PERSPECTIVES OF MONITORING AND CONTROL OF VIBRATING STRUCTURES BY COMBINING NEW METHODS OF FAULT DETECTION WITH NEW APPROACHES OF RELIABILITY ENGINEERING

Dirk Söffker
Safety Control Engineering, University of Wuppertal
Gaußstraße 20, D-42097 Wuppertal, Germany

Uwe Kay Rakowsky
Safety of Transportation Systems, University of Wuppertal
Gaußstraße 20, D-42097 Wuppertal, Germany

Abstract: The paper introduces a perspective concept of monitoring and control of vibrating structures by combining new methods of fault detection with new approaches of reliability engineering. The complete concept is demonstrated with the mechanical example of the cracked rotor.

Key Words: Fault Detection, Fault Diagnosis, Monitoring, Reliability Engineering, Reliability Control, Safety Engineering

INTRODUCTION: Reliability and safety aspects are becoming more and more important due to higher quality requirements, complicated connected processes and structures. As examples of vibrating structures to be monitored / controled and diagnosted, the following application fields are given: turbines of power plants or modern aircrafts, controled wings of advanced materials for new large aircraft concepts, truss structures of space stations, and helicopter cabines and blades.

The monitoring and control approaches commonly used for vibrating structures are based on signal analysis methods. In case of faults, system changes etc., decisions have to be made concerning the further operations of the structures, related to questions of stopping the machine, repair and maintenance strategies, and influencing the system not only related to the goal of optimizing the vibrational behavior, but also of optimizing the reliability characteristics. The two important knowledge fields which determines this process are:

• knowledge about qualitative and quantitative effects of the faults
or in general of system changes, and the

• knowledge about the reliability characteristics of the components and the system in the fault-free and the faulty state. This includes the knowledge about the past stress of the system and the detailed knowledge about the effects of the actual changes / faults related to reliability and safety questions.

Today these decisions are typically handmade and not solved in a problem adequate way. Contemporary reliability engineering offers three ways to improve the performance of a system relevant for safety:

– decrease the number of components,
– increase the reliability properties of selected components, and the
– use of redundancy concepts for selected components or modules.

To decide which of these concepts is the best one, the design-team provides a detailed model of the system during the early construction phase. The model is supposed to be as close to reality as possible, but it is often based on assessments about the behavior of the system in the operation phase. A lot of estimations have to be made about external influences and their influence on reliability characteristics.

The idea of this paper is to overcome these person- and problem- related decision problems.

The problem is considered from a system theoretic point of view. The idea is to get a better and objective inner view to the system and its changes. Assuming that knowledge concerning the consequences of these changes is available, the actual state of the system can be expressed by reliability characteristics. These relations can be also used vice versa for control approaches.

The paper is organized as follows: This section introduces into the problems of causal fault detection and related operating decisions. Getting a better and more objective inner view into the structure some requirements to Fault Detection and Isolation (FDI-) Approaches are formulated from the point of view of the closed loop consideration of section 2. In section 3 the interaction of the elements of the proposed **S**afety and **R**eliability **C**ontrol **E**ngineering (SRCE-) approach are declared. Section 4 demonstrates the concept from a principal point of view. Therefore the classical mechanical example of a cracked rotor will be used as a principal example. Section 5 briefly shows in which application fields the proposed ideas also can be used.

SAFETY AND RELIABILITY CONTROL ENGINEERING - CONCEPT

The new Safety and Reliability Control Engineering - Concept is given in fig. 1 here firstly in detail. The system to be considered will be understand as an input-output system. In this way descriptions (e.g. differential equations) are used, which describe the time behavior of the outputs (here: measurements - signal data) and the inputs (here: operating parameter and/or control inputs).

The task of the **R**eliability **E**valuation **M**odul (REM) is the real-time calculation of the reliability characteristics of the system to be observed. Therefore only the inputs, the outputs, and advanced system informations can be used. Advanced system informations include the knowledge of the influences of changes and the ability of the modul to ensure correct informations concerning to fault changes. This implies robust approaches to ensure these properties for the use for - due to changes - variable systems. The output of this module are reliability characteristics. Problem dependent this can be

• a failure rate

$$h : t \to h(t), \tag{1}$$

• a (failure) probability density function f with

$$f(t) = h(t)e^{-\int h(t)dt}, \tag{2}$$

• or its cumulated density function F

$$F(t) = 1 - e^{-\int h(t)dt} \tag{3}$$

which is the time dependent failure probability. In most applications it would be convenient to use the failure rate.

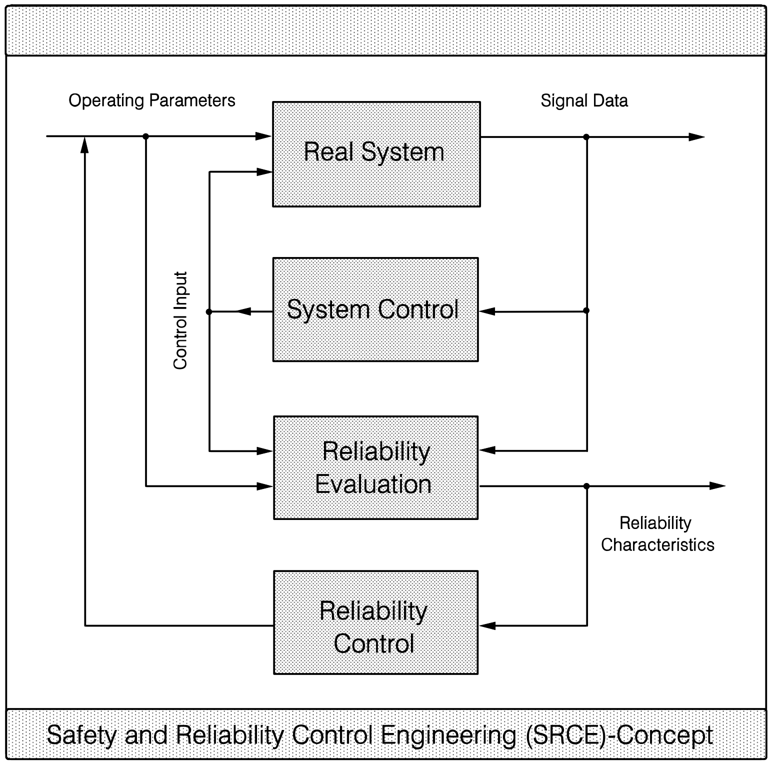

Fig. 1: Safety and Reliability Control Engineering Concept

The output of the Reliability Evaluation Module represents the actual information concerning the reliability characteristics. A simple control strategy can be easily build up by observing the output of the Reliability Evaluation Module. Related to threshold values

- alarms can be given starting intensive supervision / controling,
- or the system can be stopped immediately.

Because of the importance of this modul, this task is decribed in /4/ seperately in detail. The idea of the SRCE-Concept is to establish a closed loop approach with the goal of controling reliability characteristics. If knowlegde is available concerning the relation

Operating Parameter $\rightarrow$ Actual System Behavior $\rightarrow$ Reliability Characteristics

these causal direction has to be reversed.

If the system structure- or parameter changes due to faults, all inputs related to the goal of controling the reliability characteristics can be used as control inputs of the SRCE-control loop

$$\text{Reliability Characteristics} \begin{array}{ll} \leftarrow & \text{System Configuration / Reconfiguration} \\ \leftarrow & \text{Operating Parameters} \\ \leftarrow & \text{Maintenance and Repair Strategies.} \end{array}$$

In this way problems appear concerning the realization of the closed loop. Because of the fact that this control loop approach is not a pure technical control approach, a part of the necessary connections can not be given yet. Therefore an optimal solution will

be the use of qualitative or quantitative and unique mathematical equations, which is prefered here.
In the following some principal solutions are introduced for understanding the SRCE-idea.
i) In this way the relation $rc\,(h,f,F) = function(op,sp)$ between the set rc of reliability characteristics $rc\,(h,f,F)$ and the problem dependent operating parameters op acting on the system with the system properties sp can be used by the inverse relationship

$$op = function^{-1}(rc\,(h,f,F)_{des.}, sp)\ . \tag{4}$$

ii) If system reconfiguration strategies are also included into the SRCE-concept more difficult strategies have to be used, to solve the appearing problems.
iii) The simplest way is to change the system behavior by (inner technical) control. Due to system changes the fault-free dynamical system A_{ff} changes to the faulty-one A_f. The real-time Reliability Evaluation Module calculate the corresponding change of the rc-values as

$$\text{Actual system behavior } A_{ff} \quad \overbrace{\longrightarrow}^{\text{due to system changes}} \quad A_f \tag{5}$$

$$\text{Related reliability characteristic } rc_{ff} \quad \longrightarrow \quad rc_f\ . \tag{6}$$

The task of an (inner technical) control loop may be to adapt the control law, building up the new system $\tilde{A_f}$ to establish minimum or desired reliability characteristic $rc_{des.}$. Assuming a state space approach, the control law KB is

$$KB = -(A_f(rc_f) - \tilde{A_{ff}}(rc_{des.})). \tag{7}$$

Because of this indirect relation related to the controled value rc the correctness of the relation
Actual System Behavior $\leftrightarrow$ Reliability Characteristics
becomes to be the most important part of the SRCE-Concept.
iv) In opposite to the above mentioned inner control loop, system reconfiguration approaches lead to much more difficult problems. From a principal point of view (also using a state space representation) the problem appears as follows: The system will be modeled using the description A_{ff}. In contrast to (iii) here it is assumed that this complete model description is not problem adequate available, or the desired rc - parameters can not / should not established by this way. In spite of this disadvantage it is furthermore assumed that submodel descriptions A_{i-ff} are available and the configuration concerning the interactions built up using the relationships cf are known. The knowlegde allows the calculation of the reliability characteristics $rc_{compl.}$ of the complete system $A_{compl.}$. These assumptions allow the formulation of the resulting SRCE-problem by

$$rc_{compl.} = A_{compl.}(cf(A_{i-ff}))\ . \tag{8}$$

The degrees of freedom concerning the control of the rc are given by
• configuration of cf,
• inner (technical) control loop of the elements A_i and
• combinations of both.

Also here the main task of the concept - the establishment of relations -
Actual System Behavior $\leftrightarrow$ Reliability Characteristics
becomes very important.

ELEMENTS OF THE SRCE CONCEPT:

Causal fault detection approaches for establishment the relation: measurements - reliability:

The proposed concept controling the reliability characteristic of a system will be applied to mechanical structures. Here the main tasks are

• the determination of suitable strain characteristics describing mechanical system states which allow to establish connections to the reliability characteristics and
• building up control laws.

Assuming that beside the measurements, system informations (e.g. input - output relations as differential equations or linguistic (fuzzy) input - output relations as qualitative description) are available, different paths of creating connections from the measurements to the interesting reliability characteristic values are possible, cf. fig. 2.

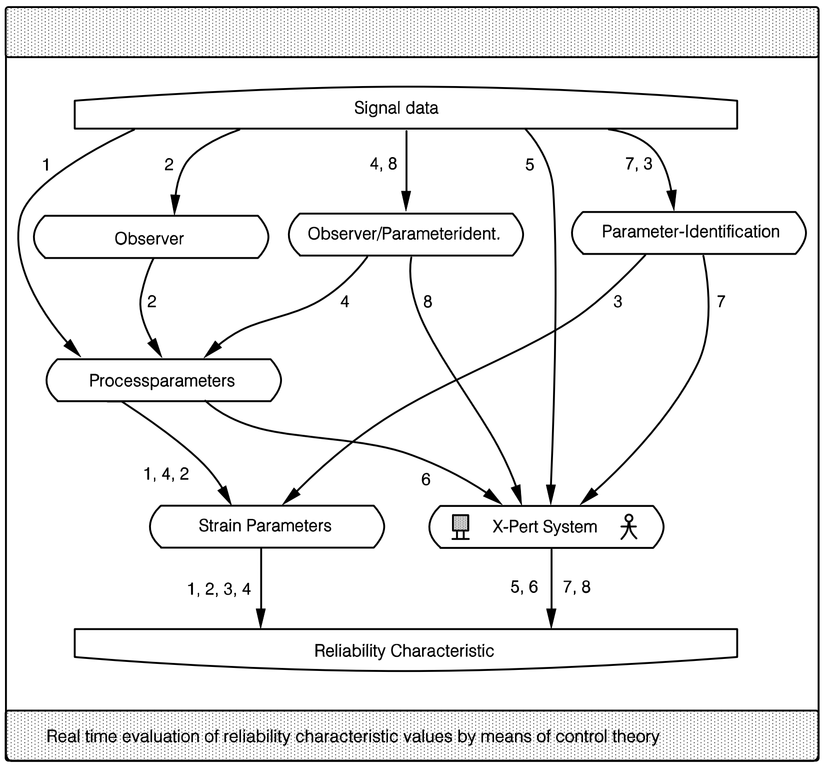

Fig. 2: Paths from Measurements to Reliability Values

Starting with the goal of the Reliability Evaluation Module - the establishment of reliability characteristics two paths are possible:

• a **physical oriented path**, and
• a **phenomenological oriented path**.

Because of the fact that the measurable signal does not content the interesting reliability expression intermediate levels are introduced, which allow the stepwise transition.

Both paths connect intermediate levels (of physical parameters (physical path) or of linguistic formulated - or in general qualitative - expressions) with the goal of building

up connections to the reliability characteristic values to be looked for. Both paths can be found using the experimental related knowledge of the life-time behavior of the structure or the estimation knowledge and experience of the reliability analysis team, cf. /4/.
The more physical oriented path uses physical intermediate levels. The most important level therefore is the level described by strain parameters. Here the reliability related term 'strain' is described by the mechanical related term 'stress', here used as mechanical stress.
In mechanical structures these kind of level is typically directly related to the reliability parameters. Therefore the classical experiments are done and expressed with series of figures of Wöhler - curves. These strain parameter level typically can not be derived directly form the measurable signals. In simple cases the different strain parameters (here: mechanical stresses) will be summarized by handmade formulas with practical proved coefficients.
Different situations appear:

• The measurable values represent the process parameters directly and only has to be combined using non-variant system parameters to get the strain parameter, typically by some algebraic equations (Path 1).

• Inner states of mechanical structures often are not measurable. Parameter changes also can not be measured. Observer techniques, parameter identification techniques or combined approaches, can be used to get an inner view into the system using inner states (e.g. to the process parameters to be looked for) and other relations modeled using system informations (Paths 2,3,4). Using measurements and observer-based estimated inner states, process parameters can be calculated. Remarks related to the use of such techniques are given in /8/. The important criteria of these techniques is the ability of building up causal connections between measurements and outputs of these advanced modules, to get a real view to the system changes.

The principal ideas using advanced control techniques for monitoring and supervision are illustrated briefly for parameter identification approaches and observers in the sequel.

Real time calculation of Reliability Characteristics: This important part of the concept is declared in detail in /4/.

Reliability control approach: Core of the control approach is the idea of controling not a physical value of the system, but the reliability characteristic of the system as an indirect value like a quality item.
This indirect parameter represents the comparison of the structure to be observed, related to the experience of a collective of identical structures (past experience), or the assessment with this structure (estimation) respectively.
The SRCE-control approach should be distinguished clearly from classical control approaches. A schematic comparison is given in fig. 3 as follows. Using the reliability control ideas introduced in section II an control loop will be established. Because of the non-existence of the necessary relationships at this stage of development of the SRCE-concept the control loop scheme can be only declared from a principal point of view.
For mechanical structures the typical strain parameter seems to be the mechanical stress σ. The stress σ results by relations of

$$\sigma = \sigma(\text{Forces, Torques Geometry}) \tag{9}$$

and is - concerning to reliability aspects - related to maximal tolerable mechanical stress of the structure

$$\sigma_{rc,max,tol} \; = \; \sigma_{rc,max,tol}(\quad \begin{array}{l} \text{Forces, Moments, Load History, Material Properties,} \\ \text{Temperature, Environment Influences} \;). \end{array} \qquad (10)$$

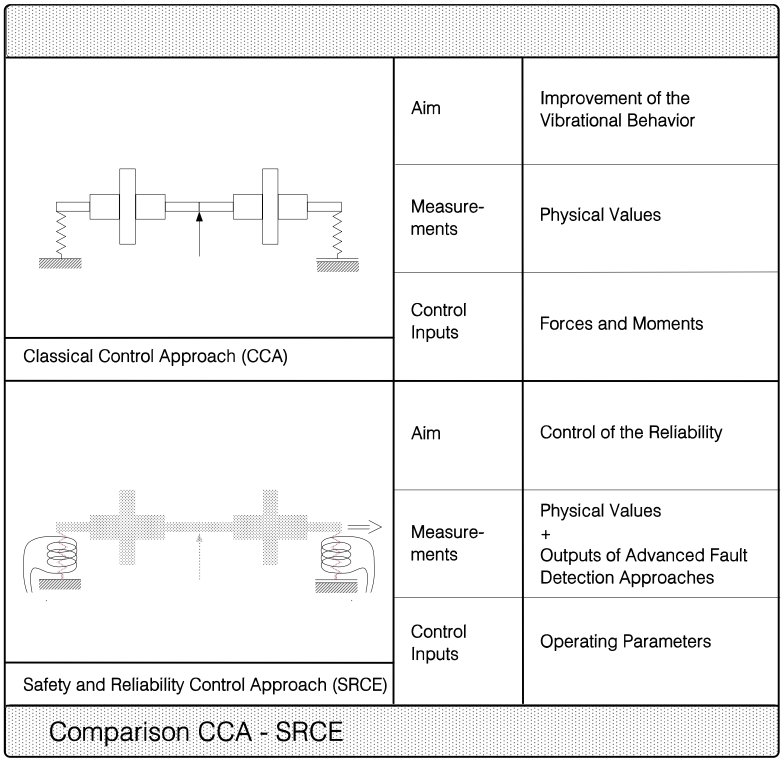

Fig. 3: Comparison CCA - SRCE approach (cracked rotor example)

The connection between the load history of mechanical stresses and strains and the failure rate is assumed to be described by the material depended Wöhler curve.

The mechanical stress σ directly depends on the static loads l_s, the dynamics loads l_d, the circular and rectangular cross sections W_p, W and the area A by

$$\sigma \; = \; \sigma(l_s, l_d, W_p, W, A) \; : \; rc \, , \qquad (11)$$

which corresponds to a set of reliability characteristics rc. The reliability related stress $rc_{tol} \, : \, \sigma_{tol}$ depends additionally from the load histories $l_s(t), l_d(t)$, from the time t because of material ageing processes, from the preload history $l_s(t-\tau), l_d(t-\tau)$, the temperature ϑ as

$$\sigma_{tol} \; = \; \sigma(l_s, l_d, W_p, W, A, t, l_s(t-\tau), l_d(t-\tau), \vartheta). \; : \; rc_{tol} \, , \qquad (12)$$

The idea given in eq. (5) can be used for control. Typically only a few parameters can be used for SRCE-control (e.g. the dynamical load by decreasing the power, the angular velocity of rotating systems etc.) depending on the problem and the structure itself.

The control loop is closed by the system changes itself. System changes are detected by the REM and analyzed concerning the reliability. The loss of reliability

$$\Delta rc = rc_f - rc_{tol} \qquad (13)$$

has to be canceled by the SRCE-control loop.
In general the problem can be formulated as the compensation of the reliability-characteristics-decrease $\Delta rc = rc_f - rc_{tol.}$ caused by system changes due to

$$\Delta rc = rc_f(W, t, A, \vartheta) - rc_{tol.} = \Delta rc_{SRCE}(l_s, l_d, l_s(t-\tau), l_d(t-\tau), W, A, \vartheta). \quad (14)$$

This includes that system changes leading to cracks etc. resulting in changes of W, A or because of material ageing properties t, ϑ and can be determined. On the other hand Δrc_{SRCE} can use repair strategies to improve geometry properties W, A or in general operating parameters l_s, l_d, or use some known facts of improving material properties by intelligent preloading strategies using $l_s(t-\tau), l_d(t-\tau)$.

SRCE - EXAMPLE: CRACKED LAVAL ROTOR: The task of the SRCE-example of the cracked rotor is to control the reliability characteristic of the failure rate of the laval rotor similar example given in fig. 4.

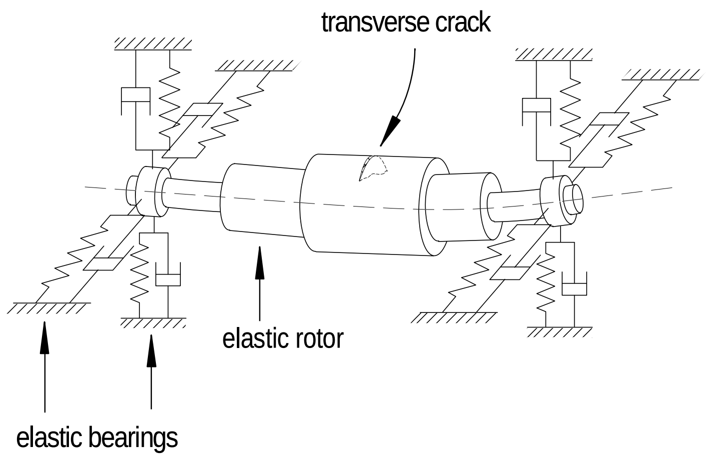

Fig. 4: Principal example of the cracked rotor
Firstly the classical supervision problem will be declared briefly. In the following the new SRCE-concept ist principally applied to this practical problem.
Classical supervision concept: During the stationary operation, measurements are taken from the bearings. Using signal analysis methods the frequency behavior will be monitored very well. Changes of the mechanical structure are leading to signatures of the spectrums, to changes concerning the amplitude of the observed vibrations etc. . Using human or artificial pattern recognition, comparing the vibration amplitudes with maximum allowed values, changes can be detected. Because of the fact, that the causal relation between these parameters and the physical reason is not unique, a very difficult decision - problem for the operating staff appears, which depends on the knowledge and experience of and with the system and also of economical and psychlogical constellations. In the - from a statistical point of view - rare case of a transverse crack, different phenomena - viewing the vibrational behavior - appears. Therefore different diagnosis philosophies exist. (e.g. /3,9/). Independent from the unsafe and ambiguous decision, no statement can be given about the depth of the crack and the real reducing of the technical functionality and the reliability. To be sure, the operation has to be stopped, the machine should be taken apart. Related to the viewed fault the operation is continued with lower strain parameters up to the next repair or inspection date, or the system

has to be repaired immediately. The complete process is strongly handmade and can be optimized in several cases using available techniques.
As a common goal of the application of advanced techniques the introduced SRCE-concept can be used.
SRCE - Concept: The relevant RME-modul for crack detection consist of two parts. The first part is the Proportional-Integral Observer (PIO) /7/, which is applied to the cracked rotor /6/. Here (with the same measurement information as used for the classical supervision concepts - the displacements of the bearings -) and additionally the mechanical description of the fault-free system, the effects of the crack are estimated directly at the crack location. This means by using the system information A_{ff} and simple measurements y, the PIO gives the crack depth as output, cf. fig. 5.

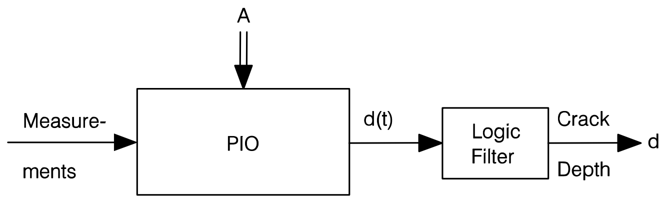

Fig. 5: Scheme of the PIO as RME-element
The crack depth d directly reduces the mechanical properties of the cross sections W, W_p directly. The explizit knowledge are given in the works of Mayes and Davies /2/. Here these analytical - geometry and material properties considering - algebraic formulas are used to give the relation crack depth - loss of cross sections as shown in fig. 6.

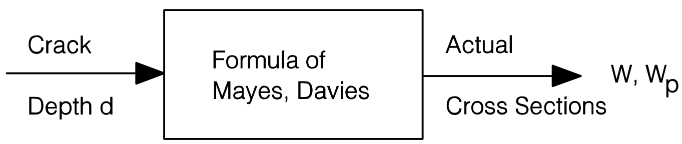

Fig. 6: Establishing the relation crack depth - cross sections
Assuming that the mechanical stresses of the simple structure of the Laval rotor are described by

$$\sigma_b = \frac{M_b}{W} = \frac{mg\varrho^2 L}{2W} \text{ and} \quad (15)$$

$$\tau = \frac{M_t}{W_p} = \frac{P}{2\pi n W_p} \quad (16)$$

with the bending moment M_b, the torsional moment M_t, the mass m, the gravity g, the density ϱ, the length L of the rotor, the power P, the revolutions n and the cross sections W, W_p shown in fig. 7.

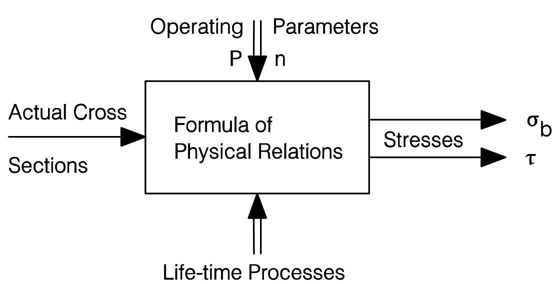

Fig. 7: Physical relations leading to strain parameters (here: mechanical stresses)

In contrast to a new approach illustrating advanced reliability modeling strategies /4/, here the old practically proved formula combining mechanical stress parameters is used, resulting to one compatible mechanical stress value

$$\sigma_c = \sqrt{\sigma_b^2 + 3(\alpha_o \tau)^2} \tag{17}$$

with the practically found parameter $\alpha_o = 0.63$ for turbine steel, cf. fig. 8.

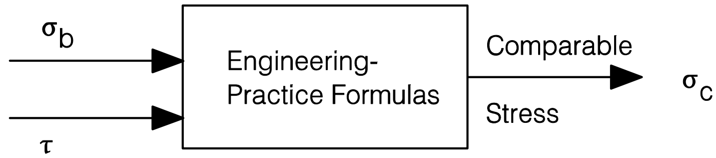

Fig. 8: How to combine two strain parameters to one

This parameter can be compared with the values found by numerous experiments combining the mechanical stress values, the number of stress changes and the failure rate: called Wöhler - diagrams, cf. fig. 9.

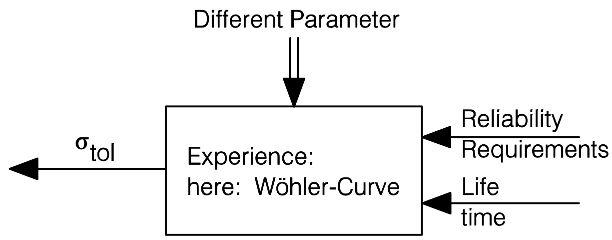

Fig. 9: Simple Wöhler diagram

The formula describing the time dependent strength properties with a failure rate of 1% is

$$\sigma_{rc}(N) = \left(\frac{\lg \frac{\sigma_F}{\sigma_D}}{\lg \frac{N_F}{N_D}} N + \lg \sigma_F - \lg N_F \left(\frac{\lg \frac{\sigma_F}{\sigma_D}}{\lg \frac{N_F}{N_D}}\right)\right) ind[N_D - N] + \lg \sigma_D \; ind[N - N_D] \quad \text{with} \tag{18}$$

$$ind[arg] = \{ \; 1 \text{ for arg} \geq \; 0; \; 0 \text{ for arg} < \; 0 \; \} \text{ with} \tag{19}$$

$\sigma_F, N_F, \sigma_D, N_D$ as pairs of the Wöhler curve and N as the number of stress changes. The goal of this example is to control the failure rate of 1%. Working at a lower stress level for σ_D, this means that the structure theoretically has in infinity life-time. Due to a crack at N_1 load cycles the mechanical stress increases. At load cycle N_2 the SRCE-control detect an inacceptable loss of the failure rate, because of the control goal dependent logic assumed for this example given in fig. 10.

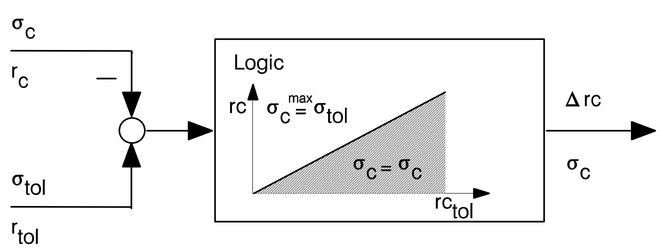

Fig. 10: Example dependent steering logic of the control unit.

Here different logic or analytic functions as control laws are possible. Potential field oriented approaches with the aim, that the max. rc-bound can not reached, are also of interest.

If the control unit works, in the case of setting restrictions to the allowed comparible stress $\sigma_{tol} = \sigma_{c,des.}$ the SRCE-control laws can be calculated using the inversion of eqn. (15-16) by

$$P_{des.} = \sqrt{\frac{2\Pi n W_p}{3\alpha_o^2}(\sigma^2_{c,des.} - \frac{m^2 g^2 \varrho^2 L^2}{2W})}, \tag{20}$$

given in fig. 11.

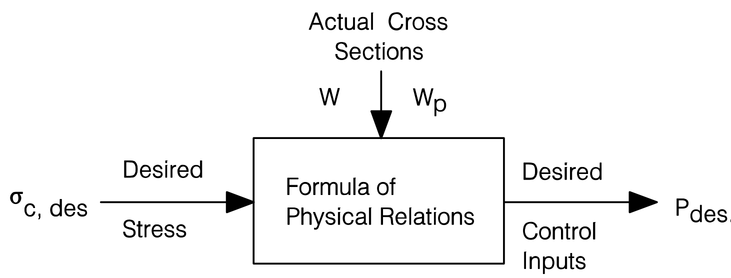

Fig. 11: Calculation of the desired control input

Using the operating parameter of the power P the SRCE-loop for this simple example is closed. The complete loop is given in fig. 12.

PERSPECTIVES OF THE SRCE CONCEPT: The idea of the SRCE-concept, the optimization of the life-time operation of systems by integration of

- advanced fault detection and isolation schemes for monitoring,
- the reliability evaluation module for calculation of reliability relevant values, and
- the control unit integrating inner loop control, maintenance- and repair strategies

into a mainly automated concept, can be also applied to other problems, in which the repair and maintenance strategy are more relevant, e.g. automated manufactoring processes, or in which reconfiguration approaches are important, e.g. safety relevant industrial processes. An advanced example is the space station concept with automated repair-control.

CONCLUDING REMARKS: This paper introduces a perspective concept of monitoring and control of vibrating structures by combining new methods of fault detection with new approaches of reliability engineering. The concept of the introduced Safety and Reliability Control Engineering (SRCE-) approach is based on advanced modules of control and reliability engineering. Fault detection and isolation approaches, which allow causal fault detection, describe the actual system state and allow a view into the system. These informations are used by the Reliability Evaluation Module (REM) to calculate reliability characteristics.

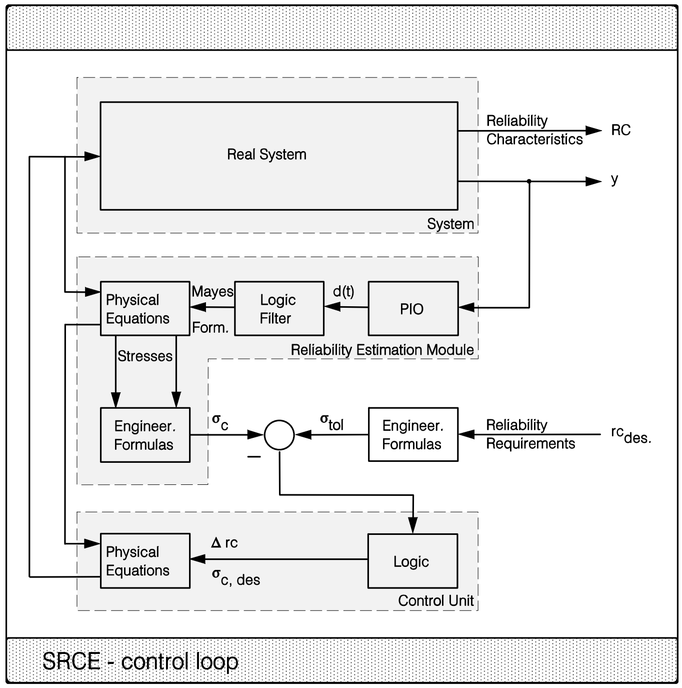

Fig. 12: Complete SRCE-loop applied to the cracked rotor example

The control loop can be established by turning back the knowledge needed for the real-time reliability determination. The complete concept is applied to the mechanical example of the cracked rotor.

REFERENCES:

/1/ Isermann, R., 1988, "Identifikation dynamischer Systeme I,II", Springer.

/2/ Mayes, I.W.; Davies, W.G, 1980, " A method of calculating the vibrational behavior of coupled rotating shafts containing a transverse crack", *Journal of Vibration, Acoustics, Stress and Reliability in Design*, Vol. 106, pp. 139-145.

/3/ Muszynska, A., 1982, "Shaft crack detection", *Proc. 7th Maschinery Dynamics Seminar*, Edmonton.

/4/ Rakowsky, U.K.; Söffker, D., 1997a, "Real time reliability evaluation of vibrating mechanical structures", submitted to: *12th ASME Conference of Reliability, Stress Analysis and Failure Prevention.* Virginia Beach, 1997, accepted.

/5/ Rakowsky, U.K.; Söffker, D., 1997b, "Safety and Reliabibility Control Engineering - Part I: Real Time Reliability Evaluation", in preparation.

/6/ Söffker, D.; Bajkowsky, J.; Müller, P.C., 1993, "Detection of cracks in turborotors - a new observer based method", *Trans. ASME - J. Dyn. Sys. Meas. Control*, Vol. 115, pp. 518-524.

/7/ Söffker, D., 1995, "A new model based tool for fault detection and isolation in machine- and rotordynamics", *Proc. 11th ASME Conf. Reliability, Stress Analysis, and Failure Prevention*, Boston, USA.

/8/ Söffker, D., 1997, "Robust fault detection of large vibrating structures by means of control theory - some principal remarks", submitted to: *12th ASME Conference of Reliability, Stress Analysis and Failure Prevention.* Virginia Beach, 1997, accepted.

/9/ Wauer, J., 1990, "On the dynamics of cracked rotor: a literature survey", *Applied Mechanics Reviews*, 43, pp. 13-17.