



AEROSPACE INFORMATION REPORT

AIR7061™

Issued

2026-02

Failure Modes for High-Lift Actuation Load Paths

RATIONALE

There is a need to provide the aerospace industry with a reference that can be used by the design community to understand typical failure modes of highly loaded, complex mechanical components in high-lift actuation systems to help ensure that the system design and safety assessments are based on design knowledge and experience. This document fulfills this need.

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1. SCOPE

This SAE Aerospace Information Report provides examples of single failure modes for components used in fixed-wing, high-lift actuation systems' load paths, as well as the typical hazards posed by those failures at the aircraft level.

1.1 Purpose

The purpose of this document is to assist in the verification of the design and System Safety Assessment focusing on typical high-lift actuation solutions for civil aircraft that are certified to 14 CFR Part 25/CS-25 airworthiness regulations.

NOTE 1: This document addresses only the mechanical failures of the high-lift system load path, of the applicable functional failures described in this document.

NOTE 2: Failure modes associated with the Flap/Slat controller monitoring system are not covered in this document.

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.

AIR6016 Description of High Lift Control Systems

ARP4754 Guidelines for Development of Civil Aircraft and Systems

2.1.2 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

2.1.3 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

14 CFR Part 25 Airworthiness Standards: Transport Category Airplanes

2.2 Definitions

ALERT: This is a generic term used to describe a flight deck indication meant to attract the attention of and identify to the flight crew a non-normal operational or aircraft system condition.

NOTE: Warnings, Cautions, and Advisories are considered to be alerts.

ANALYSIS: This is an evaluation based on the decomposition into simple elements.

ASSESSMENT: This is an evaluation based on engineering judgment.

CASCADING FAILURE: This is the induced failure result of an initiating failure mode or failure condition.

CATASTROPHIC: This is a failure condition that would prevent continued safe flight and landing.

FAILURE: This is a loss of function or a malfunction of a system or a part thereof.

NOTE: This differs from the ARP4754 definition and conforms to the AC/AMJ 25.1309 definition.

FAILURE CONDITION: This is a condition with an effect on the aircraft and its occupants, both direct and consequential, caused or contributed to by one or more failures, considering relevant adverse operation or environmental conditions.

NOTE: A Failure Condition is classified per the severity of its effects as defined in FAA AC 25.1309-1A or EASA AMC 25.1309.

FAILURE EFFECT: This is the description of the operation of a system or an item as the result of a failure, i.e., the consequence(s) a failure mode has on the operation, function, or status of a system or an item.

FAILURE MODE: This is a specific way in which a system or item may fail.

FUNCTIONAL HAZARD ASSESSMENT (FHA): This is a systematic, comprehensive examination of functions to identify and classify Failure Conditions of those functions according to their severity.

HAZARD: This is a potentially unsafe condition resulting from failures, malfunctions, external events, errors, or a combination thereof.

HAZARDOUS: This is a failure condition that would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be:

- (i) A large reduction in safety margins or functional capabilities;
- (ii) Physical distress or excessive workload such that the flight crew cannot be relied upon to perform their tasks accurately or completely; or
- (iii) Serious or fatal injury to a relatively small number of the occupants other than the flight crew.

LATENT FAILURE: A failure which is not detected and/or annunciated when it occurs.

MAJOR: This is a failure condition that would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be, for example:

- A significant reduction in safety margins or functional capabilities
- A significant increase in crew workload or conditions impairing crew efficiency
- Discomfort to the flight crew
- Physical distress to passengers or cabin crew, possibly including injuries

MINOR: This is a failure condition that would not significantly reduce aircraft safety, and which involves crew actions that are well within their capabilities.

NOTE: Minor Failure Conditions may include, for example, a slight reduction in safety margins or functional capabilities, a slight increase in crew workloads, such as routine flight plan changes, or some physical discomfort to passengers or cabin crew.

WARNING: This is the level of alert for conditions that require immediate flight crew awareness and immediate flight crew response.

ZONAL ANALYSIS: This is an analysis that has the objective of ensuring that the equipment installations within each zone of the aircraft are at an adequate safety standard concerning the design and installation standards, interference between systems, and maintenance errors.

NOTE: In those areas of the aircraft where multiple systems and components are installed in close proximity to each other, it should be ensured that the zonal analysis would identify any failure or malfunction which by itself is considered sustainable but which could have more serious effects when adversely affecting other adjacent systems or components.

2.3 Abbreviations

AC	Advisory Circular
AFM	Aircraft Flight Manual
AMC	Acceptable Means of Compliance
BIT	Built-in Test
CAS	Crew Alerting System
CFD	Computational Fluid Dynamics
EASA	European Union Aviation Safety Agency
EICAS	Engine Indication and Crew Alerting System
FAA	Federal Aviation Administration
FHA	Functional Hazard Analysis
GRA	Geared Rotary Actuator
HLS	High-Lift System
IBD	Inboard
LRU	Line Replaceable Unit
OBD	Outboard
OEM	Original Equipment Manufacturer
PDU	Power Drive Unit
V _{FE}	The maximum airspeed with the flaps extended

3. GENERAL DESCRIPTION OF HIGH-LIFT ACTUATION SOLUTIONS

Design solutions for high-lift actuation architectures and components have reached a relatively stable level of maturity over the last few decades. The industry has acquired experience with the failure modes of these devices and developed best practices aimed at failure mode detection and containment.

This document offers a brief discussion on the mechanical load path failure modes experienced with mechanically synchronized electro or hydro-mechanical actuation components used in high-lift systems. The discussion will address the basic implementation of the function, failure modes experienced with these solutions, and protections that are put into place to mitigate the failure modes exhibited with the design features under review.

3.1 High-Lift Functions

High-lift systems are used to increase the amount of lift from the wing during take-off and landing to enable the aircraft to take off and land at the lowest speeds safely possible. They also increase the stall angle of attack and provide additional drag to assist in slowing the aircraft down for landing.

Flap systems increase total lift for a given angle of attack by increasing the wing planform area and/or camber. Leading edge slat, leading edge flap, and/or trailing edge flap systems permit the wing to attain higher angles of attack by re-energizing the boundary layer on the upper surface of the wing. There are typically several settings, selectable by the pilot or control system, for take-off, approach, and landing operations.

Figures 1 and 2 show the main types of flaps and slats that are used on aircraft.

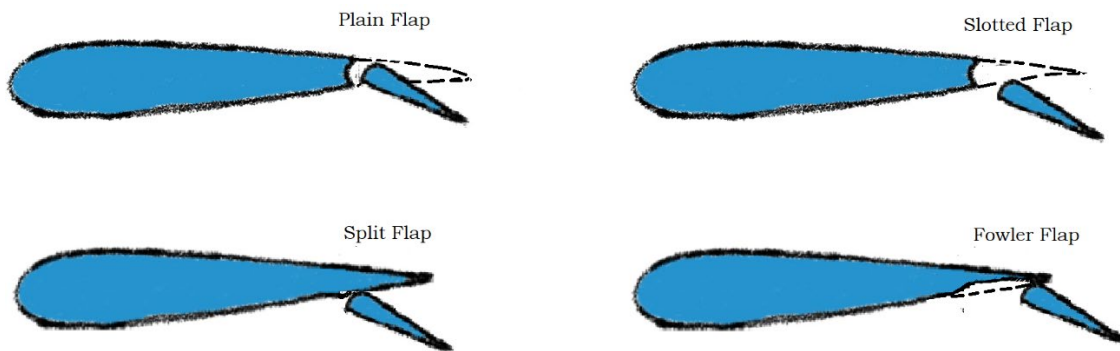


Figure 1 - Types of flaps

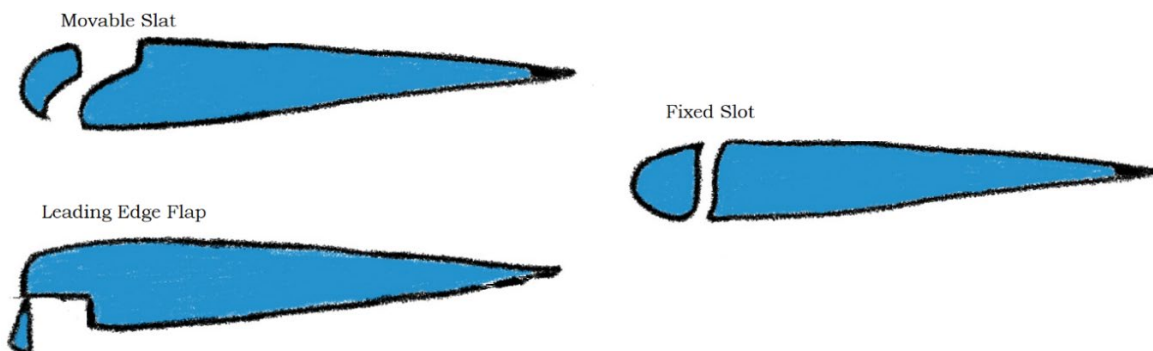


Figure 2 - Types of slats

The wing houses the attachment structures, tracks, and actuation components that enable the flap or slat extension and retraction. High-lift surfaces may be actuated about a simple hinge, deployed along a track or linkage, or a combined track and linkage system. This document will discuss in more detail the types of components that are used in these actuation systems and the typical failure modes associated with them.

The slat and flap mechanical actuation systems are typically comprised of three main assemblies:

- A Power Drive Unit (PDU)
- The drivelines
- Rotary or linear actuators

More detailed descriptions of these assemblies and their typical failure modes are discussed in 5.1 (PDU), 5.2 (Driveline), and 5.4 (Actuators).

Some implementations exist that replace the federated Power Drive Unit/Driveline architecture with distributed powered actuators. Fully distributed architectures, either hydraulic or electric, are not discussed in this document; however, the actuation components may share some of the same failure modes discussed herein.

Examples of high-lift systems used in civil aircraft are shown in Figures 3 to 6. The various sensing system architectures used for high-lift position control and monitoring are presented in AIR6016.

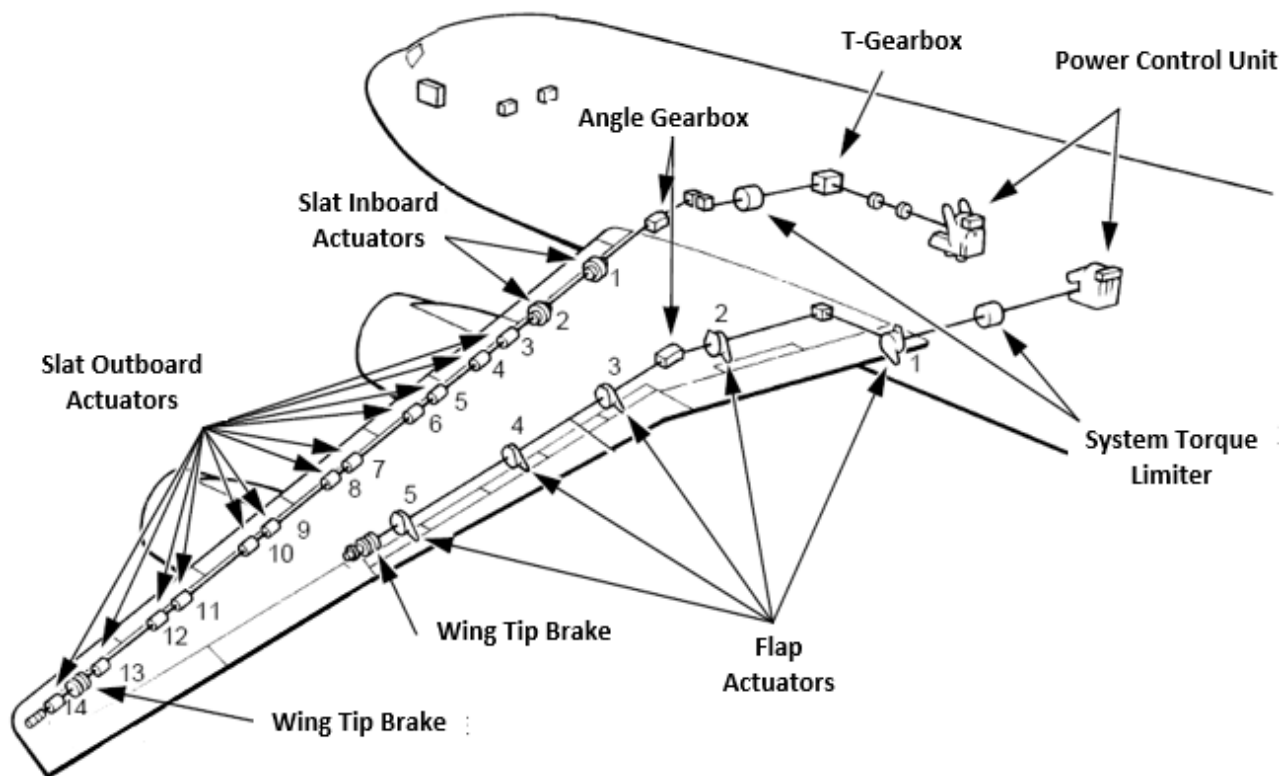


Figure 3 - Airbus A330/A340 flap and slat actuation system

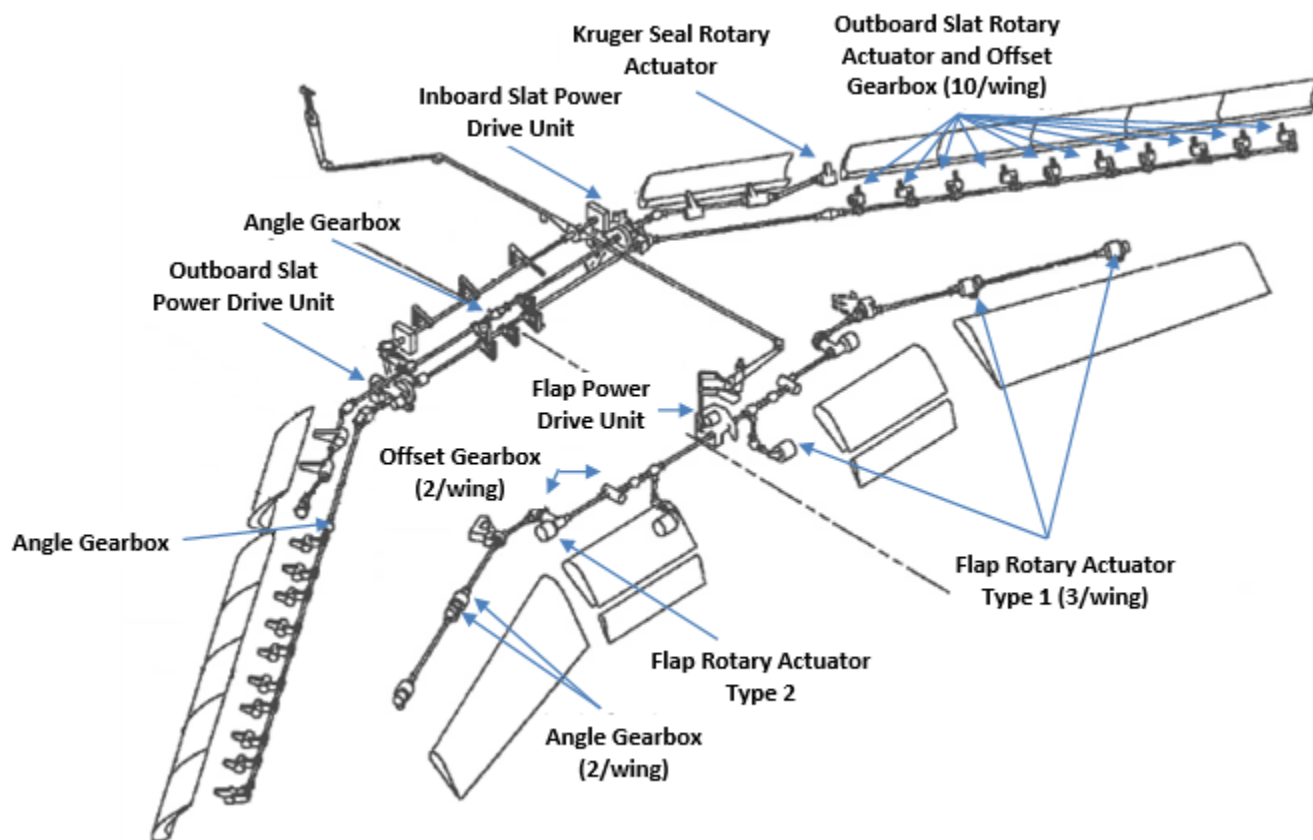


Figure 4 - Boeing 767 flap and slat actuation system

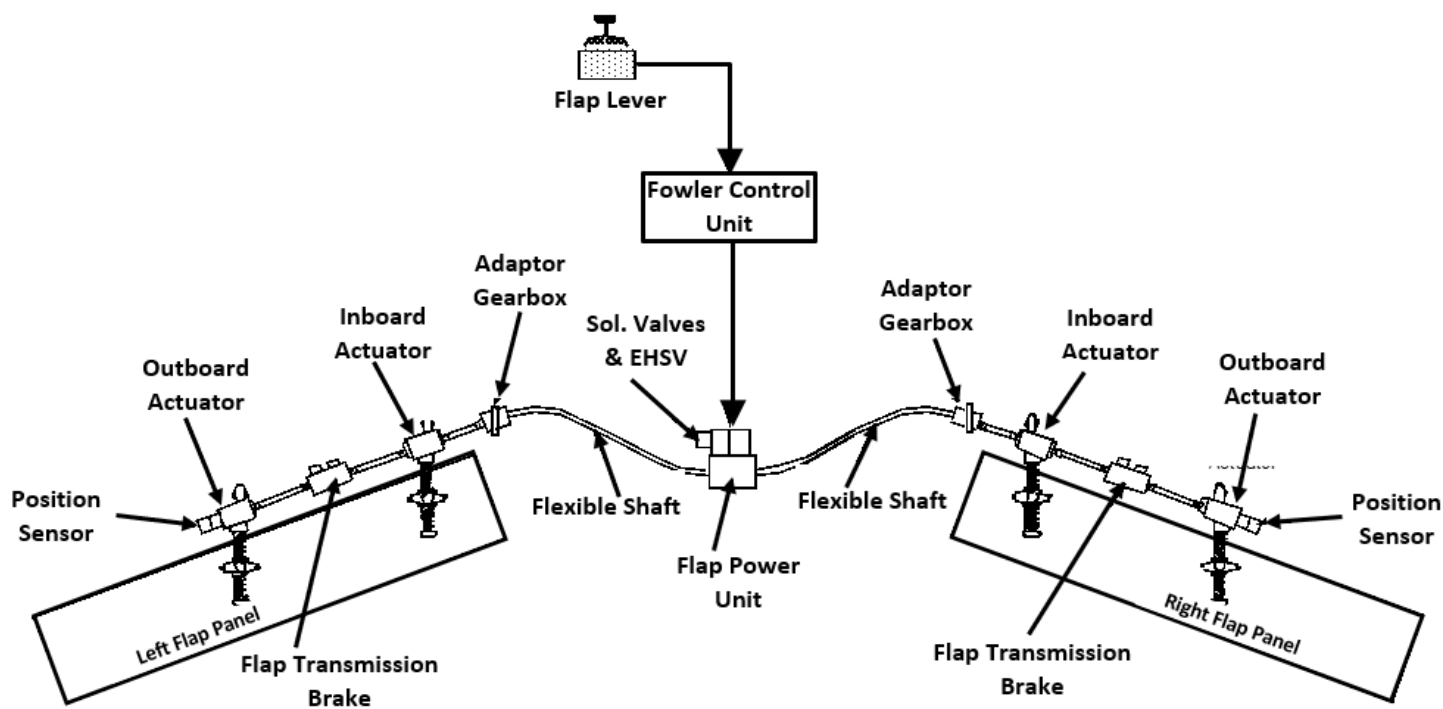


Figure 5 - Bombardier CL300 flap actuation system

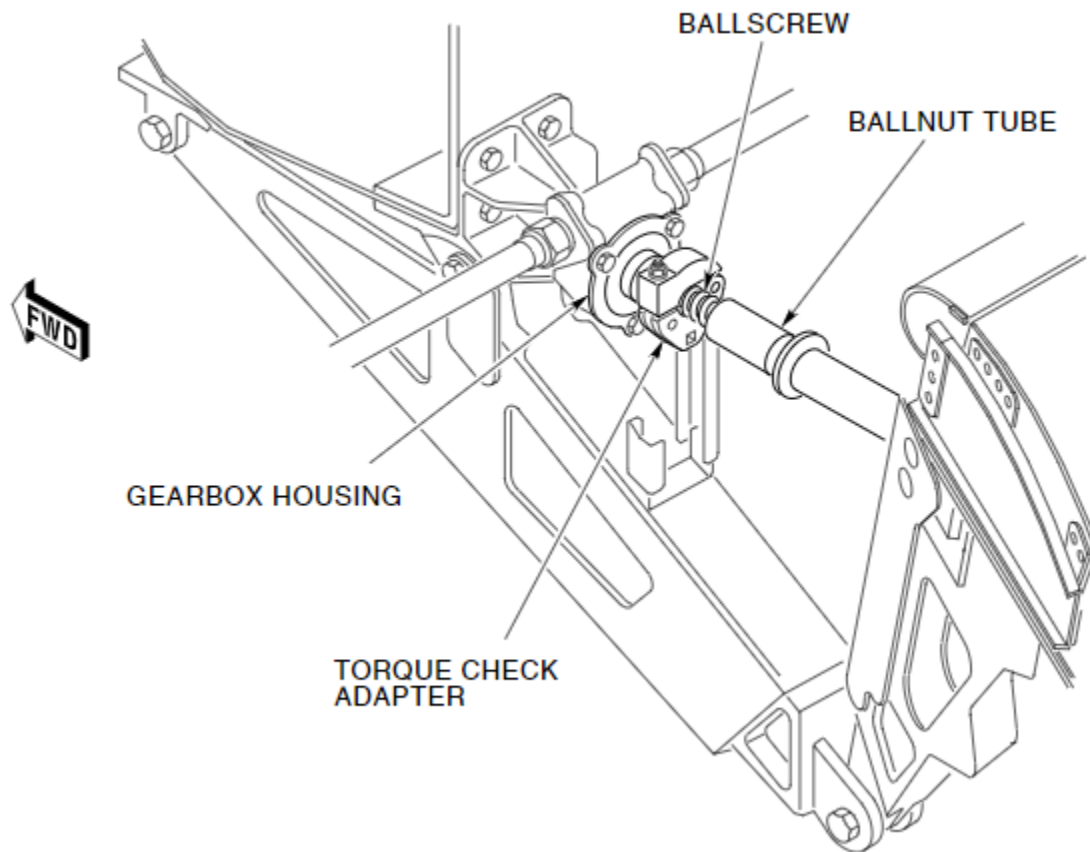


Figure 6 - Bombardier Challenger 605 flap drop hinge mechanism
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4. HIGH-LIFT SYSTEMS FUNCTIONAL FAILURES

4.1 General

The OEM will define the high-lift system functional failures in the HLS Functional Hazard Analysis (FHA), which is derived from the Aircraft Functional Hazard Analysis. The HLS FHA will also assign the severity and permissible probability for each functional failure. Analyses and tests are performed early in the design cycle to validate the severity classification. The HLS system designers will then design the system with the appropriate level of reliability, redundancy, monitoring, and protection to ensure that the probability of system failures is appropriate for the severity assigned to them.

After the completion of the system design, the OEM and HLS system designers will verify that the design requirements have been implemented correctly and adequately in the design through analysis and testing.

The typical system functional hazards in a high-lift system are:

- a. The symmetric loss of function – the failure to move when commanded
- b. The asymmetrical loss of function – the difference of movement between the high-lift surfaces on the left and right side of the aircraft
- c. Uncommanded motion – surface movement without a command
- d. Panel skew – the difference in position between the inboard and outboard ends of a high-lift surface

- e. Panel blowback – the failure to maintain the selected position, i.e., the panel is back driven by the surface aerodynamic load
- f. Panel detachment – the complete or partial departure of the panel from the aircraft
- g. Actuation System overspeed – the rate of actuation exceeds the maximum rate
- h. The high-lift surface moves to the incorrect position, i.e., actual surface position differs from the selected position

The hazards discussed below may be applied generally to the flaps or the slats due to the similarity of the architectures and components if no distinction is made in a section.

The combined loss of both flaps and slats is not discussed as it would not be the result of a single failure of highly loaded, complex mechanical components. If the aircraft level effect of the hazard differs between flaps or slats, the text will address it.

The effectiveness of the detection schemes is verified via the system dynamic analysis, as well as qualification and rig testing. The rig testing is typically conducted with the complete installation (e.g., surfaces, tracks/rollers, and actuation) and simulated air loads on the surface.

4.2 Failures of Fail-Safe Actuation Concept

The panel in motion is controlled by one or more actuators along multiple tracks or hinges such that jams and disconnects result in stopping the flap/slat motion, and an annunciated fail-safe retention of the panel. Actuators on most 14 CFR Part 25/CS-25 aircraft are driven by a common rotating driveline to ensure symmetric surface deployment across the wingspan. If an approved equivalent means is considered, the design assurance of the system should ensure that the high-lift asymmetry is mitigated.

Protection means for mechanical failures in high-lift actuator systems typically use a braking function to stop uncommanded motion, and torque limiters to prevent structural damage. This leaves the aircraft in a known flying condition that the flight crew manages through AFM instructions.

The failure modes need to be fully understood to properly develop the protection means and system architecture. Mechanical failures can manifest themselves in the following categories:

- a. Reduced torque capability
- b. Full disconnect with no torque capability
- c. Increased friction
- d. Full actuation jam

Failures resulting in a torque reduction or the disconnect of an actuator are typically accommodated by the other actuator on the panel, but they need to be detected by active monitoring or periodic maintenance to ensure they don't contribute to a larger aircraft hazard when combined with additional failures.

Failures resulting in actuator jams need to be considered in the context of alerting the flight crew of the loss of motion and in the context of protecting the aircraft structure from damaging loads through and around the jammed load path and to ensure adequate control resulting from asymmetric and skewed panel deployment.

4.3 Loading Direction

An important aspect when considering and analyzing failures is the direction of the aerodynamic load versus the direction of actuation. The aerodynamic load will either be aiding or opposing the actuation motion. For example, in the case of aiding aerodynamic loads, as shown in Figure 7, it might be that not enough skew is generated to trigger the skew protection function. This condition may remain latent, depending on the monitoring schemes in place.

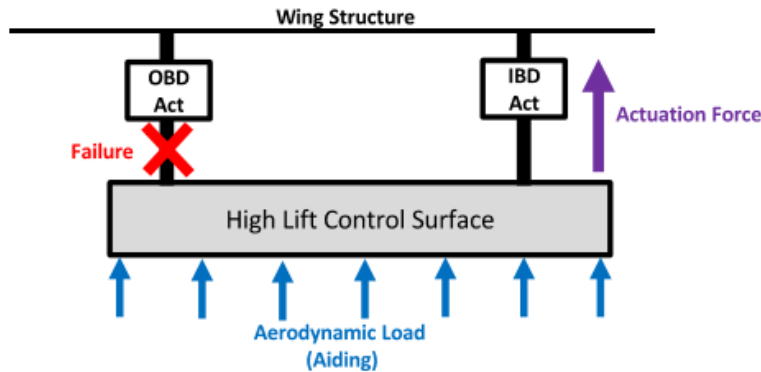


Figure 7 - Aerodynamic force aiding the actuation direction

In the case of the opposing aerodynamic load, as shown in Figure 8, the dynamic response due to the failure might result in overloads on parts of the installation.

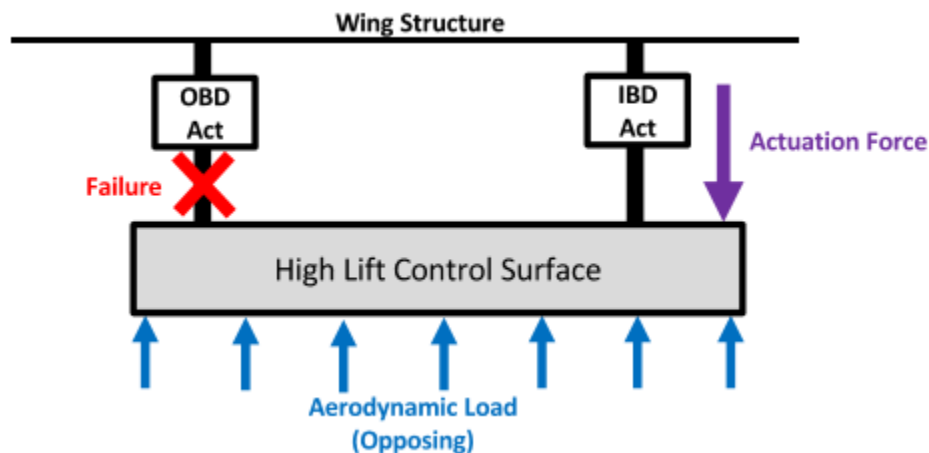


Figure 8 - Aerodynamic force opposing the actuation direction

A dynamic analysis/modeling of the skew, jam, and asymmetry failure cases should be conducted to determine the effect of aiding and opposing aerodynamic loads. This analysis/modelling also serves as input to define cases that should be tested.