INTERNATIONAL DESIGN CONFERENCE - DESIGN 2004
Dubrovnik, May 18 - 21, 2004.

RELIABILITY OF ACTIVE SYSTEMS - AN ESSENTIAL DESIGN ASPECT FOR COMMERCIAL SUCCESS

A. Büter, T. Melz and H. Hanselka

Keywords: reliability of active systems, structural durability, adaptive helicopter rotor blade

1. Introduction

Answering questions of the reliability of modern, lightweight, passive and active structural systems is getting more and more important for ensuring the safety of systems. High reliability is crucial especially for the application of complex active technologies in general, aerospace systems or in military systems e.g. noise controlled helicopters. This is because for these applications there is an increased probability that a failure of a subsystem will lead to unrecoverable system malfunctions, endanger the complete system or even lead to the total loss of this. This is in contrast e.g. to noise control systems for vehicles where a system failure would only decrease the passenger comfort until system repair.

Here, the term reliability is defined as the probability that a system will fail after a certain operating or service period. Failure may also mean operational modifications which may lead to critically altered system functions. The reliability and with this the maximum service life of the system with a required safety standard can be determined by a system reliability analysis.

In this paper examples will be given to show and assess the significance of the reliability of active systems. The usability period and the failure probability of each system component is essentially depending on the particular operational loading and specific constraints such as temperature, humidity or radiation. It is important to redefine the term failure since with complex active system consisting of highly interacting structural, electronic and software components, a mere consideration of mechanical failure would insufficient.

The system reliability analysis especially for active systems produces the possibility to quantify the failure probability with respect application specific concerns and with this to optimise these systems.

2. System Reliability Analysis of Active Systems

The term reliability refers to the probability that system failure will not occur until after a defined period of time in operation. The “failure” is thus connected with a function that cannot be carried out anymore. The salient feature of the active systems lies in the associated *multi-functionality*, so that for such systems “failure” in the system reliability analysis must be newly defined. It must be determined at what time there is a failure, or rather which functions of a subsystem are of importance for the usefulness of the entire system.

In [Bertsche 1999] the following goals of a qualitative or a quantitative system reliability analysis are identified: Prediction of the expected reliability, identification and elimination of weak points and implementation of reference studies.

In the qualitative reliability analysis the effects of the defects and failures as well as the failure types are systematically examined. The quantitative reliability analysis includes the calculation of the predicted reliability, the failure rate analysis and the probabilistic reliability prediction.
In the following section the special features of the qualitative and quantitative reliability analysis are demonstrated using the example of an active helicopter rotor blade [Büter 2000] shown in figure 1. While there must be a concrete application for the quantitative examination, the qualitative examinations of the active system can also be generally performed in the first approximation.

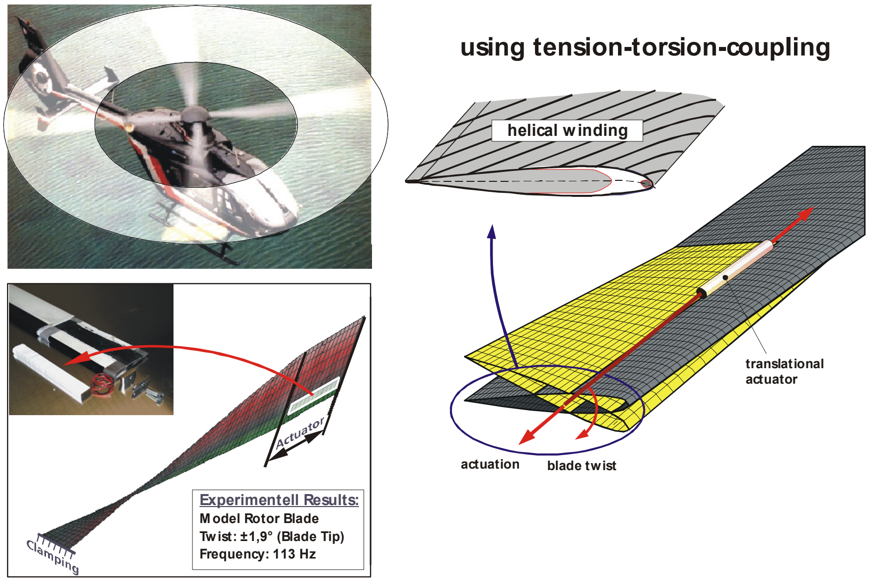


Figure 1. Adaptive Blade Twist Concept

The Adaptive Blade Twist (ABT) concept allows to directly control the twist of the helicopter blades by smart adaptive elements and thus to positively influence the main rotor area which is the primary source for helicopter noise and vibration. Since the interaction of non-stationary helicopter aerodynamics and elastomechanical structural characteristics of the helicopter blades causes flight envelope limitations, vibration and noise, a good comprehension of the aerodynamics is essential for the development of structural solutions to effectively influence the local airflow conditions and finally develop the structural concept. Therefore the ABT concept will be presented with respect to these considerations.
This concept is based upon the actively controlled tension-torsion-coupling of the structure. For this, an actuator is integrated within a helicopter blade that is made of anisotropic fiber composites material. Driving the actuator results in a local twist of the blade tip, in such a way that the blade can be considered as a torsional actuator. Influencing the blade twist distribution finally results in a higher aerodynamic efficiency. [Büter 2001]

2.1. Qualitative Reliability Analysis Performed on Active Systems

The effects of the defects and failures of the entire system, as well as the failure type analysis are very significant for the development phase of active systems, since the defects and failures of the subsystem can also lead to a breakdown of the entire system. *As a result, the function of an active noise reducing measure is unimportant, for example, for the helicopter flight. However, concerning defense technology, the failure of this subsystem increases the detectability, which can then indirectly lead to a loss of the helicopter after all.*
In order to meet all demands and to be able to specify the term “failure” in association with a function, the different functions must first of all be examined during the reliability analysis.

A. The *function of the structure* e.g. load bearing function is taken on by the mechanical system comprised of the non-activated or activated structure.

B. The *activating function* is taken on by the electrical system comprised of the actuator and sensor function of the integrated materials as well as the connected electronic system.
C. The *function of the active system* e.g. *active noise reducing function* is taken on by the active total system, which is comprised of the structure along with its additional function of e.g. noise reduction.

The term *"function of the structure"* summarizes the mechanical requirements on the entire system. The structure, comprised of various materials must withstand all inner and outer loads and environmental conditions while remaining safe to operate.

The requirements placed on the electrical components of the active system are summarized under the term *"activating function"*. This means that the use of the active structure, which depends upon the activation of the piezoceramic elements, must be ensured during the operating time of the total structure.

The term *"function of the active system"* summarizes the requirements on the active total system under special consideration of the interaction [Büter 2000] between the mechanical and electrical components of the structure. These interactions include, for example, the changes of the mechanical loads when the actuators are activated or the influences of the mechanical structure on the requirements on the electrical components of the active total system.

The following examples portray and describe the effects of one defect in a chain of effect, in order to make the interactions and the influence on the various functions (A), (B) or (C) clear.

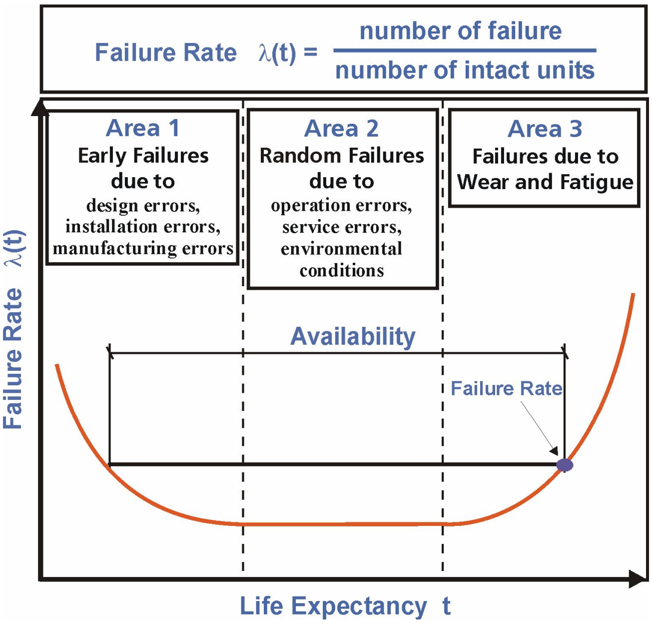
Example: **Piezoceramic stack actuator integrated into a structure.**
Defect: Too much self-heating of the actuator as a result of the material hysteresis during dynamic actuator operation.
Effects:
⇒ Heightened thermal load of the actuator (fatigue) (A)
⇒ Increase in the capacity and in the required amplifier output (B)
⇒ Decrease in the actuator efficiency (C)
⇒ The regulator will increase the control voltage in order to achieve the set/target value.
⇒ Heightened electrical load of the actuator (fatigue) (B)
⇒ Further temperature rise
⇒ ...

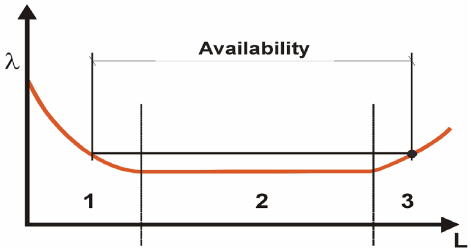
The local heating of the structure with strong thermal gradients can give rise to
⇒ inner mechanical tension, (A)
⇒ a shift in the mean voltage, (A)
⇒ a change of fitting conditions, (C)
⇒ modified transmission characteristic, (C)
⇒ additional loads (A)
⇒ ...

2.2 Quantitative Reliability Analysis of Active Systems

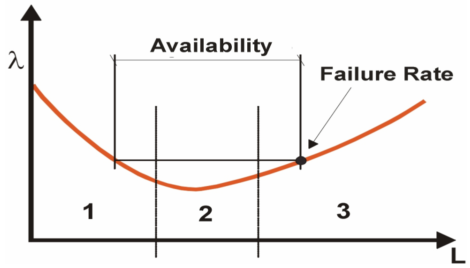
For a quantitative system reliability analysis, the failure characteristics of individual system components or subsystems are used. In figure 2 the special features of the failure characteristics known also as the "bathtub curve" are displayed. The key figures of the failure characteristics of each system component include the availability at a specific failure rate. The loads specific to the operation are derived from the availability or time in operation. With the help of the *failure rate* the actual system reliability analysis can be carried out. The failure characteristics of electrical and mechanical systems differ as shown in figure 2.

A noticeable plateau in section 2 corresponding to random failures means that so-called wear out defects are excluded. Consequently, for a system that is intact, the probability for its "survival" of the next time interval is equally big at any given time. This assumption excludes failures that are caused by aging, since this would make them time dependent.





Failure characteristic for electrical systems



Failure characteristic for mechanical systems.

Figure 2. Failure Rate Diagram [9]

Aging can only be excluded if the wearing parts of a system are replaced early enough. This assumption continues to require constant operational and environmental conditions. In mechanical systems the probability for the “survival” of the next time interval varies with time t in interaction with the respective loads. Wear out defects, i.e. failures, which are caused by aging, must also be taken into account. Therefore, section 2 corresponding to random failures shows a curve, which is essentially dependant upon the individual operational loads.

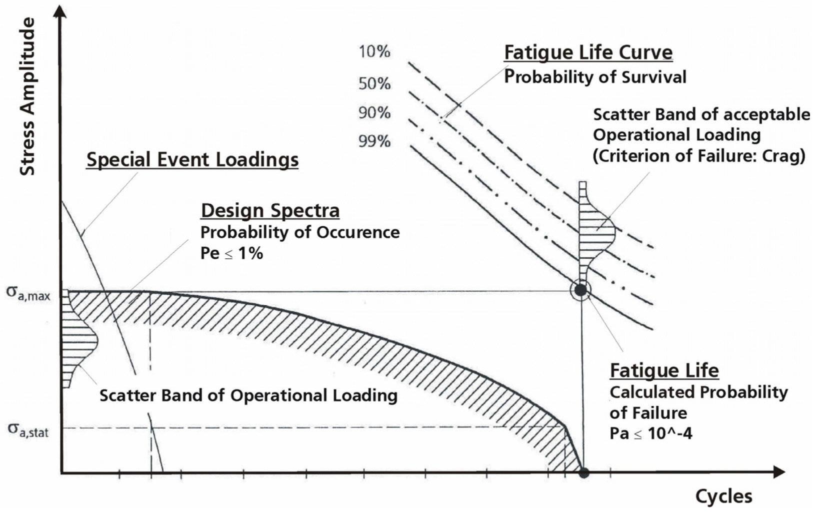


Figure 3. The result of a structural durability examination

The key figures of the failure characteristics necessary for a reliability analysis determine the availability corresponding to a acceptable failure rate. With the knowledge of the operational loads, the failure rate for a specific time in operation (availability) can be determined through a structural durability examination. The availability and the associated failure rate of each system component is considerably dependant on the respective operational load. This availability is also determined by the operational spectrum, i.e. the operational load, for a structure and must also take the specific operational boundary conditions (temperature, moisture, …) into consideration. A reliable overall assessment of the system requires an exact knowledge and consideration of the expected load spectra. The structural durability examination, which aims to determine the life expectancy of specific parts or subsystems under realistic loads, supplies the data for a well-founded, reliable system reliability analysis. Based on this system reliability analysis the influences and effects of the changes in the system can be theoretically estimated or experimentally determined. Figure 3 shows the result of a structural durability examination for a *mechanical system*.

The design spectrum and the special events describe all the loads that appear over the entire time in operation and thus are directly connected with the availability of the structure. According to [11] all loads along with their damage relevant effects should be taken into consideration when design spectrum is determined, e.g.

- Peak loads or special events (e.g. impulsive loads) lead to plasticizings, allocation of residual stress and are connected with structural yield strength, fracture behaviour and behaviour of functions.
- Alternating amplitudes and large number of cycles are connected with fatigue behaviour, friction corrosion (e.g. slip joint, screwed joint, fastening with adhesive).
- Large centrifugal force or changing temperatures cause an influence on the mean stress, varied conditions of fits and additional loads.
- Multi-axial loads lead to multi-axial states of stress with varied strength.
- The type of load (bending, tension, torsion) influences the fatigue behaviour and the life expectancy.

If the assumption is made that during the structural durability analysis the amplitudes of the design data and the structural durability are statistically normally distributed, then the probability of survival is also normally distributed. From these distributions the life expectancy for a specific mathematical probability of failure can be determined. The mathematical probability of failure, which is only valid for a specific availability due to the design spectrum used, is directly connected with the failure rate and consequently all the necessary data for a reliability analysis is given with this information.

According to [11], the validity of the testing methods used must be continually assessed as a result of new designs, materials, operating procedures or connecting technologies. Basically, these examination methods can also be used with electrical or active, i.e. combined *"electro-mechanical"* (electrical & mechanical), systems, whereby the software aspect (regulation, data processing) must also be considered. The type of loads must likewise be expanded accordingly.

The quality of a quantitative reliability analysis of a total system directly depends on the quality of the determined failure characteristic of the individual components. For this purpose, the knowledge of the operation specific loads is necessary, since they are important input data for the structural durability examination.

When determining the operation specific loads for active systems, the problem arises that the loads of the passive "active" structure can be altered during their activation. In return, the initiated actuator work is dependent on the condition of the actuator and of the structure, on the type, location and size of the sensor signal and on the type of control. In this way the loads of the active structure will *reallocate* as compared to the passive "active" structure. Type and location of fatigue will change. As a result, various cases must be considered during the structural durability examination:

Case 1: *Passive „active" structure* - Structural durability examination of the passive "active" structure during the introduction of the application-specific "external" loads.

Case 2: *Active structure* - Structural durability examination of the active structure during the introduction of the application-specific "external" loads.

Case 3: *Active structure with intermittent breakdowns of the active system components* - Examination of structural durability for the active structure on the assumption that the active component failed within a definite time period.

A design of the structure and the proof of the operational reliability for the loads mentioned in cases 1 and 2 lead to "maximal" safety, yet do not exclude lightweight construction. Case 1 examines only the *function of the structure* and does not do justice to the demands of the loads in the active case, since *reallocation* is not taken into consideration during the operation of the actuator. In contrast, case 2 examines the *function of the active system*, under consideration of the *activating function* and the *function of the passive structure*, yet does not examine the changes of the loads connected with a failure of the actuator. Case 3 gets rid of this limitation, but requires a useful definition of the failure time period, which should be directly connected with the probability of failure of the electric, i.e. electronic, components. Case 3 merges into case 2 for structure systems, in which a failure cannot be afforded and in which the probability of failure due to redundancy takes on very low values.

3. Summary

The issue of reliability concerning the safety of systems becomes increasingly more important in the development of modern, light, passive as well as active structural systems. Within the scope of this publication it was shown that the type of the "failure" becomes more complex in active systems, since several functions are involved. The question should be posed, at what point is a failure detected or rather what functions of a subsystem are significant for the usability of the total system? In this way the failure type analysis gains a particular importance and should be carried out with special care in defense technological applications because of the connection between technical and military issues.

Regarding the quantitative analysis of the system reliability, it was shown that a structural durability examination extended to include operational specific loads of the electrical subsystem supplies all the necessary key figures for a system reliability analysis. However, the complexity of the active system is also reflected in loads, which are considerably influenced by the active engagement and therefore making only a consideration of the total system useful. If the failure of the active components is acceptable for the primary function of the total structure, then the resulting changes in the loads must also be taken into consideration during the structural durability examination.

In summary, it can be established, "that there does not exist magic solutions, but that a path is only passable, which gets to the bottom of very different questions with the same care and then takes all of these questions into consideration during the design process" [Focke 1938].

References

Bertsche, B. and Lechner G., „Zuverlässigkeit im Maschinenbau", Springer-Verlag, Berlin 1999.

Büter, A.; Breitbach, E., "Adaptive Blade Twist - Calculations and Experimental Results", Aerospace Science and Technology, Heft 4, 2000, pp 309-319

Büter, A. ; Ehlert, U.-C. ; Matthias, M. ; Breitbach, E. "Adaptive Rotor Blade for Vibration Reduction", 9. ARO International Workshop on Aeroelasticity of Rotorcraft Systems, Ann Arbor, USA, Oct. 2001

Focke, H., "Der Focke Hubschrauber", Luftwissen 1938., pp 33-39.

Fischer, G., "Betriebsbeanspruchung und Festigkeitsnachweis von Schienenfahrzeugrädern," in Eisenbahningenieur 49(3) 1998, pp80-82.

Andreas Büter
Fraunhofer Institut für Betriebsfestigkeit LBF
Bartningstr. 47, 64289 Darmstadt, Germany
Telephone: +49(0)6151/705-277, Telefax: +49(0)6151/705-214
E-mail: bueter@lbf.fhg.de