ESTIMATION OF FATIGUE DAMAGE DURING OPERATION OF A DYNAMIC SYSTEM

M. Bílý[x] and J. Prohácka[x]

A system of works for the estimation of operating fatigue life of a dynamic system is described covering dynamic structural properties, analysis of a dynamic process and its transformation to a stress concentrator, fatigue damage assessment and fatigue life calculation. The dynamic system represents a multiple random input - one output linear system. The damage process is analysed based on the monitored or simulated ordinates and the characteristics are used as input data for fatigue damage hypotheses and feedback information for redesign and/or adaptive control.

INTRODUCTION

Despite a long time effort, designing against fatigue still remains one of the most difficult engineering problems whose successful solution cannot be always guaranteed, as documented by occasional operating fractures. This is mainly due to a vast number of factors conditioning the operating fatigue life such as operating loads, material characteristics, design features, etc., having synergetic effects. Moreover, it should be kept in mind that fatigue crack initiation and propagation often result not because of an inadequate strength calculation but because of excessive operating loads and/or inconvenient dynamic structural properties giving rise to localized stresses due to the dynamic effects (especially resonances). Thus in practical design procedures and mainly in complex CAD approaches, four areas of variables are to be considered simultaneously: typical operating random loads (or

[x] Institute of Materials and Machine Mechanics of the Slovak Academy of Sciences, Bratislava, Czechoslovakia

their statistical characteristics), dynamic variables (frequency transfer functions $H_j(f)$), design parameters (notches, statistically determinate or indeterminate systems, welds, etc.) and material fatigue characteristics (limit state curves). Either of them can have a decisive effect on the resulting fatigue endurance and so to reach an optimal solution all of them are to be dealt with iteratively in a closed loop.

Furthermore, there are mechanical systems (nuclear power stations, boilers, air planes) whose performance and so operating regimes are to be controlled and adjusted, e.g., according to the exhausted fatigue life. Hence, the operating process in a critical location is monitored and the fatigue life is continuously calculated, providing the feedback signal for the adaptive operating control.

The purpose of the work reported here, is to characterize the whole chain of problems depicted in Fig. 1 aimed at determining and control of fatigue life of a dynamic system.

DYNAMIC SYSTEM

Consider a dynamic system excited by an external input operating random processes $x_j(t)$ and characterized by the transfer functions $H_j(f)$, where f denotes frequency. Providing that the system is linear, the input processes are stationary and without extraneous noise we can compute the partial output processes $y_j(t)$ using the convolution integral

$$y_j(t) = \int_0^\infty h_j(z)\, x_j(t - z)\, dz \tag{1}$$

and thus the operating process y(t) in an interesting and as usually critical plain location equals

$$y(t) = \sum_{j=1}^{n} y_j(t), \tag{2}$$

where $h_j(z)$ is the inverse Fourier transform of the transfer function $H_j(f)$ given as

$$h_j(z) = \int_0^\infty H_j(if)\, \exp\,(i2\pi fz)\, df\ , \tag{3}$$

where $i = \sqrt{-1}$.

If the external processes are known in the form of time series $x_j(t)$ they can be directly inserted into eq. (1) in order to obtain y(t). But in majority of practical cases they are characterized by various statistical characteristics, such as a probability density function of ordinates, autocorrelation function, power spectral density, transition probability density functions between ordinates or peaks, etc., and so they are simulated using various simulation models. Because in these cases the corresponding real time simulation algorithms allow to simulate also non-stationary processes (see Čačko et al. (1)), such an approach should be preferred.

In accord with Fig. 1 the first "dynamic part" of the fatigue damage estimation can be avoided if we are directly concerned with the internal damage process y(t) in a critical plain location. Such a process can be either taped, or monitored or characterized by its statistical characteristics.

TRANSFORMATION TO A NOTCH ROOT

Considering that practically all sources of fatigue damage initiation are located in notch roots (holes, grooves, welds, etc.)it is indispensable to transform the "plain" process to the "concentrator" process which in fact conditions the final fatigue life. This can be done in two ways.

Process transformation

Suppose that material during repeated loading follows the cyclic stress-strain curve expressed by eq.

$$\varepsilon_a = \sigma_a/E + \left(\frac{\sigma_a}{K}\right)^{1/n} , \tag{4}$$

where ε_a and σ_a are strain and stress amplitudes, respectively, K is the cyclic strength coefficient and n cyclic strain hardening exponent. Then according to the Neuber formula, the true stress amplitude σ_p and true strain amplitude ε_p in the notch root, characterized by the strength reduction factor K_F, are related as

$$\sigma_p \ \varepsilon_p = K_F^2 \ \sigma_a \ \varepsilon_a . \tag{5}$$

To perform this transformation practically the random process to be analysed should be sampled at a higher frequency (say, at least 10 times the maximum frequency contained in it) to discover all local peaks, determining the local ranges a_i (Fig. 2). These ranges (irrespective whether they represent stress or strain) are then substituted into equation (4), from which the remaining characteristic is computed, i.e. from ε_{ai} → σ_{ai} and from σ_{ai} → ε_{ai}. Both ε_{ai} and σ_{ai} are then inserted into equation (5) and knowing K_F the notch peak values σ_{pi} and ε_{pi} are obtained iteratively (σ_{pi} and ε_{pi} should also obey equation (4)). The original "plain" process is recalculated in this way, characterizing the notch root behaviour.

It is to be noted, however, that the suggested method is used when the process is further analysed in the scope of the correlation theory only. Nevertheless, its validity should be further verified, the criterion being the final fatigue life.

Macroblock transformation

The macroblock of sinusoidal cycles with various amplitudes a_i can be transformed to the notch root in a similar way as in the previous case. But here the amplitudes ε_{ai} and σ_{ai} are clearly defined (Fig. 3), having been determined by the rain flow method.

DAMAGE PROCESS ANALYSIS

The internal random process y(t) or its simulated substitution is analysed either in the scope of the correlation theory or by the rain flow method. With respect to the practical utilization of various possible statistical characteristics we get in the first case a probability density function of ordinates p(x) and/or power spectral density S(f), and in the second case a set of sinusoidal cycles as usually grouped together to a set of blocks, forming a macroblock (Fig. 3).

Calculation of the correlation theory statistical characteristics represents no problems if the analysed process is stationary. Considering however that more than 50 % of operating processes are non-stationary, the practical analysis respecting these properties is for the time being more an art than science. Thus, if the test of stationarity proves the non-stationary properties, the only practical way is to divide such a process into segments which are considered to be stationary. Because the practical experience clearly shows that any non-stationarity influences in a negative way the fatigue life, it is urgently needed to work out a practical analysis of non-stationary random processes and provide its results for newly formulated fatigue damage hypotheses.

An easier way in this respect offers the rain flow analysis which can be equally well applied both to stationary and non-stationary processes. But even in this area it is worth performing further research works. Also note that recently this method has been modified to perform the counting of closed loop amplitudes continuously and so no process segmentation is required.

FATIGUE DAMAGE AND LIFE ASSESSMENT

Depending on the operating random process analysis adopted two different kinds of fatigue damage accumulation hypotheses can be applied. Based on the macroblock representation we could use some well known formulae derived by Palmgren-Miner, Corten-Dolan, Kliman (2) and others which together with the Wöhler or Manson-Coffin curve yield the fatigue life, being a multiple of the macroblock repetition.

A less clear situation is met however when the result of the process analysis is in the form of p(x) and S(f). Although the literature presents various stochastic hypotheses, according to our knowledge only two of them are directly applicable, viz. the Raikher and Kliman formulae (2), exploiting the evaluated S(f), parameters of the cyclic stress-strain curve and Manson-Coffin curve.

Taking into account that both the random process analyses and fatigue damage hypotheses inherently contain inestimable errors, our long time experience suggests that it is appropriate to use both ways of the random process analysis together with all the fatigue damage hypotheses available. Although this will not "improve" the result, it offers a certain estimation of the scatter. Desk top calculators make it an easy job.

REFERENCES

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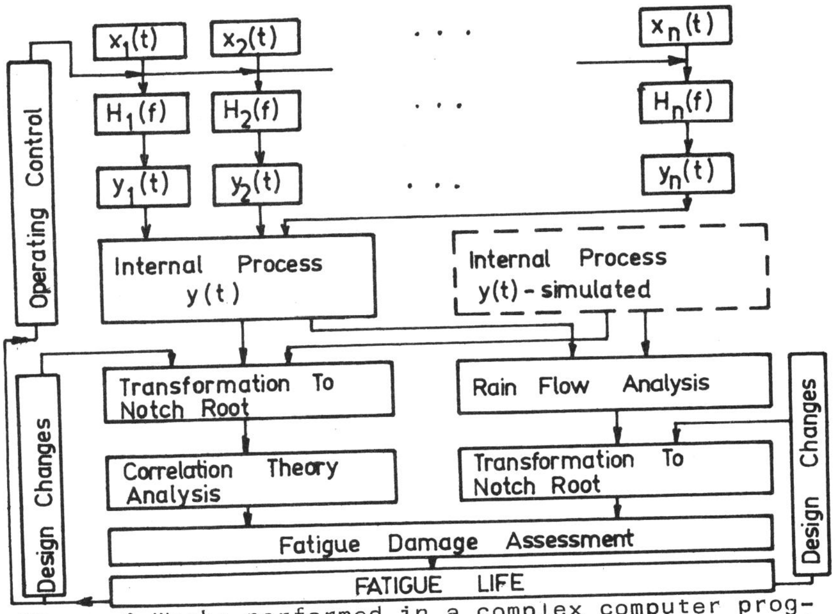

Figure 1 Works performed in a complex computer programme for fatigue life estimation and system control

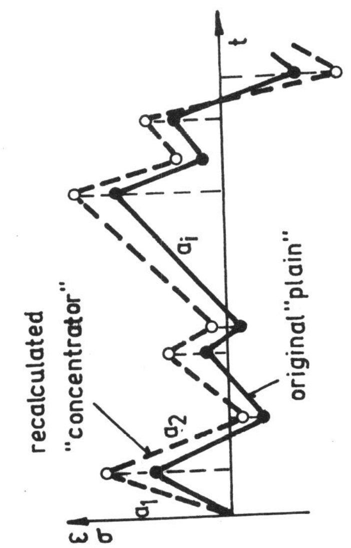

Figure 2 Plain process transformation to notch root

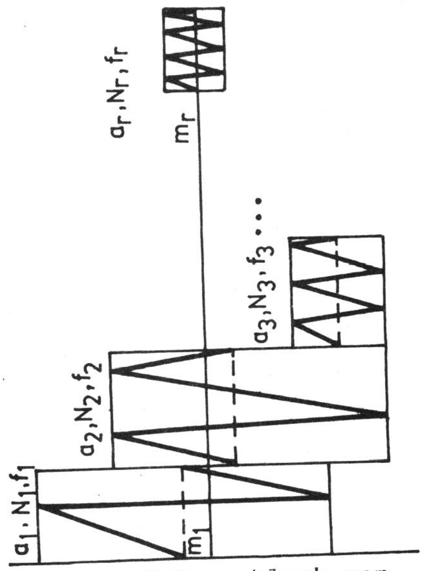

Figure 3 Macroblock composed from r blocks