Reconsidering the Role of Fatigue Irregular Testing in Scientific Conclusions About the Fatigue Limit

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Abstract

We propose using the irregular loading fatigue testing to study the crucial topics of the subject, for instance, concerning the fatigue limit. This characteristic is important to know (1) for test accelerating; (2) To guarantee stable, reliable service. Comparative studies under block and random loading present an opportunity to draw conclusions without the ultra-sound frequencies loading, which are at some extend controversial. We present an example of proposed method application. The second stage of fatigue – namely, the crack propagation stage, is also considered (in reference). There the main idea is similar – the irregular testing provides an opportunity to judge about the maxim among the small amplitudes, which are not harmful. Direct experimental estimation of true fatigue limit requires the testing under ultra-sound frequencies, which is not under the questions nowadays.

Keywords: Mechanical fatigue, endurance limit, block loading, Linear damage summation, statistics.

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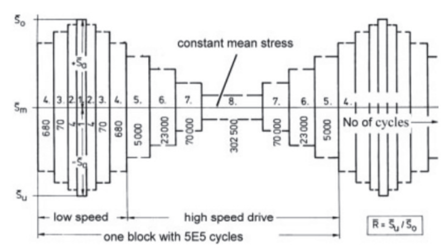
1 Introduction

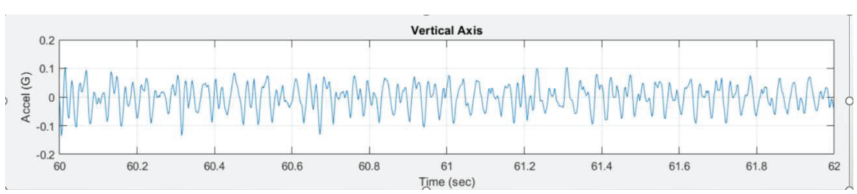
Historically, the phenomenon of fatigue (initially in metals, and more recently in composites) has been studied when specimens are loaded with a sinusoid. A typical example of regular loading is sinusoidal lo ading: frequency (w) and amplitude (A) are constant: $X(t) = A \sin(wt + \phi)$.

Much has changed in testing practice over the past decades. Increasingly, scientists are using irregular processes. Irregular means block and (pseudo) -random loading (Figures 1(a) and 1(b)). Initially, Gassner suggested using block loading for testing aircraft structures [1], and then, with the development of testing technology and software, tests under random loading were increasingly used, as they were closer to the actual loading of machines in operation. It should be emphasized that testing techniques and methods are developing, but calculation methods for the most part still gravitate towards a base based on testing under harmonic loading.

They have addressed the efficiency of the metals by testing devices under the impact of several loadings namely block or random loadings. They have



a)



б)

Figure 1 Examples of the block (a) and random (b) loading during fatigue tests.
(About 1,b. Tom Irvin, an engineer, IOWA, USA, traveled on the ferry on September 6, 2021. He recorded the following vibration data using an accelerometer app on his Android Smartphone (Pixel 3 XL), which was placed on a small table between two seats on the passenger deck).

tried to study the behavior of fatigue curve on the devices to accumulate the occurred damage of the

Further, this article shows how one can judge the damage threshold by testing specimens under block loading.

One of the topics, the study of which seems to be the most relevant, is the study of the threshold (i.e., the largest of the stress amplitudes that do not affect the accumulation of damage). It is of interest to study this phenomenon both at the stage of initiation and at the stage of crack propogation [2]. This is essential: (a) from the point of view of the acceleration of tests – if stresses do not affect the accumulation of damage, then they can be discarded during testing; (b) carrying out calculations of durability using updated information on the behaviour of the fatigue curve in the region of ultra-high durability. This article shows how one can judge the damage threshold by testing specimens under block loading.

It should be noted that carrying out certification tests only under harmonic loading (plotting the usual fatigue curve and kinetic fracture diagram) can no longer satisfy inquisitive minds. More and more researchers are inclined to the need to carry out tests under irregular loading to determine the properties of the material. Sunder [2] proposes to determine the crack propagation threshold by testing under irregular loading according to a special program. With the approach he proposed, not only is the experiment very close to real operating loading, but it also provides an opportunity to study the physics of the crack propagation process. Thus, when testing aluminum samples with original pseudo-random loading based on the TWIST standard, Sunder showed [2] how and at which manner exactly, sequence-sensitive near-tip residual stress affects fatigue crack growth.

The result obtained made it possible to propose a method for assessing the rate of crack growth, taking into account crack closure and the influence of residual stresses formed during crack growth.

Concerning the first stage of fatigue, namely, the crack initiation stage we can mention [3]. To overcome drawbacks of regular testing, the authors of [3] introduced the so-called ‘model curves’ which are based on irregular testing under standard sequences (TWIST, FALSTAFF).

Figure 2 shows a block of loading of a tractor part [4]. Some of the loading steps are below the endurance limit (dashed line in the figure). Based on Miner’s linear summation hypothesis [5], they should be discarded in tests and calculations. It should be noted, however, that there are two circumstances that prevent doing this: (1) often this is the lack of reliable data on the behaviour of the fatigue curve at ultra-high loading numbers $N > 10^8$;

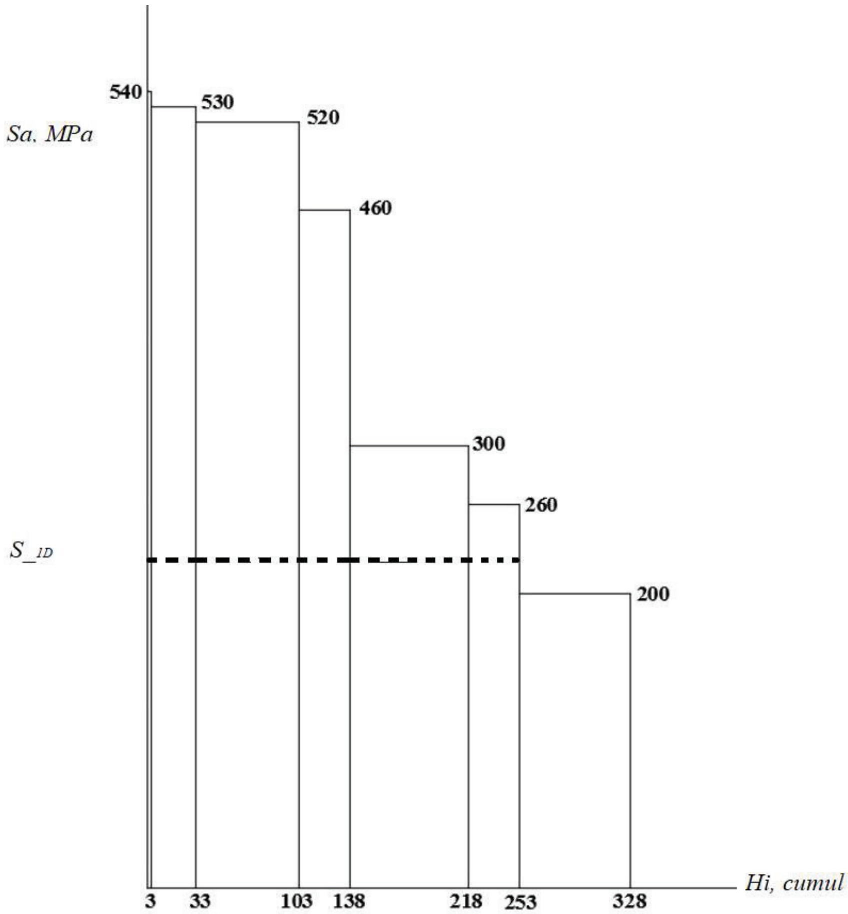


Figure 2 Loading block for the farm-machine investigation, obtained on the base of the analysis of the service modes [4Berrez 2].

(2) lack of information on the phenomenon of material degradation under the action of operational loading (i.e., in the presence of overloads).

Concerning remark number 1. There are numerous examples of how materials previously believed to have unlimited endurance, overcoming plateaus, again demonstrated failures at ultrahigh bases [6 bath]. An example of the results of such tests for composites is shown in Figure 3.

If previously there was no possibility of conducting such tests, then since the 1980s such technical feasibility has appeared [8] and is now a very common test method; (2) there are experimental data indicating a change

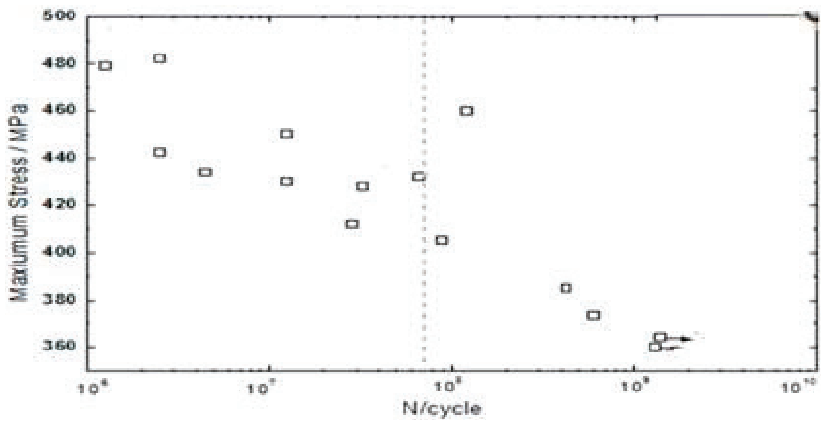


Figure 3 Fatigue Curve of Composite Specimens built with Using Ultrasonic Testing [7 wei].

(degradation) in the properties of materials during operational loading, in which overloads are inevitably present. In [9], along with the well-known "secondary" fatigue curve, also called the Gassner curve [1], the concept of a calculated-experimental modified fatigue curve is introduced. Its equation is constructed on the basis of experimental data when testing at least two levels of irregular (i.e., block or random) loading of samples. It is also possible to judge the course of this curve from the results of service tests.

At the stage of fatigue crack initiation, there is a high risk of overshooting the threshold stress (here it is called unlimited fatigue limit). Perhaps this concept is just a convenient abstraction. It is a generally accepted fact that there is no unlimited endurance limit for non-ferrous and aluminum alloys. Research in the field of gigacycle fatigue, carried out intensively at the very beginning of the current millennium, has shed some light on this issue [6]. In ancient times, academician Sørensen hypothesized a gradual decrease in the endurance limit [10]. At the same time, there is a very fuzzy line between the secondary fatigue curve (Gassner curve) and the fatigue curve with overloads.

Concerning remark number 2. Observations of failures in service, as well as crack growth under service loading, are often very informative from the point of view of testing scientific hypotheses. For example, in the practice of observing the propagation of cracks in the elements of hydraulic turbines [11], the development of cracks was noticed at stress amplitudes below the assumed threshold level. One of the possible reasons is the influence of extremely rare significant overloads during starts (10–20 starts per year) at a frequency of operating amplitudes of 50–100 Hz. To assess the damaging effect of small amplitudes under overload conditions, it is advisable to carry out tests with a previously germinated crack in accordance with the operational (two-frequency in this case) loading unit.

According to experts, the accuracy of assessing durability depends on 70% of the determination of loads. It is very important for researchers to agree on what is more important for fatigue – the distribution (and sequence) of extrema, processed further by the "rainflow" method, or the averaged characteristic of the standard deviation (and its frequency distribution – spectral density). The answer to this question determines the important questions of recording and processing random loading processes, in particular, the method of identifying peaks [12]. The issues of choosing modes for creating a generalized block for calculation require a thorough analysis of the damaging effect of combinations of factors. Some service modes have so little damaging effect that they can be considered idle time – time passes, and the resource is not consumed. At the same time, one cannot ignore the factor of the natural ageing of materials. This phenomenon is typical for composites even more than for metals.

To assess the variability of the estimate, the authors propose to use the method of address Markov matrices in the calculations [13]. To assess the scatter of fatigue life at the stage of fatigue crack propagation, the authors use the method of peak modeling based on targeted Markov matrices, which will allow one to navigate the selection of available assessment models based on a qualitative experiment. For the analysis of methods based on spectral density, a method of modeling a continuous process by a sequence of extrema is required [14].

In Figure 4, we schematically depicted an algorithm that allows simulating a random sequence of peaks for testing on an address Markov matrix.

Selection of the next extremum in a row is performed on a base of target matrix, similar by shape to one shown in Figure 4. The algorithm also employs the random number generator.

2 Method

The author of the article proposes a method that makes it possible to draw conclusions about the behaviour of the fatigue curve based on operational and laboratory tests under irregular loading, as being closer to reality. Such

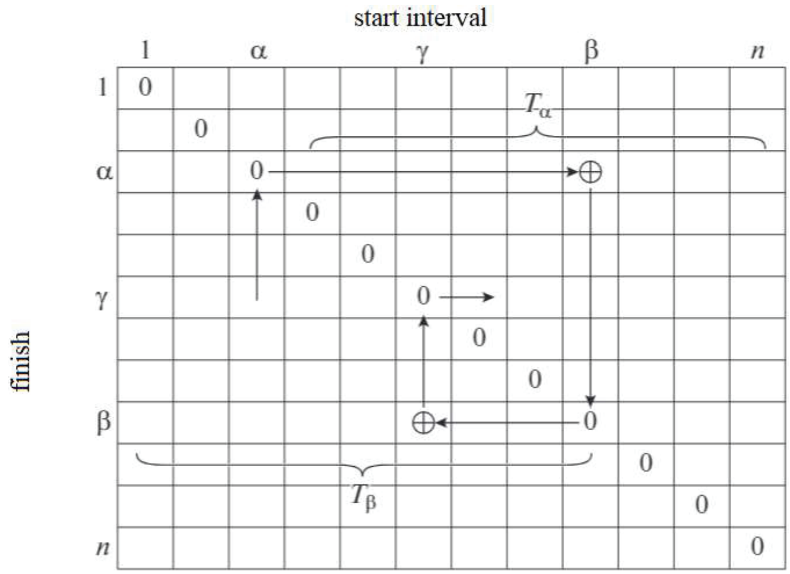


Figure 4 Schematic representation of the random sequence of extremum modelling.

tests, due to the presence of vibrations with small amplitudes in the loading processes, can make it possible to indirectly estimate their contribution, both at the stage of initiation and at the stage of crack propagation. Such research is also important in terms of reducing test time.

In [9] to estimate the parameters of the modified fatigue curve A* and m* in the form $\lg(\mathrm{N}) = \mathrm{A}^* * -\mathrm{m}^* * \lg(\sigma_\mathrm{a})$.

We propose to minimize the error by a least square method:

$$\Psi = \sum_{i=1}^{k} \left[\lg \left(\sum_{j=1}^{w} n_{ij} (\sigma_{ij})^{m*} \right) - A* \right]^2$$

where n_i is the cycles number with amplitude σ_{ai} until fracture.

The error surface for one of performed test series under irregular loading looks like:

Those values (m* = 6.8 and A* = 21.5) providing the minimum of Ψ, will serve as the new constant in Basquin's equation. It guarantees the non-biased longevity estimation by Miner's hypothesis if future experiments.

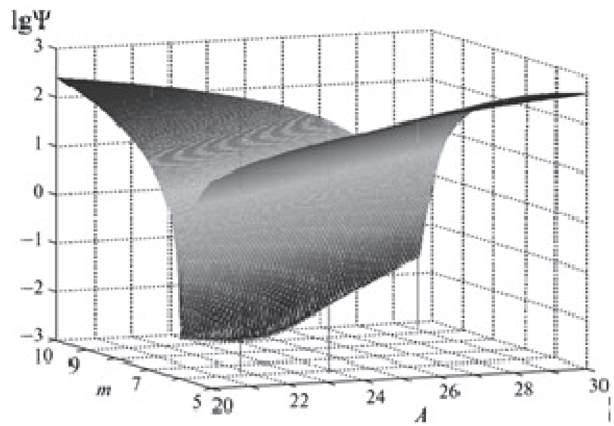


Figure 5 The error surface for the experiments with irregular loading.

3 Conclusions

In this paper we wanted to draw the readers' attention to the possibility and usefulness of investigation the fatigue properties of materials through the irregular loading. It has been shown, that under witty planned experiment you can get the important results concerning the lows of fatigue damage accumulation.

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Biography

Irina Gadolina was born in Moscow in 1954. In 1977 she has been graduated from Moscow Technical University with a major of Mechanic – Investigator. Since when Gadolina has been working for Mechanical Research Institute of Russian Academy of Science (IMASH RAS) and deal mostly with reliability under fatigue impact. Random loading and Machine learning are also in scope of her interests. Gadolina got her PhD in 1990. She published more than 120 papers and chapters in the scientific books. In the nearest future Gadolina plan to perform thoroughly planned fatigue experiment for considering impact of the mutual important factors employing the experimental design methodology.