The application of the *SRCE*-concept for monitoring high-speed automotive tires

Dirk Söffker
Safety Control Engineering, University of Wuppertal, Germany

Matthias Rinne
Safety Engineering, University of Wuppertal, Germany

ABSTRACT: The contribution introduces into the *SRCE*(Safety and Reliability Control Engineering)-concept. The aim of the concept is monitoring and control of reliability characteristics. Therefore the online determination is illustrated and applied to automotive tires.

Söffker, D.; Rinne, M.: The application of the *SRCE*- concept for monitoring high speed automotive tires. in: Schueller, G.I.; Kafka, P.: Safety and Reliability, Proc. of ESREL'99, München-Garching, September 13-17, 1999, pp. 1083-1089.

1 INTRODUCTION

Safety and reliability aspects are becoming more and more important for industrial products and processes due to higher quality, economical and ecological requirements. Human experts or artificial expert systems are required for supervision and monitoring tasks. The methods commonly used are based on signal analysis methods or - since a few years - based on FDI (fault detection and isolation) schemes as new tools of control engineering. In case of faults, system changes etc., decisions have to be made concerning the further operations of machines or processes. The task to estimate the consequences of system changes or the effects of minor faults is difficult. In most cases the system is stopped or the power is reduced up to the moment of trustworthy assessment of the new situation and its consequences.

The idea combining methods of control and reliability engineering is not new. In (Sffker et al. 1998) this idea is illustrated for supervision and monitoring purposes of real, aged, and modified systems. The idea of the introduced *Safety and Reliability Control Engineering*-concept *SRCE* includes the controlling of the reliability characteristics by combining fault detection and diagnosis schemes of control engineering and reliability engineering approaches dealing with mathematical statements about the system reliability, cf. fig. 1.

The core of the concept is a module called *Reliability Evalution*. The task of this modul is the calculation of reliability characteristics, here called determination of online reliability characteristics.

This includes the consideration of aging and damaging effects as well as the individualized load history. In (Sffker et al. 1998) the task of such a module is characterized only verbal. In (Sffker 1998) the module is explained mathematically and justified. In this contribution the development of the related online failure rate will be used for monitoring purposes of automotive tires as a popular example. The contribution is organized as follows: Chapters 2 and 3 repeat the results from former work, chapter 4 introduces in general the calculation of the online-failure rate which is applied to automotive tires in chapter 5.

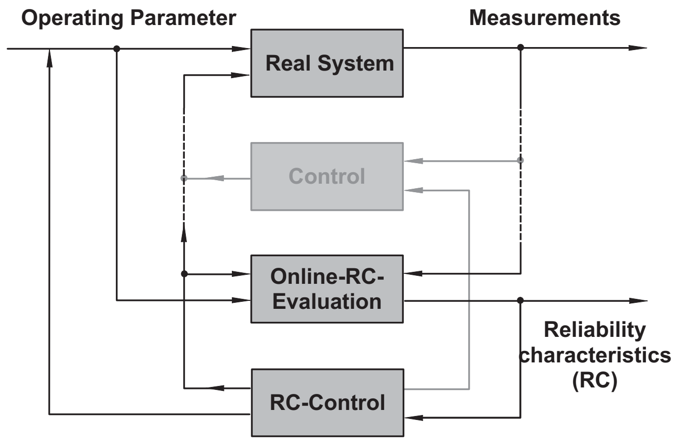

Figure 1. Scheme of the *SRCE*-concept (after (Sffker et al. 1998))

2 THE *SRCE*-CONCEPT

The idea of the *SRCE*-concept is understanding reliability characteristics as system characteristics to be controled. The inputs of the *SRCE*-scheme can be operating parameters or known effects of repair- and maintenaince strategies.

The disturbances of the *SRCE*-system to be controled are effects of aging, faults or the desired values of the common system control, cf. fig. 1.

The classical reliability characteristics are the failure rate h(t), the time-to-failure distribution function F(t) and the reliability function R(t).

These functions can be found empirically by analyzing the time behavior of the number of operating elements as the living part of a large number N_o of identical systems with identical loads.

The relevant relations between the reliability characteristics are

$$F(t) + R(t) = 1 \,, \qquad (1)$$

$$h(t) = -\frac{1}{R(t)} \frac{dR(t)}{dt} \qquad (2)$$

These connections are known from textbooks (Ramakumar 1993, Birolini 1991). These characteristics describe the failure behavior as a function of time. This implies the following assumptions: i) The considered system is identical to the ones used for getting experimental reliability data. ii) The load-time function is identical to the one of the experiments.

3 ONLINE RELIABILITY CHARACTERISTICS

If it is necessary to consider an individual system with a specific load history not comparable with those of the experimental data, it is necessary to

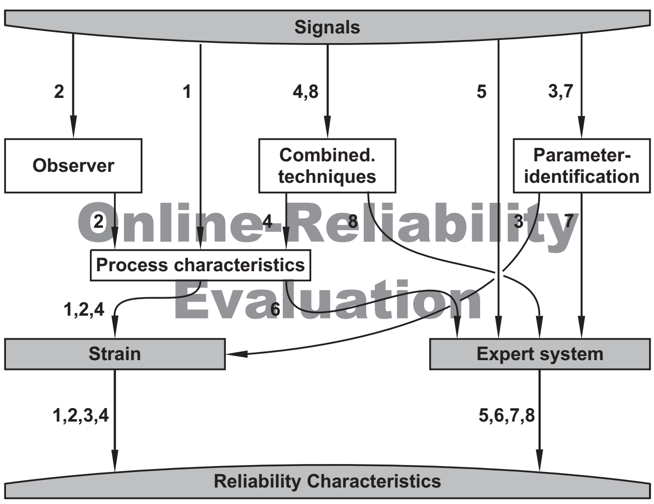

Figure 2. From signal data to reliability characteristics

(after (Sffker et al. 1998))

enlarge the classical characteristics and definitions. For the *SRCE*-concept it is also necessary to include the effects of load dependency and load history. The goal is to establish the connection load - reliability characteristics and actual life-time - reliability characteristics. by mathematical expressions. The model can be used for control- and supervision purposes using the relation vice-versa. The principal paths from available signal data to reliability characteristics are shown in fig. 2.

To overcome the mentioned disadvantages of classical reliability considerations a combination of the considaration of time-variable wear-out (damaging) effects and a modeling approach of the storage use (Nutzungsvorrat DIN 31051) seems to be useful. The use of the system leads to the use up / wear out of the storage use. With a defined probability this leads to the loss of functionality, if the storage use is empty. This is the moment of system failure.

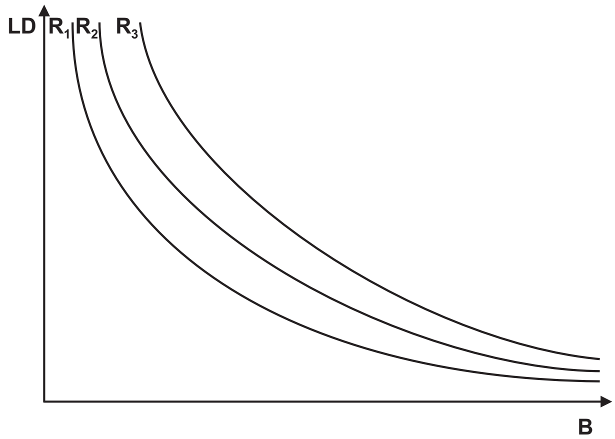

Figure 3. Principle connection Load B - Reachable life-time L - reliability function R

4 ONLINE-DETERMINATION OF THE FAILURE RATE

The connection between external load B and the reachable life-time L can be found by experiments and may be given in fig. 3.

The different curves represent different reliability functions R_i, with $R_1 > R_2 > R_3$. The classical diagram for specialized material patterns is the Wöhler-Diagramm (Gnilke 1980).

From a principle point of view this diagram combines the assumption of a specific load and the reachable life-time by the reliability function.

4.1 *Damage accumulation*

The idea in (Miner 1945) is to connect every use of the system with a micro-damage contribution. The micro-damages accumulates to the whole damage. The accumulation of the micro-damages over the life-time leads in the moment of the reachable life-time to system failure.

The principle idea is the combination of load-specific use and damage. Therefore, linear and nonlinear damage mechanisms can be used. Also the accumulation of the damaging effects can be done by linear or nonlinear accumulation mechanisms. The idea of a linear damage model and a linear accumulation mechanism was already used in 1920 by Palmgren for the reachable life-time calcualation of roller-bearings with varying loads (Palmgren 1964).

This idea can also be used for the calculation of the contribution of the i-th use with the load B_i, with the time of use l_i and the corresponding reachable life-time L_{i,R_x} which is linked to the reliability R_x of the considered experimental data base.

Assuming a simple linear damage mechanism, the individual damage contribution s_{i,R_x} of the i-th use can be calculated by

$$s_{i,R_x} = \frac{ld_i}{LD_{i,R_x}(B_i)} \quad (3)$$

Introducing the accumulated abstract damage $S_{R_x}(B(t))$ as

$$S_{R_x}(B(t)) = \sum_{k=0}^{i} s_{i,R_x}(B_i(t)) \text{ ...with the qualities} \quad (4)$$

$S_{R_x}(B(t=0)) = 0$ for new systems and $S_{R_x}(B(t=t_{L_{reachable}})) = 1$ for the system in the moment of system failure. All derived statements are valid with a probability of R_x.

This is the usual approach with bearing and gear calculations (Gnilke 1980). The principle idea of calculating online reliability characteristics is independend from the linearity assumptions of the accumulation mechanics or the damage mechanism.

4.2 *Load- and life-time dependend reliability characteristics*

The actual safety and reliability state of a system is characterized by

- the actual load $B(t_{akt}) = B_{akt}$,
- the actual (summarized) damage $S(t_{akt}) = S_{akt}$ and
- the summarized actual life-time (time of use) $L(t_{akt}) = L_{akt}$.

The functions represented in fig. 4 are assumed as based on the same empirical data as those of fig. 3. Lets assume a linear damage accumulation mechanism and consider a defined moment of the actual life-time L (which combines the system state and the empirical data material) and the actual damage S. Both values describe the actual system state. Using the actual damage S_{akt} and the scale defined by the actual life-time L_{akt}, the concrete value of the failure $S = 1$ in the empirical data material can be determined, cf. fig. 4.

The illustration of fig. 4 uses the reliability function value of R_2 as the base for the consideration.

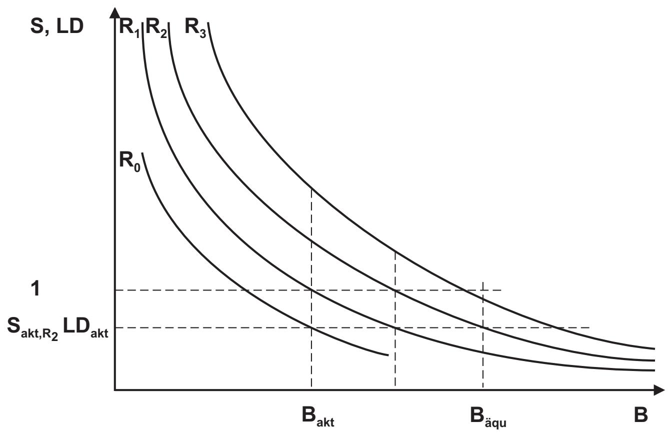

Figure 4. Describtion of the actual load- and life-time dependend realibility

These graphical illustrated interrelations can be used for various considerations determining on-line-reliability characteristics, which should not be considered here. These considerations are developed in (Sffker 1998).

The classical failure rate of reliability engineering h(t) is the ratio of the development of actual failures to the number of aliving elements of the given number of considered elements. This means the conditional probability of the system to fail in the next unit of time.

The following steps have to be done:

1. Measure l_i of the individual use
2. Define the corresponding $L_i(B_i)$
3. Calculate s_{i,R_x} using $l_i, L_i(B_i)$

4. Calculate S_{R_x} using s_{i,R_x} and 'older ones'
5. Define the point (S_{akt,R_x}, B_{akt}) of fig. 4
6. Calculate $h_{BS}(B_{akt}, S_{akt})$ using a suitable database

Based on the connections of fig. 4 the equivalent load- and life-time dependend failure rate can be defined by

$$h_{BS}(B_{akt}, S_{akt}) = - \left(\frac{R_1(B_{akt}, S_{R_2} = 1) - R_0(B_{akt}, S_{akt,R_2})}{(1 - S_{akt,R_2})} \right) \frac{1}{R_{akt}} \quad (5)$$

or in general as

$$h_{BS}(B_{akt}, S_{akt}) = \ldots\ldots\ldots\ldots$$
$$- \frac{\partial R(B_{akt})}{\partial S} \frac{1}{R_{akt,x}(B_{akt})} =$$
$$- \frac{\partial R(B_{akt})}{\partial S} \frac{1}{R_x} =$$
$$- \left(\frac{R_1(B_{akt}, S_{R_x} = 1) - R_0(B_{akt}, S_{akt,R_x})}{(1 - S_{akt,R_x})} \right) \frac{1}{R_x} \quad (6)$$

The quality of the developed (and calculated) online reliability characteristics strongly depends on the availability of sufficient empirical data resp. correlated L, B, R-functions. This is necessary to build up a narrow mesh of functions needed for eqn. 5 and 6.

As a result it can be seen that the failure rate $h_{BS}(B_{akt}, S_{akt})$

- necessarily depends on S_{akt} and on L_{akt},
- increases with growing damage S_{akt},
- increases with the growing difference $R_1(B_{akt}, S = 1) - R_0(B_{akt})$, and
- is connected with the reliabity function in the same manner as in the classical definition.

Now it is clear how the failure rate can be used for monitoring as well as for control purposes within the *SRCE*-concept. For supervision tasks the online calculation of $h_{BS}(B_{akt}, S_{akt})$ is sufficient. For *SRCE*- control purposes the relation

$$\frac{\partial R(B_{akt})}{\partial S} \ldots\ldots\ldots\ldots \quad (7)$$

can be used as input due to the direct dependability from the actual load B_{akt}.

So the control of the failure rate can be realized by shifting B_{akt}, cf. fig. 4, due to the controling of operating parameters changing the actual load B_{akt}.

5 MONITORING HIGH-SPEED AUTOMOTIVE TIRES

An application example of the calculation of the load and actual life-time dependend failure rate of a high speed automotive tire should conclude the contribution. The detailed study is given in (Rinne 1998). Here also the related discussion of tire-material is repeated. The strain of automotive tires results from different physical effects. External damages caused by impacts etc. are not considered. Here only the regular use up to the failure is of interest. The resulting parameter is the life-time L. The life-time is given in distances (km or miles). The remaining inputs to L are the velocity V, der pressure P, the load A and the environmental temperature T_u (Rinne 1998).

The different effects are connected in a nonlinear manner with L. The velocity V is connected with the distort E of the tire. Both influences the resulting tire-temperature T_R. The distort E depends on the pressure P and the load A. The resulting tire-temperature T_R also depends on the environmental temperature T_u. T_R is strongly connected with the life-time L .

In (Rinne 1998) the relation

$$T_R = \frac{2}{3} T_u + (V - 20) E * F \ldots\ldots\ldots \quad (8)$$

combines the stresses T_u, V, E, A, P to the strain T_R, with a tire-specific constant F.

Figure 5 shows experimental results connecting T_R with L. The standard conditions for such tests are V = 160 Km/h, A = 475 Kg, P = 2.0 bar, T_R = 105 ° and give 100 % L. The experimental results represented in Fig. 5 are the base for the introduced *SRCE*-monitoring scheme. It is assumed, that beside the experimentally given function R_2 further functions for different reliability behavior R_i exist, here with $R_2 = 0.5$ $R_1 = 0.75$ and $R_3 = 0.25$.

For practical examinations is seems to be necessary to determine the complete set of functions. Furthermore it will be assumed that the considered tire is new.

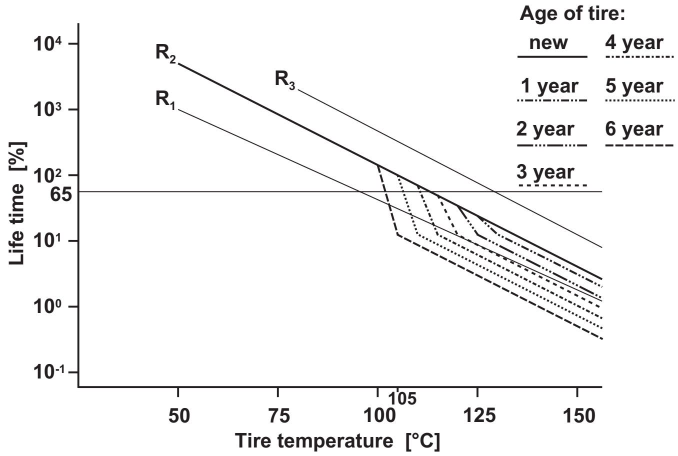

Figure 5. Life-time dependency (modified from (Rinne 1998))

5.1 *Example*

The life-time for standard conditions should be L = 100.000 Kilometer. The tire will be used by two different usages:
1. use: 20.000 Kilometer with $T_R(1) = 120°C$
2. use: 40.000 Kilometer with $T_R(2) = 85°C$ For the different usages the individual damage contributions result to:
1. use:

$$s_{1,R_2} = \frac{l_i}{L_i(T_R(1), R_2)} = \frac{20.000}{0.35 * 100.000} = 0.57 \tag{9}$$

2. use:

$$s_{2,R_2} = \frac{l_i}{L_i(T_R(2), R_2)} = \frac{40.000}{5 * 100.000} = 0.08 \tag{10}$$

The new failure rate can be calculated for different moments:
1. moment of 1. use:

$$h_{BS}(T_R, S) = \dots\dots -\frac{(R(T_R, S_{R_2} = 1) - R(T_R, S_{R_2}))}{(1 - S_{R_2})}\frac{1}{R_{akt}} = -\frac{(0.25 - 0.9\,)}{(1 - 0)}\frac{1}{0.9} = 0.72 \tag{11}$$

1. moment of 2. use:

$$h_{BS}(T_R, S) = \dots\dots -\frac{(0.75 - 0.85\,)}{(1 - 0.57)}\frac{1}{0.85} = 0.27 \tag{12}$$

last moment of 2. use:

$$h_{BS}(T_R, S) = \dots\dots -\frac{(0.75 - 0.8)}{(1 - 0.65)}\frac{1}{0.8} = 0.17 \tag{13}$$

Three different alternatives for the 3. use should be compared:
1. alternative: $T_{Ra1} = 110\,°C$

$$h_{BS}(T_R, S) = \dots\dots -\frac{(0.475\ - 0.525\,)}{(1 - 0.65)}\frac{1}{0.525} = 0.27 \tag{14}$$

2. alternative: $T_{Ra2} = 120\,°C$

$$h_{BS}(T_R, S) = \dots\dots -\frac{(0.25\ - 0.525\,)}{(1 - 0.65)}\frac{1}{0.525} = 1.5 \tag{15}$$

3. alternative: $T_{Ra3} = 130\,°C$

$$h_{BS}(T_R, S) = \dots\dots -\frac{(0.15\ - 0.525\,)}{(1 - 0.65)}\frac{1}{0.525} = 2.04 \tag{16}$$

The calculation example illustrates different aspects:

- The precision exactness of the calculations depends on the database. Here differences are used to approximate the differential operator. So the results can not be optimal (results of eqn. 12,13).
- The transition from the 2. to the 3. use shows with the alternative $T_{Ra1} = 110\ °C$, that the failure rate may be constant in the case of increasing strain.
- The strain $T_R = 120\ °C$ at the beginning of the usage S = 0.0 leads to a lower failure rate than in the moment of the abstract damage S = 0.65. This shows the life-time dependency of the new failure rate.

For monitoring purposes the actual failure rate can be easily compared with tire-type specific treshold values. This leads to the fact that strongly used tires should be used with decreasing strain to get a constant failure rate.

This includes that aging systems (here: tires) during their life-time are getting more sensitive to strong strains. This consequence is also known from practical experience (Rinne 1998). Two strategies optimize the problem situation:
i) Increasing of the tire-pressure leads to the decreasing of the distort E and tire temperature T_R.
ii) Usages with lower velocity also decreases the tire-temperature.

Using the new quality of life-time and strain-dependent failure rate, it can be easily understood that both strategies allow the use of old tires with high accumulated stresses with low failure rate.

6 CONCLUSIONS

The contribution introduces the Safety Reliability and Control Engineering Concept. Core of the approach is the definition of a life-time and strain-dependent failure rate. This new kind of failure rate allows a new probabilistic view to systems. Using this kind of failure rate the loop for realiability control can be closed. The contribution includes the example of the failure rate analysis applied to a high speed automotive tire.

ACKNOWLEDGEMENT

The authors like to thank the reviewers for formal and english language related hints and suggestions.

REFERENCES

Birolini, A. 1991. *Qualität und Zuverlässigkeit technischer Systeme.* 3. Auflage: Springer-Verlag.

Gnilke, W. 1980. *Lebensdauerberechnung der Maschinenelemente.* München, Wien: Carl Hanser Verlag.

Miner, M.A. 1945. Cumulative Damage in Fatigue. *ASME Journal of Applied Mechanics.* 12 (1945). A-159 - A-164.

Palmgren, A. 1964. Grundlagen der Wälzlagertechnik. 3. Auflage. Stuttgart: Frank'sche Verlagsbuchhandlung.

Ramakumar, R. 1993. *Engineering Reliability: Fundamentals and Applications.* New Jersey, USA: Prentice Hall.

Rinne, M. 1998. *Realisierung eines SRCE-Konzeptes am Beispiel der berwachung eines Kfz-Reifens.* Student Thesis. Safety Control Engineering. Uni Wuppertal.

Söffker, D.; Rakowsky, U.K.; Müller, P.C.; Peters, O.H. 1998. Perspektiven regelungs- und zuverlässigkeitstheoretischer Methoden zur Überwachung dynamischer Systeme aus sicherheitstechnischer Sicht. *at-Automatisierungstechnik* 46 (1998), 295 - 301.

Sffker, D. 1998. Zur Online-Betimmung von Zuverlssigkeits- und Nutzungskenngren innerhalb des *SRCE*-Konzeptes. *at-Automatisierungstechnik.* accepted.