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Frequency-domain fatigue life estimation with mean stress correction

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ABSTRACT

Two frequency-domain fatigue life calculation methods are presented which take into account the impact of the mean stress effect. The emphasis is set on the algorithm for fatigue life assessment of the method proposed by the authors. It is supplemented with a mean stress effect correction. Correction method is based on the direct transformation of the zero mean stress Power Spectral Density (PSD) due to mean stress. The method is verified on the basis of own results for the S355JR steel. The authors analyze five models for the designation of the probability density function used in the calculation process. The results are presented in the form of probability distributions after PSD transformation and the calculated fatigue life is being compared with the experimental life in fatigue comparison graphs. An analysis of the choice of a mean stress correction model is also widely discussed and a fatigue life estimation is also performed. The method proposed by the authors is being compared with the Kihl–Sarkani method for mean stress correction in frequency domain.

1. Introduction

The phenomenon of material fatigue, which occurs due to the impact of time varying forces is one of the main reasons for material failure [1,2]. The variable forces which are the main reason for this effect can be divided into two groups with constant amplitude loading and random loading. Those loads can be described with the use of deterministic formulas or with the use of stochastic theory [3–5]. The mean stress effect in fatigue life assessment is a well-known issue discussed widely in the literature [6–10]. The mean stress is an extra static load in the form of an additional time independent load applied to the construction e.g. as a results of self-weight, prestressing of springs or compressive stress in a screw connection [11,12]. Engineers have to take into account those kind of extra loads and prevent early fatigue failure or other construction defects. Although the literature presents solutions for the correction of mean stress in the time domain (cycle counting methods) it is rare to find a solution in the frequency domain (spectral method). The authors have presented theoretical backgrounds of mean stress correction method that can be used in the frequency domain [13]. For this purpose a Power Spectral Density (PSD) transformation is used. The transformation process is realized with the use of well-known mean stress compensation models. The fatigue life is being calculated with the use of Probability Density Functions (PDF) of stress amplitudes as well as Palmgren–Miner damage accumulation hypothesis. The presented correction method is verified with own test results obtained for the S355JR steel under narrowband and broadband loading. The method is being compared with the method proposed by Kihl and Sarkani [14]. The verification is being done also with the use of experimental results and calculations performed by Kihl and Sarkani for cruciform shaped welded specimens. The proposed calculation procedure can be used for narrowband as well as for broadband loading characteristics, independently from the spectral method for determination of the PDF of amplitudes.

The mean stress value used in the process of fatigue life assessment is presented as the static component of the stress history according to the formula:

$$\sigma_m = \lim_{T\to\infty} \frac{1}{T} \int_0^T \sigma(t)dt. \quad (1)$$

For the constant amplitude loading the mean stress value is usually defined as the algebraic mean of the maximum and minimum stress value in one loading cycle. Following that, some basic formulas can be presented:

- Stress range

$$\Delta\sigma = \sigma_{max} - \sigma_{min}, \quad (2)$$

where σ_{max} and σ_{min} are respectively maximum and minimum stress.

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Nomenclature

A and φ	scale functions
$K(\sigma_m, P)$	mean stress compensation coefficient
$G_\sigma(f)$	power spectral density of a centered stress course
$H(f)$	frequency response function
λ	damping factor
$\sigma(t)$	stress history
σ_a	stress amplitude
σ_m	mean stress
σ_{max}	maximum stress
σ_{min}	minimum stress
$\sigma^{\prime f}$	fatigue strength coefficient
$\Delta\sigma$	stress range
$p(\sigma_a)$	stress amplitude probability density function
R	stress ratio
R_e	yield strength
R_m	tensile strength
α_k	material-dependent parameter for the Kwofie method
t	time
T_{cal}	calculated fatigue life
T_{exp}	experimental fatigue life
ξ_i	moments obtained from power spectral density for $i = 0, \ldots, 4$
μ	variance
γ	coefficient calculated with the use of spectral moments
w, α, β	factors calculated for the Zhao–Baker probability density function
C, m	constants from the Basquin curve
b	weight function dependent from the PSD
v_p	factor calculated for the Benasciutti–Tovo probability density function

- Stress amplitude

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}. \tag{3}$$

- Mean stress

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}. \tag{4}$$

- Stress ratio

$$R = \frac{\sigma_{min}}{\sigma_{max}}. \tag{5}$$

All these parameters describe the stress course as shown in Fig. 1a. Some possible values of the stress ratio R are presented in Fig. 1b.

1.1. Mean stress correction methodology for time-domain

The mean stress effect is still a problem in regards to fatigue life assessment in the time domain for variable loading. Nevertheless there are existing solutions to this problem which refer to the transformation of stress amplitudes with the use of linear and non-linear mean stress compensation models. As presented by Łagoda et al. [15] three paths can be taken while calculating the fatigue life:

- without compensating for the mean stress, not preferred in most practical cases, usually gives an overestimation of the lifetime,
- transformation of stress amplitude in regards to each stress cycle and its mean stress value after cycle counting,
- transformation of stress history with global mean stress value before cycle counting.

Following the third path we can transform the stress history with the appropriate formula:

$$\sigma_T(t) = [\sigma(t) - \sigma_m] \cdot K(\sigma_m, P), \tag{6}$$

where $[\sigma(t) - \sigma_m]$ is the fluctuating part of the loading history; $K(\sigma_m, P)$ is the transformation coefficient that can be calculated out of majority compensation models for mean stress σ_m and material parameter P, for example:

For Goodman's model [16]

$$K_{Go} = \frac{1}{1 - \frac{\sigma_m}{R_m}}, \tag{7}$$

For Morrow's model [17]

$$K_M = \frac{1}{1 - \frac{\sigma_m}{\sigma'_f}}, \tag{8}$$

For Gerber's model [18]

$$K_{Ge} = \frac{1}{1 - \left(\frac{\sigma_m}{R_m}\right)^2}, \tag{9}$$

For Kwofie's model [19]

$$K_K = \frac{1}{\exp\left(-\alpha_K \cdot \frac{\sigma_m}{R_m}\right)}, \tag{10}$$

For Niesłony–Böhm model [12]

$$K_{NB} = 1 + \sigma_m \left(\frac{1-R}{R+1}\right) \frac{\sigma_{aN,R=-1} - \sigma_{aN,R}}{(\sigma_{aN,R})^2}, \tag{11}$$

where K_{Go}, K_M, K_{Ge}, K_K, K_{NB} – coefficients determined on the basis of appropriate models, R_m – tensile strength, σ'_f – fatigue strength

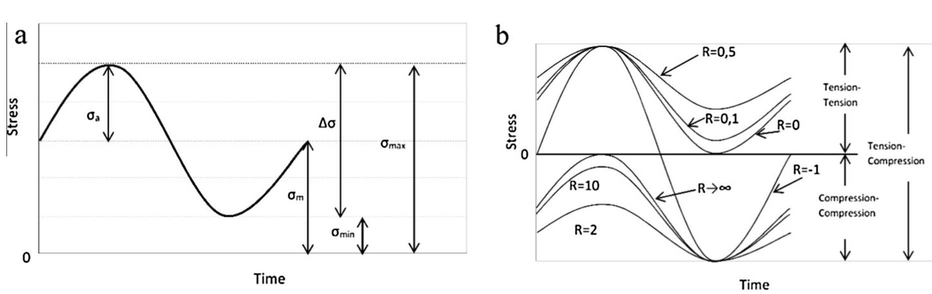

Fig. 1. (a) Basic parameters describing the constant amplitude stress course and (b) some possible values of the stress ratio R [35].