FACTA UNIVERSITATIS
Series: **Mechanics, Automatic Control and Robotics** Vol.3, N° 13, 2003, pp. 707 - 714

MODELLING OF A MATERIAL DEGRADATION AND DAMAGE MECHANICS IN MACHINE STRUCTURES UNDER SERVICE LOADING

UDC 620.1 539.388.1

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Abstract. *Problems of fatigue life estimation of materials and structures are discussed in the paper. Service loading is assumed as a continuous loading process with possible discontinuous events, which are caused by various operating manoeuvres. The damage mechanics in a material is due to a cumulative degradation process, which corresponds to formation of closed hysteresis loops in the stress-strain diagram. The damaging process is then represented either by rain-flow matrices or by a fatigue damage function. The fatigue damage function is derived using some hypothesis of a fatigue failure criterion. The method enables a very effective estimation of a service life and/or reliable evaluation of residual life of any complicated machine structures under various types of loading and environmental conditions. This approach creates a good basis for CAD/CAE technologies and for powerful expert systems in structural and machine engineering.*

1. INTRODUCTION

Optimisation of structure design is a decisive condition for effective production. It is exceptionally significant in mechanical and material engineering, because either economy demands or waste effects could be considerable in this case. Progressive CAD and CAE techniques have an indisputable advantage compared to traditional empirical-experimental methods because they are by far more quick and less expensive. So that to accelerate calculation procedures, we must have a suitable databank of operating parameters and of their influence upon a service life.

The parameters that affect a durability of structure parts are following: operating loading, structure characteristics, material properties and environmental conditions. Then we must use an appropriate method to estimate a service life and dependability for each combination of the parameters. Methods that enable these objectives are created by a combination of an empirical-experimental, theoretic-analytical and computer-simulation approach.

Received October 20, 2002

The fundamental problem is to respect a complete time loading history with possible non-homogeneous events. Usually, the simulated loading is simultaneously transformed into closed hysteresis loops using a rain-flow method, and a damage accumulation is estimated according to failure hypotheses. In the case of composite materials, various material characteristics as well as material joints must be respected. That brings much more complications in comparison with procedures used for homogeneous materials.

2. SERVICE CONDITIONS MODELLING

The most serious problem in modelling of damage mechanics is to analyse and simulate operating conditions. The correct simulation of service conditions is the necessary condition of a successful performance. Service conditions consist of following items:

a. *operating loading* (generally, random loading with superimposed discontinuous damaging events),
b. *material characteristics* (endurance limit and ultimate strength, S-N curve, fatigue diagram, etc.),
c. *structure parameters* (notch stress concentrators, surface treatment, welds, etc.),
d. *environmental properties* (corrosion, friction, high/low temperatures, radiation, etc.).

The analysis and modelling of service conditions are the input operations in the simulation procedure, according to Fig. 1.

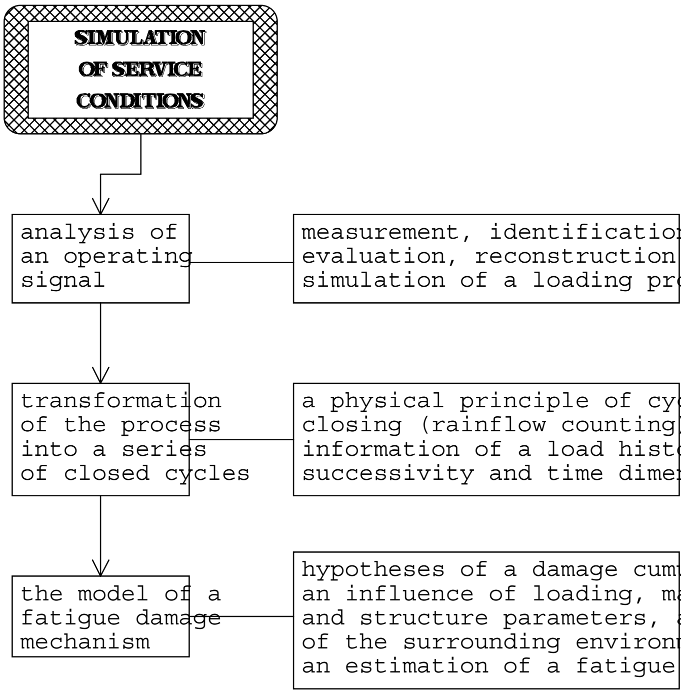

Fig. 1. Diagram of a simulation procedure

2.1. Operating loading

The analysis and simulation of the operating loading are the most important and complicated problems in the procedure. Methods how to perform the tasks are described in [1]. The methods summary is introduced in Fig. 2.

An operating loading is mostly considered as a stationary or non-stationary stochastic process. Such a process is completely described by its both probability density function (including a mean value and variance) and power spectral density (auto-correlation function). However, various discontinuous events that are mostly caused by manoeuvres and special service conditions must be respected, too. This problem significantly complicates a simulation procedure, and new non-standard methods and algorithms must be applied [2].

It is also very important to have a reliable algorithm of counting of closed hysteresis loops. Rain-flow methods mostly render possible the procedure only after a definite block of closed loops and they suppose the knowledge of the entire time history before starting to count. In such a case, it is, however, possible neither continual monitoring of a fatigue damage after each cycle nor a running estimation of a residual life during an operation.

The algorithm of a simultaneous signal generation and rain-flow counting was proposed in [3]. The method enables to respect a contribution of each closed hysteresis loop in the stress/strain domain continually, corresponding to the on-line generation of a loading process. Compared with traditional methods, a computer memory is saved, and monitoring of damaging is possible, too.

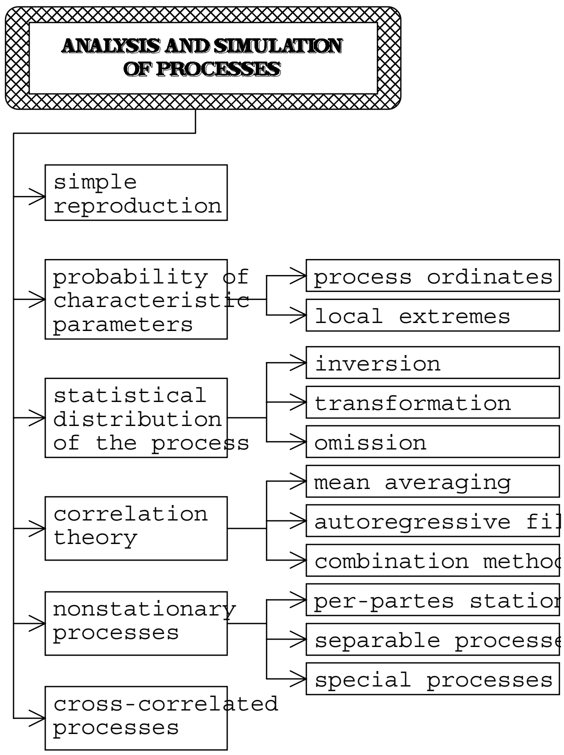

Fig. 2. Methods of a signal processing and generation

2.2. Material characteristics

An information of material characteristics of individual structure components is necessary for estimation of a fatigue damage. The most important characteristics are e.g. elastic modulus, shear modulus, strength limit, yield stress, fatigue limit, Wöhler curve, cyclic deformation curve, etc.

All the parameters must be identified before a simulating procedure, in order to be included into calculation algorithms. Characteristics for each structure component could be considered separately, what enables an investigation of composite structures. It is possible to suppose the time dependence of the characteristics, too. Therefore, we can also investigate composite materials with non-stationary properties.

2.3. Structure parameters

Simulated loading must be decomposed for the structure, according to the fatigue strength theory. In order to determine a real fatigue life curve, we must know structure characteristics, e.g. stress intensity factors, notch coefficients, surface sensitivities, size factors, welding parameters, etc. These parameters are then implicitly included in the actual endurance limit, and this way, into calculation relationship, too.

In the case of multi-axial loading, some hypothesis of a stress recalculation must be applied. For example, the strain energy hypothesis for a combination of bending and torsion has the form

$$\sigma_{eq} = \sqrt{(\sigma_a + \psi_\sigma \sigma_m)^2 + 3(\tau_a + \psi_\tau \tau_m)^2}\ , \tag{1}$$

where σ_a is the amplitude of a normal stress, σ_m is the mean value of a normal stress, τ_a is the amplitude of a shear stress, τ_m is the mean value of a shear stress, and ψ_σ, ψ_τ are corresponding sensitivities to the asymmetry of a cycle.

2.4. Environmental properties

Parameters that correspond to environmental conditions have a serious influence upon a fatigue life, too. The factors are above all: corrosion, high or low temperatures, friction, radiation, etc. They could be also implicitly included into a calculation relationship. The advantage of this approach is again in the ability to consider a possible non-stationary environmental characteristics. That is very convenient for composite structures, too.

3. ESTIMATION OF A MATERIAL DEGRADATION

Two basic methods for an estimation of a material degradation can be mostly used (Fig. 3). The first one is based on a rain-flow matrices creation, and according to the other method, we must specify a fatigue damage function.

3.1. Rain-flow matrices of loading and damaging

The rain-flow matrix of loading (*RML*) is created by elements $l_{i,j}$; $i = 1,2,...,n$; $j = 1,2,...,n$, which represent the number of hysteresis loops that have been originated in the i-level and that have started their closing in the j-level. In the case of non-stationary loading processes, and for non-linear hypotheses (or for cyclic unstable materials), the time moment of a given loop (or it's closing sequence) is also important, if need be an information about the foregoing hysteresis loop (or about more loops), too. Then, the rain-flow matrix must be extended by the next dimension, i.e. it must be a three-dimensional one.

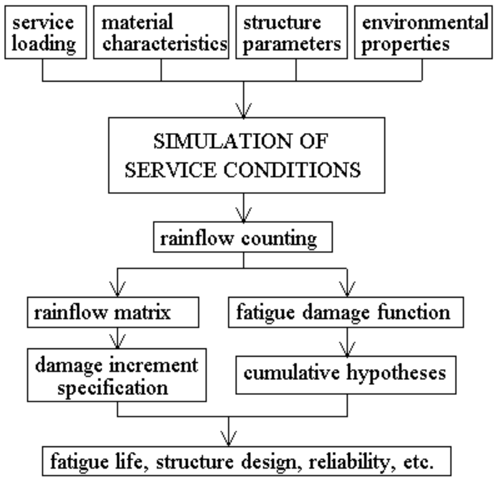

Fig. 3. The estimation procedure

Each closed hysteresis loop produces some definite corresponding damaging influence. Indicating a damaging effect of the loop as $d_{i,j}$, we would obtain also a square rain-flow matrix of damaging (*RMD*) which is composed of the elements $d_{i,j}$. *RMD* could be three-dimensional, too. There is no problem, how to identify a damage quantity $d_{i,j}$, i.e. how to identify a damaging effect of a sole hysteresis loop. For this purpose, we must use some of hypotheses of a fatigue cumulative damage. In the case of a linear rule of fatigue damaging, we constitute two-dimensional *RMD*. Though, if we accept some non-linear hypothesis, the rain-flow matrix should be three-dimensional, too.

Having both the *RML* and *RMD*, we can calculate the estimation of an accumulated fatigue damage *D* as their scalar product, i.e.

$$\boldsymbol{D} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \sum_{j=1}^{n} \boldsymbol{l}_{\mathrm{i,j}} \boldsymbol{d}_{\mathrm{i,j}} \,. \tag{2}$$

If rain-flow matrices are three-dimensional, the third parameters must be respected, too [4].

3.2. Fatigue damage function

A creation of a fatigue damage function is the other possibility how to estimate a degradation. Such a function is determined in the following form

$$D_n(\sigma_a) = k(\sigma_a) n^{m(\sigma_a)} ; \;\; k(\sigma_a) > 0 ; \;\; m(\sigma_a) > 0 \,, \tag{3}$$

where $k(\sigma_a)$ and $m(\sigma_a)$ are definite parameters which could be identified on the basis of fatigue damage criteria.

The function depends both on the number of passed closed cycles and on the character of loading, i.e. on amplitudes and mean values of the cycles. Using this method, a continuous monitoring of a fatigue damage process is possible, and the time history is respected, too. The choice of the damage criterion is the problem in this case, because the well-known linear Miner´s hypothesis is frequently not the optimal one, and other hypotheses must be adjusted to a special case, i.e. only the sole closed cycle is in each block of a macro-block, then. Frequently, the derivative function of a fatigue damage addition is applied in the form

$$d_n(\sigma_a) = k(\sigma_a)m(\sigma_a)n^{m(\sigma_a)-1}, \tag{4}$$

that corresponds to the above mentioned damaging effect of a definite closed loop. Summing the function, the number of cycles till the critical damage accumulation N_{kr} can be estimated according to the relationship

$$\sum_{n=1}^{N_{kr}} d_n(\sigma_a) \le 1 < \sum_{n=1}^{N_{kr}+1} d_n(\sigma_a)\,. \tag{5}$$

4. COMPUTER NETWORK OF A FATIGUE LIFE PREDICTION

The procedure of a fatigue damage evaluation in order to predict a fatigue life is shown in Fig. 4. We can dispose either of experimental measured results or of computer simulated data. Experimental data are processed using a regression analysis or a frequency distribu-

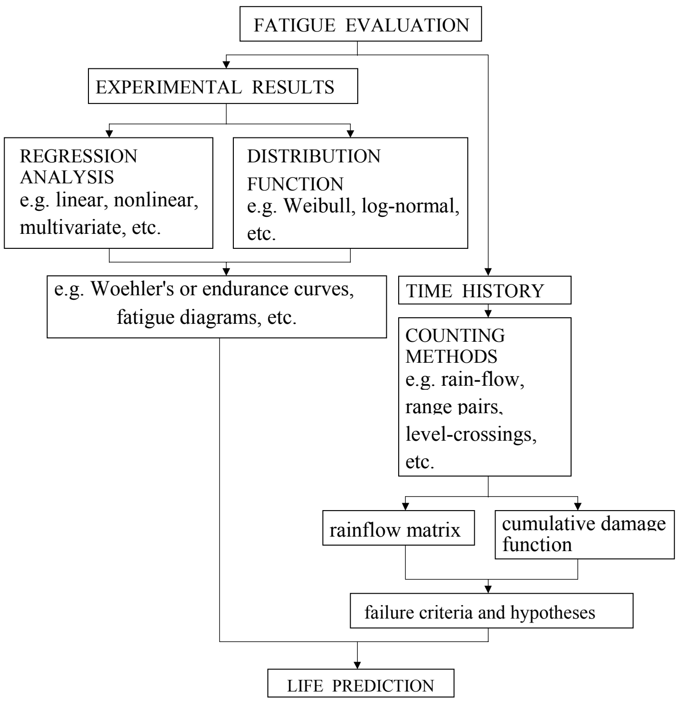

Fig. 4. The procedure of a fatigue life evaluation

tion function is determined. The processed results have various forms, e.g. Haigh diagram, Wöhler curve, etc. The results can be directly used in the expert databank.

For an estimation of a cumulative fatigue damage, some failure criterion or hypothesis must be applied [5]. A selection of possible hypotheses is optional and it depends on a specific situation or on a philosophy of a fatigue damaging process. All results are used in a life estimation, residual stress evaluation, structure reliability prediction, etc.

The computer network system creates a closed loop (Fig. 5). An information from the central databank is transported to users through a computer network system. Users can use databank data and compare them with new real experimental and simulated results. New knowledge can be then recurrently transmitted to the central system, so that to enrich the databank as well as to correct and improve the data.

The computer network system enables to link with an unlimited number of investigators or customers. Therefore, the described expert system is a very useful and necessary tool for progressive CAD/CAE technologies. This way, a lot of tasks can be solved, e.g. an estimation of a fatigue life of a given structure under given loading, optimisation of a material choice, structure dimensioning, investigation of an environmental conditions influence, etc.

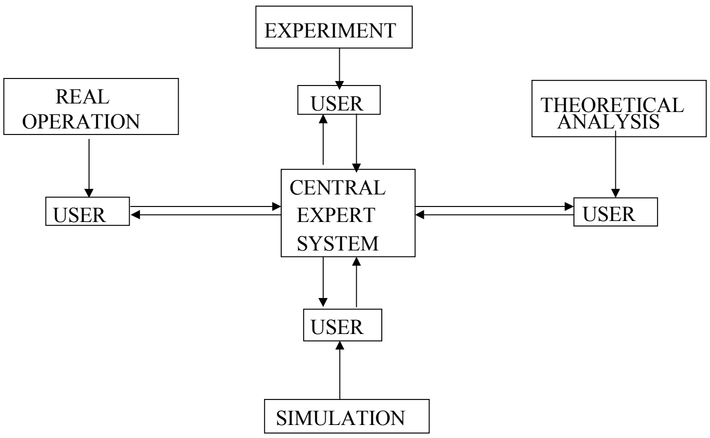

Fig. 5. Computer network system

The computer network system also brings at least two next advantages, in comparison with traditional theoretic-experimental methods:

a. New knowledge and experience can be immediately used by a vast number of engineers, researchers and designers.
b. Better co-operation between investigators and producers are evident, too. That aids to design machine structures in the optimum way.

5. CONCLUSIONS

The presented procedure enables a simulated estimation of a fatigue damage accumulation. It is possible to predict a residual fatigue life of composite structures, too. The submitted approach has an indisputable advantage in comparison with traditional theoretic-experimental methods, owing to a wide flexibility and time, materials and energy saving. It is possible to investigate any complicated structures with a number dangerous spots under multi-axial loading, where an experimental research is hardly realisable.

The method can be applied in a non-destructive evaluation of a structure life, damage tolerance investigation, structure durability prediction, etc. Creation and application of a material databank are very effective in this case, therefore, the method creates a good basis for expert systems and CAD/CAE technologies. It is also possible to modify and improve the method according to new experimental results or experience in order to make the most trustworthy estimation of a service reliability. Using a computer network, the expert system can be used by a lot of engineers and researchers in the stage before the first prototype production.

Acknowledgement. *This work was supported, in part, by the Slovak grant agency for science VEGA, Project No. 2/2029/22.*

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MODELIRANJE DEGRADACIJE MATERIJALA I MEHANIKA OŠTEĆENJA KOD MAŠINSKIH STRUKTURA PRI SERVISNOM OPTEREĆENJU

Jozef Čačko

U ovom radu razmotreni su problemi procene trajanja materijala i struktura pri zamoru. Pod servisnim opterećenjem podrazumeva se kontinuirani proces opterećivanja uz moguče slučajeve diskontinuiranja, koji su uzrokovani raznim radnim manevrima. Mehanika oštećenja u materijalu postoji usled kumulativnog procesa degradacije, koji odgovara stvaranju zatvorenih histerezijskih petlji u dijagramu napon-dilatacija. Proces oštećenja je tada prikazan ili preko "kišovitih" matrica, ili preko funkcije oštećenja zamorom. Funkcija oštećenja zamorom izvodi se korišćenjem neke hipoteze kriterijuma loma usled zamora. Metod omogućava veoma efikasnu procenu servisnog trajanja i/ili pouzdanu procenu zaostalog trajanja ma kojih komplikovanih mašinskih struktura pri različitim vrstama opterećenja i uslovima okoline. Ovaj pristup pruža dobru osnovu za CAD/CAE tehnologije i za moćne stručne sisteme u tehnici konstrukcija i mašina.