

Reliability Modeling Approach and Hydraulic Actuators Designed Hinge-Moment Capability

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ABSTRACT

The hydraulic actuators are used to power flight control surfaces of the aircraft and to ensure surface movement. A system of two or three actuators is usually designed depending on the surface and intuitively these actuators are considered as a redundant architecture from a reliability and functionality point of view. The proper reliability modeling of the system of actuators must consider the system's functionality and design constraints for the remaining available actuator hinge-moment in the event of a partial or total actuator failure. As a result, this will affect the reliability assessment of that design. Furthermore, this system of actuators is also designed to provide a second function involving an assurance of the surface stiffness and damping. Generally, this second function does not require necessarily the same number of available actuators in order to be fully provided. Therefore, the criteria for the reliability model might be different depending on the failure definition and severity related to the specific function and the assumed redundant architecture for one function might not be valid for the second function. This will obviously result in a significantly different level of computed reliability. Additionally, this difference in the reliability modeling might lead to some difficulties in the assessment of potential latent failures at the actuators' system level related to the various functions of the actuator. This paper provides an approach to reliability modeling and latent failures designation for the system of actuators designed to perform two or more different functions. Specific actuator failure modes and their respective combinations resulting in a reduction in hinge-moment capability are discussed in regards to the criticality of the related failure conditions associated with both functions. The resulting failures at the system of actuators' level might be latent depending on the system's configuration in a partially failed state and on the specific failure mode. However, this latency may be designed out if the actuator is accurately specified. Some factual application examples are provided in order to illustrate the discussed topics.

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INTRODUCTION

Reliability modeling is a basic engineering activity during the safety assessment of technical systems. The accuracy and correctness of the reliability model is a fundamental parameter in regards to the adequacy of the reliability and safety analysis of any given system. In the aerospace industry, the reliability analysis is a fundamental step in safety assessment during the aircraft or system design evaluation in order to show compliance against quantitative reliability requirements as postulated in the applicable regulations, for instance FAR/CS 25.1309 [1], [2].

A reliability model has to represent a flawless picture of the system's functional interdependencies providing a means to a detailed reliability analysis in view of a design assessment or improvement, if necessary. More specifically,

the reliability model is very helpful in allocating the reliability budgets and identifying critical items and a single point of failure. The reliability model is derived from a functional system's requirements and architecture. The model represents specific modes of operation and needs to be consistent with a failure definition of the system under analysis.

For non-repairable systems, the main reliability characteristic is the probability of success over a given period of time and it is a system reliability function. To be able to determine this function, a reliability model has to be built involving the definition of the system required function and the computation of probability of being in an operating system state. The probability of a successful system operation is the sum of the probabilities of being in an operating state and is a function of system design architecture. Thus far, no

assumptions regarding the failure distributions need to be made; any probabilistic distribution might be substituted by the probability used into the reliability model development [3], [4].

There are a number of methods that can be used to perform the reliability modeling of real technical systems. Among them, the Fault Tree, the Dependence Diagram or the Markov Model are examples of very popular and currently used methods in reliability analysis [5], [6]. After identifying the failure condition under analysis, these methods can be applied to determine what a single failure or combinations of failures can exist at the lower levels, which might result in a given failure condition. The entire set of developed models, for dedicated aircraft design, facilitates technical reviews and safety assessments in regards to the certification process.

The reliability, as a technical characteristic of a technical system, is a derivative of the design process and all design decisions and assumptions. Reliability modeling usually intuitively considers any dual or triple components providing the same function as a redundant architecture from a reliability and functionality point of view. However, the appropriate reliability modeling of that potentially redundant architecture must consider the real design functionality resulting from the design decisions, assumptions and constraints.

The system of two or three actuators is usually designed depending on the aircraft flight control surface and these actuators might intuitively be considered as a redundant architecture from a reliability point of view. Nevertheless, the proper reliability modeling of that system of actuators must consider the system functionality based on the design-specific constraints for the remaining available actuator hinge-moment in the event of a partial or total actuator system failure. As a result, this will affect the reliability assessment of that design and might lead to different conclusions regarding the specific design characteristics. This aspect of the reliability modeling and the assessment for the system of flight control surface actuators will be discussed in this paper. The relationship between the design assumption related to the actuator designed hinge-moment capability and achieved reliability at the actuator subassembly level will be presented. The resulting potential for the latent failures depending on the design details decisions will also be provided.

RELIABILITY MODELING

The assessing and quantifying reliability is essentially a problem in probability modeling. A system usually consists of a number of components. In the simplest case, each component has two states, operating or failed. When a set of operating components and a set of failed components is clearly defined, it is possible to recognize the status of the system. The problem is to compute the probability that the system is operating, i.e. the reliability of the system. The concepts and methods of the probability theory are used to compute the reliability of a given system.

The system is defined as an assembly of components being in a specific interaction which determine the system behavior. From a reliability point of view, the system provides the intended function if all its components operate without failure, but the system might also operate successfully if a subset of components has failed. The dedicated structure function is a reliability model that determines the status of the system regarding the status of its components. This structure function is used to compute the reliability of the system based on the operating or failed status of its components.

Similarly to the system, each component may have two possible states, i.e., operating or failed. The status of the component "i" can be defined by the binary random variable X_i as follows;

$X_i = 1$ implies component "i" is operating

$= 0$ implies component "i" is failed.

Consequently, the vector $X = (X_1, X_2, \dots, X_n)$ provides the status of the components related to a given system and there are 2^n possible realizations of this vector.

The structure function $\Phi(X_1, X_2, \dots, X_n)$ which has a value of 1 or 0 for each of the 2^n possible vectors X provides the status of the system, operating or failed, given the status of each component. This function is a model of the system reliability function and can be used to assess the system's reliability.

The component reliability p_i is the probability that a component is in an operating state and provides an intended function. The component failure probability $q_i = 1 - p_i$ is the probability that a component has failed. Therefore, $p_i = P\{X_i = 1\}$ and $q_i = P\{X_i = 0\}$ are respectively the probability that the component is still operational and the probability of component failure.

The probability that the system is operating correctly provides an evaluation of the system's reliability function depicted by R . It is the probability that the structure function $\Phi(X_1, X_2, \dots, X_n)$ is equal to 1.

$$R = P \phi X = 1 = E \phi X]$$

(1)

Certain types of systems that frequently arise in practice might be solved by using the structure function defined above.

Series System

The system in which all components must be operating for the system to be in an operating state is called a series system. In other words, the failure of any one component will lead to the failure of the system. It has to be understood that an expression "series" does not imply the physical arrangement of the components but it describes the system behavior in case of a failure of one of its components. The

general structure function of a series system with “n” components is given by:

$$\phi X = X_1 \cdot X_2 \cdots X_n \quad (2)$$

According to the definition of a series system, all the states of the component must equal 1 for the structure function at the system level to equal 1. Therefore, the reliability of a series system (R_{ss}) is the probability that all the components in the system are in an operating state. For “n” independent components this probability is expressed by:

$$R_{ss} = p_1 \cdot p_2 \cdots p_n \quad (3)$$

Generally speaking, the majority of the technical systems are designed as a series system from a reliability standpoint.

Parallel System

A system of “n” components for which the operating state of at least one component is equivalent to the operating state of the system is called a parallel system. In other words, all the system components must fail before the parallel system fails. The structure function must have the value of 1 when at least one component variable X_i is equal to 1 and must have the value of 0 only when all variables $\{X_i\}$ are equal to 0 simultaneously. The function that satisfies these conditions is:

$$\phi X = 1 - (1 - X_1)(1 - X_2) \cdots (1 - X_n) \quad (4)$$

The reliability of a parallel system is the probability that all of the components do not fail. Assuming a functional independence of the components, the reliability function for the parallel system is expressed by:

$$R_{ps} = 1 - (1 - p_1)(1 - p_2) \cdots (1 - p_n) \quad (5)$$

The reliability of a parallel system is increased over the series system architecture.

k-out-of-n System

The system build from “n” components is considered to perform the intended function if any “k” out of the “n” components are in an operating state.

$$\phi X = \begin{cases} 1, & \text{if } \sum_{i=1}^n X_i \geq k \\ 0, & \text{if } \sum_{i=1}^n X_i < k \end{cases} \quad (6)$$

This illustrates that a structure function is not a simple polynomial expression but involves a logical condition.

The reliability of a k-out-of-n system is the probability that “k” or more components over “n” are still working. Assuming independence and considering that all components have the same reliability $p_i = p$, the binomial distribution can be applied to compute the system reliability [7]:

$$R = \sum_{i=k}^n \binom{n}{i} p^i (1-p)^{n-i} \quad (7)$$

The use of redundancy is common in systems for which failure has particularly severe consequences, such as in the space program or for very complex systems with many components.

Reliability as a Function of Time

The reliability of a component is expressed as function of time. In aerospace practice, a common assumption is that components have an exponential distribution for time to failure. In this case, the component of reliability is provided by the following expression:

$$R(t) = P(\text{failure time} \geq t) = e^{-\lambda t} \quad (8)$$

The parameter λ is called the failure rate of the component and is given in units of failures per unit of time. This distribution for failure time implies that the probability that the component fails in the next small interval of time is independent of how long the component has been working. For this distribution, age is not the determinant of failure. It is often adopted for electronic components, and is also appropriate when the component itself is a complex system of many parts. Once the system has been in operation for some time, many of the parts would have failed and been replaced. The system becomes a mixture of old and new parts, and the failure rate approaches a constant.

One of the advantages of the constant failure rate assumption is obtained with a series system. In this case, the system reliability is provided by:

$$R_{ss}(t) = p_1(t) \cdot p_2(t) \cdots p_n(t) = e^{-\lambda_1 t} e^{-\lambda_2 t} \cdots e^{-\lambda_n t} = \exp - \sum_{i=1}^n \lambda_i t \quad (8)$$

The system failure rate is the sum of the component failure rates:

$$\lambda_{ss} = \sum_{i=1}^n \lambda_i \quad (9)$$

The reliability of a parallel system with the exponential distribution of the components is equal to:

$$R_{ps}(t) = 1 - (1 - e^{-\lambda_1 t})(1 - e^{-\lambda_2 t}) \cdots (1 - e^{-\lambda_n t}) \quad (10)$$

However, the failure rate of the parallel system is a complex function of the component failure rates and can be approximated by [8]:

$$\lambda_{ps}(t) \cong n t^{n-1} \sum_{i=1}^n \lambda_i \quad (11)$$