International Journal of Fatigue 91 (2016) 328–336

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Lightweight-structural durability design by consideration of variable amplitude loading

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ARTICLE INFO

Article history:
Received 24 May 2015
Received in revised form 21 July 2015
Accepted 27 July 2015
Available online 4 August 2015

Keywords:
Variable amplitude loading
Cumulative damage
Lightweight design

ABSTRACT

The technical importance of variable amplitude (spectrum) loading is not only given by obtaining much longer fatigue lives compared with those determined under constant amplitude loading with the maximum value of the spectrum. It also enables the lightweight potential resulting from proper consideration of the exceeding of the Woehler-lines (constant amplitude loading) by the Gassner-lines (variable amplitude loading) for a required duration. The degree of exceeding at the required service duration allows higher design stresses than under constant amplitude loading and is decisive in determining to what extent cross sections and hence weights can be reduced. However, the experimental determination of Gassner-lines is time and cost consuming, while their estimation by cumulative damage, i.e. fatigue life, calculations, is subject to underlying large uncertainties. Therefore, especially for safety–critical parts, experimental verifications and service inspections are indispensable.

1. Introduction

When the size of an amplitude changes during loading, this is formally regarded as variable amplitude loading, even if only two or three different amplitude levels are involved. However, such loadings with few amplitude levels are more of academic interest, because practical industrial applications, Fig. 1, are dominated by various load–time histories, Fig. 2, with amplitude spectra of different intensities.

As, in all of the above presented industrial sectors, the overall aim is structural durability, i.e. the ability of a structure or a component to withstand changing time-dependent cyclic loads, but also quasi-static and impact overloads, that occur during service, taking into account the environmental conditions such as temperature or corrosion, the following paper which is an extended version of [1] will concentrate on realistic variable amplitude loadings, i.e. spectrum loadings, and important basics, which should be considered in structural durability research and design.

2. Short overview on the background and importance of designing against spectrum loading

The significance of service loads with variable amplitudes for fatigue life of components and especially for lightweight design was first recognised by Ernst Gassner. In 1939, after several service observations, he first formulated a procedure for the experimental simulation of such varying loads: the historical 8 step blocked program test with a Gauss-like distribution of amplitudes, Fig. 3 [3]. By defining a load sequence, which is repeated until failure, he described what happens in the operation of components and structures and systematised for the first time the application of spectrum loading, thus opening the way to various loading standards [4,5], which were developed over the following years straight up to the present time.

The 8 step block program was the very first standard for spectrum loading, but was then replaced in the 1970s by random loading, due to the development of servo-hydraulic testing facilities, Fig. 4. The introduction of the realistic random loading, with almost the same amplitude distribution and the same sequence length as the block program loading, resulted, due to different local plastifications in the presence of cracks and due to different crack closure states, in significantly shorter fatigue lives, Fig. 5, by factors of 3–10 depending on material, stress concentration and amplitude distribution [6]. This suggests that block program tests should be avoided. However, if constant amplitude blocks are shortened and a high degree of mixing of different load levels is achieved, fatigue life shortening effects can still be simulated by block program testing [7–9].

The contribution and merit of Ernst Gassner can be recognised from Fig. 6:

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http://dx.doi.org/10.1016/j.ijfatigue.2015.07.030
0142-1123/

Nomenclature

D	damage sum
L_s	sequence length
N	number of cycles
P	probability
R	load or stress ratio, $R = F_{min}/F_{max}$ or $\sigma_{min}/\sigma_{max}$
k	slope of the Woehler- or Gassner-line
k^*	slope of the Woehler-line after the knee point for constant amplitude loading
k'	slope of the Woehler-line after the knee point for cumulative damage calculation
K_t	theoretical stress concentration factor
T_σ	scatter of fatigue strength

Subscripts

a	amplitude
al	allowable
an	nominal amplitude
f	failure
k	knee point of the Woehler-line
o	occurrence
s	survival, sequence
th	theoretical
spec	spectrum
sec	sequence

Fatigue life is seen to increase with decreasing fullness of the spectrum: the higher the amount of small amplitudes, the longer the fatigue life. On the other hand, the increasing fatigue life displayed by the position of the Gassner-curves can be exploited for the reduction of dimensions; for a fatigue life of 10^8 variable amplitude cycles of a steering rod, the maximum endurable stresses are 50–100% higher than the constant amplitude fatigue strength, depending on the spectrum shape. So, significant reductions of cross-sectional area and component weight can be realised, approaching the material limits. However, it must also be ascertained that quasi-static or impact overloads do not exceed the structural yield point causing global plastic deformations or that impact loads with high energy do not lead to a catastrophic (brittle) failure, especially if a crack should be present [10,11]. In this context, reliability and safety aspects must also be respected. This example underlines the main contribution of Ernst Gassner regarding spectrum shape and lightweight design [9,12] which led, after the work of August Woehler (1865), to a second revolution in fatigue design.

This methodology, first developed for aircraft design, has also been adopted, since 1948, by the automotive industry. Today, a vehicle development without experimental and numerical consideration of variable amplitude loading would be unthinkable. Also in other industrial sectors, such as railway, bridge, naval and plant engineering, the lightweight design potentials of Gassner's method are recognised and are consequently applied.

3. Determination of Gassner-lines

The example in Fig. 6 reveals the importance of knowledge about the position of the Gassner-lines with regard to lightweight design potential. The question therefore arises as to how to determine the level of the particular Gassner-line, which depends on the load–time history spectrum shape. One possibility is the conducting of experiments; the other relies on fatigue life calculation.

3.1. Experimental

While the performance of constant amplitude tests is quite easy to understand, the performance and presentation of variable amplitude tests often causes difficulties: The questions most often arising are "how to define a loading sequence/spectrum" and "over which amplitude to present the fatigue life?"

According to Gassner, firstly a load sequence should be fixed, which is repeatedly applied until a defined failure is obtained [9,12], Fig. 7. The resulting fatigue life, which is allocated to a

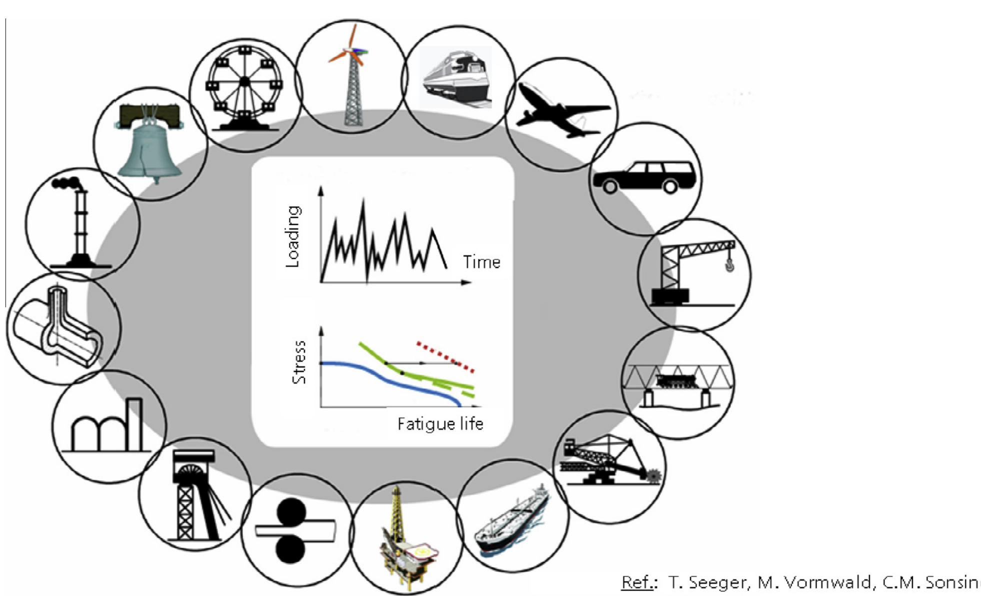

Fig. 1. Technical sectors requiring structural durability proof [1].