build more energy-efficient airplanes with reduced maintenance cost, air framers are starting to evaluate the widespread usage of electric actuation on primary flight control surfaces. Traditional hydraulic actuators are sized using the combination of surface hinge moment or stall force and deflection rate. When designing electric actuators, duty cycle has emerged as one of the most critical design parameters for the electric actuator. Duty cycle must be analyzed from the standpoint of heat generation under normal operation, holding loads and life expectancy of the electrical and mechanical components. There are many factors that affect the generation of repeatable and reliable duty cycle data. This paper discusses a statistical method for developing aircraft flight control surface actuator duty cycle to support the design of electric actuation systems for the MEA.

Nomenclature

D = Duty Cycle
τ = Duration
T = Period
ℓ_{10} = Screw life at 1,000,000 cycles
F_D = Dynamic load rating (lb)
s = Screw lead (in/rev)
f_M^3 = Cubic mean load
L_N = Load (lbs)
L_{Mean} = Mean load (lbs)
N = Number of points
σ = Standard deviation
X = Point value
Z = value reflective of % confidence
μ = Mean deviation

1 Introduction

For decades, electric actuation has been used on aircraft secondary flight control and utility systems. With recent advancements in electric motor and power electronics, air framers are starting to evaluate the widespread usage of electric actuation on primary flight control surfaces. Electric actuation is an evolving technology with high payoffs in terms of energy efficiency, reduced maintenance, improved safety, improved survivability, reduced operational cost, and overall system weight through the elimination of the central hydraulic system. The two leading electric actuation systems being considered for primary flight control surfaces are electromechanical actuators (EMA) and electrohydrostatic actuators (EHA). Of the two electric actuation systems, EMAs are showing the most promise in terms of reduced system weight, reduced maintenance cost, and design simplicity. Therefore, EMAs will be the focus of this paper.

2 Duty Cycle Impact on Electric Actuator Design

Duty cycle is among the most basic requirements for the actuator. Duty cycle typically defines operational loading conditions throughout a series of flight events (Fig. 1). It is normally looked upon as the ratio or percentage of actuator on time to off time and is expressed as shown in Equation 1.

$$D = \frac{\tau}{T} \times 100 \qquad (1)$$

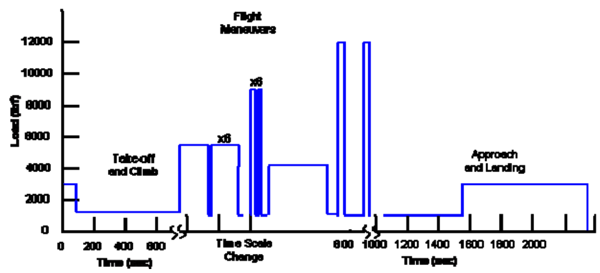

Fig. 1. Typical Aircraft Duty Cycle

Traditionally, designers have paid little attention to extracting and collecting duty cycle when designing hydraulic actuators. Hydraulic actuators have been sized by the maximum hinge moment, the control surface deflection, and at some low-q conditions [1]. Though sizing electric actuators requires the same data, duty cycle has emerged as a critical element in the design process. Proper analysis of duty cycle data will play an important role in sizing the electric actuator overall operating efficiency, thermal, and mechanical performance.

2.1 Operating Efficiency

Duty cycle data will aid the designer in sizing the electric actuator motor torque capability and power converter control techniques. This in turn affects the reliability and efficiency of the total drive system [2]. Research has shown that most motors are designed to run at 50% to 100% of the rated load. Whereas studies have shown that a motor maximum efficiency usually occurs at or near 75% of maximum load. Research has also shown that there is a linear relationship between the EMA motor speed and load (Fig. 2).

Analysis of the duty cycle of a typical aircraft control surface shows that the EMA motor operates at load far less than 50% of the rated speed. A motor's efficiency tends to decrease dramatically below about 50% load. [3] Research is under way to reevaluate the design point for motor efficiency as related to EMA power point (Fig. 3).

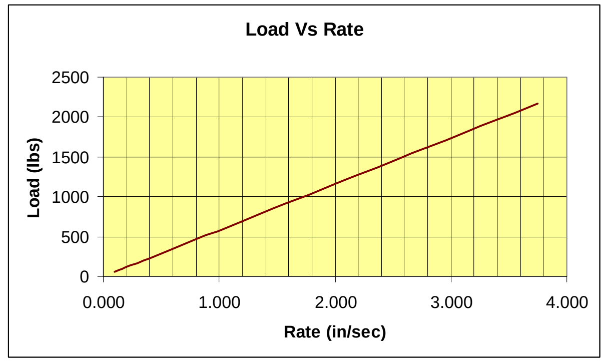

Fig. 2. Motor Land Speed Relationship

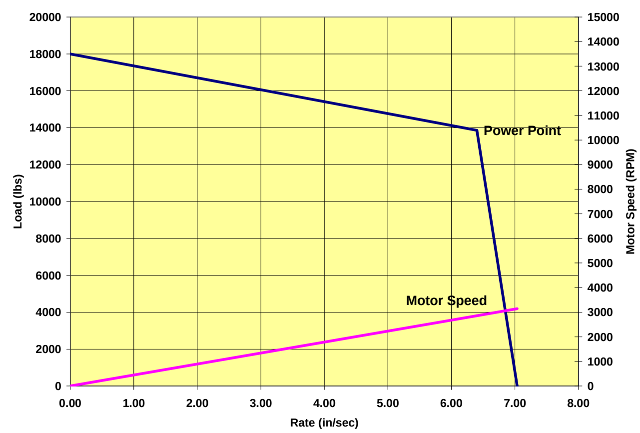

Fig. 3. Motor Speed Load Rate Curve

The load cycle of an electric actuator involves the required input power to accelerate the EMA motor against a defined load and the EMA motor operating at a speed and torque sufficient to move the control surface [7]. This in turn creates a need to consider the actuator force loads profile, heat generation loads profile, and mission duty cycle. Measures of heat generated by the motor, life of the actuator, weather, and the pilot's flying characteristics and aircraft missions are very important in the development of electric actuation.

2.2 Thermal Performance

Duty cycle data will aid the designer in predicting the thermal load profile generated by the actuator. Aircraft flight maneuvers and mission profiles generate significant actuator heat [4]. This heat is generated by factors such as load duration (holding), load interval, rate of actuation, etc. The electric actuator components have to be designed to handle these heat loads. These heat loads affect the sizing of the thermal management system, thus preventing the electric actuator from overheating and subsequently failing to operate in a proper manner.

2.3 Mechanical Performance

Duty cycle is used to predict the magnitude and frequency of loads. This impacts the design to ensure that the electric actuator meets the expected life requirements and has the ability to produce the necessary force output. Additionally, electric actuator rate (in/sec) and number of cycles per flight maneuvers (fatigue) is also determined. Designers use duty cycle data to analyze the total linear travel distance of the electric actuator. When focusing on the EMA, this analysis is used to size the ball screw or roller screw expected L10 life. The expected L10 life of a roller screw or ball screw is expressed as the linear travel distance that 90% of screws are expected to meet before experiencing metal fatigue as shown in Equation 2.

$$\ell_{10} = F_D \,/\, f_M^3 \times s \times 10^6 \qquad (2)$$

Using the above relation, the expected life of the roller screw or ball screw can be computed and displayed in the format shown in Figure. 4.

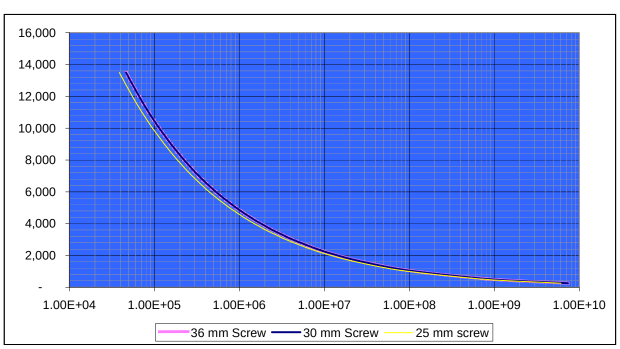

Fig. 4. Screw Projected Life Curve

Additionally, the duty cycle data can be used to generate performance curves for bearings, gears, and power electronics. This could result in the formation of an aggregate EMA performance curve. This aggregate EMA curve can be used to support and integrated strategy for prognostics and diagnostics (Fig. 5).

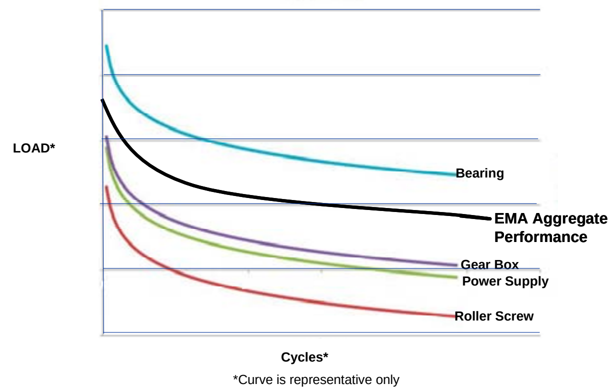

Fig. 5. Aggregate Performance Life Curve

3 Duty Cycle Development Strategies

There are many factors that impact duty cycle, which makes collecting such data a real challenge. Duty cycle is impacted by the aircraft mission, weather, and the function of the control surface. The pilot plays an important roll in gathering consistent duty cycle. To manage the collection of actuator duty cycle data, all the actuator cycles must be counted and the displacement amplitudes and time be lumped in a limited number of levels based on percent of stroke or total force applied to the control surface. The data should be segregated by flight phase; e.g., ground operation, takeoff/landing configuration, and up and away flight.

Trying to identify a reliable duty cycle database has been a major challenge. Attempts have been made to obtain good duty cycle data from military and commercial air platforms. Since reliable duty cycle data do not exist for these air platforms, manufactured data have been used by extrapolating data from flight tests of various aircraft. The methodologies used to extract duty cycle information from flight tests of these aircraft were found to be very different.

This makes it difficult to compare the resulting duty cycle directly. The application of any aircraft's duty cycle information to another aircraft is fundamentally risky, given the substantial impact of different missions, Mach number, range, and degree of surface aerodynamic balance.

4 Data Collection Techniques

In this paper, data from a series of flight test missions were simplified to load time history, which provides an easy way to specify duty cycle and facilitate thermal analysis. The mean load for the entire mission of each flight was computed by dividing the data into 8 increments of time expressed in seconds. The mean load is computed as shown in Equation 3.

$$L_{Mean} = \sum L_N \Big/ N \qquad (3)$$

L_N = Load
L_{Mean} = Mean Load
N = Number of Load Points

To ensure the correct overall mean load for the flight, the data was scanned for each level to determine which load is greater than or equal to the mean load. Data below the mean load is consolidated into an "average trim load" for the flight. The normal distribution of the load data important because there are variables are distributed approximately normally. Although the distributions are only approximately normal, they are usually quite close. A second reason the normal distribution is so important is that it provides statistical data that is easy for engineers and designers to work with. This means that statistics can be derived from many flight tests to generate normal distributions. Normal distributions are symmetric with scores more concentrated in the middle than in the tails. They are defined by two parameters: the mean (μ) and the standard deviation (σ). The behavior of aircraft flight control actuators can be approximated using the normal distribution. The basic standard deviation equation shown in Equation 4

$$\sigma = \sqrt{\sum X^2 - \left(\sum X\right)^2 \Big/ N \Big/ N-1} \qquad (4)$$

is converted into a form that is compatible with evaluating duty cycle as shown in Equation 5.

$$L_{Mean-Trim} = \sqrt{\sum L^2 - \left(\sum L\right)^2 \Big/ N \Big/ N-1} \qquad (5)$$

To demonstrate the concept, three flight conditions from a common aircraft was used in the analysis. Each of the three flights is represented by a single color. The concept desired here is to determine if load for a certain period of time would fall within an acceptable range to continue to design the electric actuator with a certain degree of confidence. The data used in this analysis are shown in the chart provides a representative illustration of the three flight data records reducing the peak actuator loads into eight individual segments (Fig. 6).

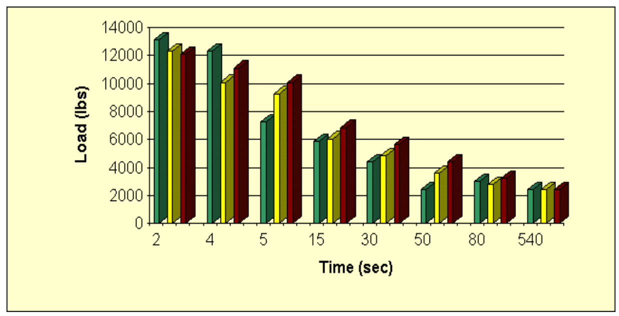

Fig. 6. Typical Flight Load Data

Figure 7 provides a computation of the mean, or "average" load widely used measure of central tendency. The mean is defined technically as the sum of all the load data points divided by n (the number of load data points in the distribution). It also provides the standard deviation and confidence level.

Time (sec)		Mean				Standard Deviation	90% Confidence Interval	
	13100	X_{Bar}	X^2	Sum X^2	Sum X	σ	Max Z	Min Z
	13100		171610000					
2	12294	12495	151138653	468972559	1405211730	533	13447	11544
	12092		146223906					
	12294		151138653					
4	10077	11152	101544379	375551730	1119262760	1110	13132	9172
	11085		122868698					
	7255		52640606					
5	9271	8868	85947162	240132147	707723702	1453	11460	6275
	10077		101544379					
	5845		34159529					
15	6046	6248	36555976	117669626	351302933	533	7199	5296
	6852		46954121					
	4434		19658992					
30	4837	4971	23396825	74899134	222422807	616	6070	3873
	5643		31844317					
	2418		5848956					
50	3628	3493	13160151	38668099	109830400	1014	5303	1684
	4434		19658992					
	3023		9138994					
80	2822	3023	7961079	27498218	82250947	202	3383	2664
	3225		10398144					
	2418		5848956					
540	2418	2418	5848956	17546869	52640606	0	2418	2418
	2418		5848956					

Fig. 7. Mean and Average Load Computation

5 The Concept of Confidence Level

The concept confidence interval appeared to be a good method to support the desired design goal. Confidence Interval is based on standard deviation and normal distribution probability. A confidence interval is a range of values that has a high probability of containing the parameter being estimated [5].

$$\bar{x} \pm z \frac{\sigma}{\sqrt{n}} \tag{6}$$

$\bar{x}$ - mean

σ - Standard Deviation

n - Number of Data Points

z - Value reflective of % Confidence

After further research on confidence interval, it was decided to summarize duty cycle data from the three previously mentioned three test flights. Because of the many factors that affect aircraft duty cycle, a 95% confidence interval is not recommended. For military fighter type aircraft applications, a duty cycle confidence interval of 90% would be acceptable. However, due to the benign nature of commercial and military transport-type aircraft, the 95% confidence interval may be suitable. For this example, the parameter being estimated for a 2-second time interval with a 90% confidence interval might look like Equation 7:

$$11544 \le \mu \le 13447 \tag{7}$$

The confidence interval is computed by using Equation 8.

$$Z = X_{Bar} \pm 3.09 \sigma / \sqrt{N} \tag{8}$$

A control chart (Fig. 8) was generated to display a quality characteristic that has been measured for the duty cycle for the three test flight missions. The chart contains a center line that represents the average value of the quality characteristic corresponding to the in-control state. Two other horizontal lines, called the upper control limit (UCL) and the lower control limit (LCL) are also drawn [6]. These control limits were chosen so that if the process is in control, nearly all of the sample points will fall between them.

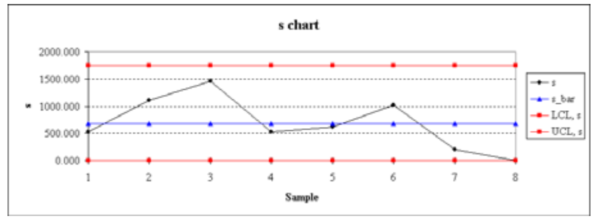

Fig. 8. Control Chart

As long as additional duty cycle data points plot within the control limits, the process is assumed to be in control. However, a point that plots outside of the control limits is interpreted as evidence that the process is out of control, and investigation and corrective action is required to find and eliminate the assignable causes responsible for this behavior. The control points are connected with straight line segments for easy visualization. The range of the load data helps define the confidence interval for a given time period. The range in the earlier example had the values of 13100, 12294, and 12092. The highest number is 13100. The smallest number is 12092. The range is therefore 13100 - 12092 = 1008 pounds of force.

In the area of hypothesis testing, an electric actuation system designed is interested in whether the heat generated by the electric motor is affected by the duty cycle. The null hypothesis is that $\mu 1 - \mu 2 = 0$, where $\mu 1$ is the duty cycle and $\mu 2$ is the heat generated by the motor. Thus, the null hypothesis concerns the parameter $\mu 1 - \mu 2$ and the null hypothesis is that the answer equals zero. In the case of electric actuation, heating of the electric actuator has shown to be sufficiently effected of duty cycle.

Flight data can be used to put together a prediction of the nominal actuator performance during all aspects of the aircraft operation. To characterize the duty cycle, the actuators performance data, load, and deflection will be manipulated to reveal the following information:

- What force must the actuator create and how often?

- What torque must the motor create and how often?
- What is the speed of the actuator?
- How many inches of travel do the ball screw or roller screw sees?
- How fast does the motor spin and how many revolutions does it perform?
- How fast does the roller/ball screw spin and how many revolutions does it perform?

6 Summary

Reliable duty cycle data is critical for designing electric actuation systems. A statistical approach using confidence interval could eliminate dependency of uncontrollable variables, i.e., pilot habits. This approach can put a percent confidence on the requirements of the thermal management system

Our approach could lead to the development of a new recommended standard for presenting duty cycle data

7 References

1. Leonard, John B., A System Look at Actuation Control and Alternative for Primary Flight Control, SAE Publication P-170, October 9, 1985
2. R. Krishnan, Fellow, IEEE, D. Blanding', A. Bhanot, A. M. Staley, Student Member, IEEE, N. S. Lobo, “High Reliability SRM Drive System for Aerospace Applications”, IEEE 2003
3. U.S. Department Of Energy, “Determining Electric Motor Load And Efficiency”, Motor Challenge, www.motor.doe.gov.
4. ARP4895, “Flight Control Actuator Displacement, Method for Collection of Duty Cycle Data”
5. Lind and Mason. (2003). Business and Research Statistics (11th ed.). New York: McGraw-Hill.
6. Control Charts as a tool in SQC (Statistical Quality Control) http://deming.eng.clemson.edu/pub/tutorials/qctools/ccmain1.htm
7. Wei Zhang, Yuanjun, Zhou, The Application of SAPWM Rectify Technology ON the Aircraft Electric Actuator, ieeexplore.ieee.org/iel5/4753968/4770630/04770981.pdf?arnumber

8 Contact Author Email Address

The authors of this paper may be contacted at the Boeing Company using the contact information below.

david.e.blanding@boeing.com
matthew.r.sexton@boeing.com
matthew.segal@boeing.com

Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper (Copyright © 2010 Boeing. All rights reserved.), for the publication and distribution of this paper as part of the ICAS2010 proceedings or as individual off-prints from the proceedings.