Selected methods of accelerated durability tests of systems and subsystems of high mobility vehicles

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Abstract. The analysis of selected methods useful in accelerated testing of systems and subsystems of high mobility vehicles has been presented. The paper contains information about a few methods applied in calculating the load signal in time and frequency domains: Constant Amplitude Loading – CAL, Peak Valley Extraction – PVE, Block Load Sequence – BLS, Statistical Exceedance Method – SEM, Increasing Load Frequency – ILF, Multiaxial Peak Valley Extraction – MPVE, Time Correlated Fatigue Analysis – TCFA, Simple PSD Scaling, Shock Response Spectrum – SRS, Extreme Response Spectrum – ERS, Fatigue Damage Spectrum – FDS. Parameters such as pseudo–damage, equivalent loads and equivalent mileage have been presented as well. Those parameters are useful when the influence of road conditions on durability of the vehicle is compared. An initial assessment has been presented on the example of a tested vehicle of high mobility. The high mobility wheeled vehicle was tested in various on- and off-road conditions at the proving ground test center. After tests the signal of load acting on a chosen element of the vehicle frame was inspected, corrected and analyzed. The goal of testing was to find the method to calculate the remaining useful life of the main part of the vehicle. The results obtained have proved the validity of the adopted accelerated testing procedure for this type of vehicles.

1. Introduction
The production of complex physical objects is always burdened with a very large number of different areas of uncertainty, which should be identified as early as possible at the design stage and their significance should be minimized to an acceptable level [1, 2]. At the same time, it should be noted that the total elimination of risk is impossible. Therefore, the very design and construction process leading to the construction of the intended object cannot be accidental, but the one that ensures a sufficiently high quality of the product. In the case of technical systems of particular importance for the state security system or of great significance for society, the design and construction process may follow the assumptions described in [3]. As for the production of vehicles intended for operation in the Armed Forces, they are expected to have, among others, very high durability limited most often by fatigue strength and resistance to the effects of long-term storage. Frequently, the reason behind the difficulty in adopting appropriate assumptions for designing is the lack of parametric data provided by the future recipient, which means that such data must be estimated by the manufacturer at the
beginning of the design and construction process based independently on the lessons learned from standardization deliverables, e.g. [4, 5]. The absence of precise data necessary for design purposes causes that individual components and assemblies must be often designed taking into account the aforementioned risks, which may lead to their oversizing or underestimation. In the design and construction process, complex tests of virtual models [6-8] are performed at the individual product development stages, which allows for the elimination of gross errors, and, after their removal, the stand tests of the component prototypes are carried out. The problem related to the lack of reliable operational data and the difficulties with the selection of appropriate tests are depicted in Figure 1.

![Figure 1. Correlation between the probability of failure and the values of loads.](image)

It shows that in the case of selecting tests that are too restrictive in relation to the anticipated service loads, the oversizing of the component occurs, eventually the weight and dimensions increase and the product utilization efficiency deteriorates. A positive effect of this situation may be the fact that the constructed technical system tolerates loads changing in a wide range, which may result from, for example, the low quality of training of users or their large number (many people use the same technical object). One of the conclusions that arise after the analysis of the data presented in figure 1 is the observation that it is necessary to know the actual loads already at the initial stage of the design and construction process to properly design and construct components and assemblies, and an appropriate accelerated method for estimating the durability of this component or a team able to verify quickly the correctness of the assumptions made must be selected.

2. Characteristics of methods for accelerated estimation of the component (assembly) durability limited by fatigue strength

Indication of an adequate method effective in quick estimation of durability requires conducting an analysis regarding the nature of service loads to which the component is subject and the type of data sought. One of the methods of choosing the method is to determine whether the component is subjected to static or dynamic loads. Another approach points to the analysis of time or frequency data. There is also one more approach that assumes that the load is uniaxial or multi-axis. Figure 2 shows an illustrative scheme of the general characteristics of the performed durability tests.
2.1 Methods determined for fatigue life tests

The following methods can be considered for durability, determination and static tests [4, 5, 9-14].

I. Methods for analyzing uniaxial loads:

a) the method using Constant Amplitude Loading (CAL), which assumes that the load is sinusoidal with a fixed amplitude, and the load frequency does not exceed 30-50% of the range until the resonance phenomenon appears. The hypothesis of linear accumulation of failures is used to estimate fatigue life. The equivalent sinusoidal load $S_{\text{sin}}$ for each determined load range is obtained from the relation:

$$ S_{\text{sin}} = \left( Z_G \cdot AD \cdot \frac{RD}{TD} \right)^{\frac{1}{b}} $$

where: $Z_G$ – the point corresponding to permanent fatigue strength, $b$ – the exponent of fatigue strength in the high-cycle range, $AD$ – accumulated damage calculated for the test purposes, $RD$ – the assumed time of the sub-assembly life (real time duration), $TD$ – the test duration. The accuracy of this method largely depends on the adopted hypothesis of damage accumulation and on the representativeness of input loads. Therefore, it is important for component testing to use the load courses previously registered on other comparable objects in adequate operating conditions. The best effects of this method are observed in its application to sub-assemblies with an uncomplicated construction.

b) the method of reducing measurement data to peaks and valleys (Peak Val ley Extraction - PVE), in which a simple reduction of the amount of data used to record the load course is carried out in such a way that leaves the data that correspond to maximum values (peaks) and minimal (valleys). In the consequence of the applied method, the data which result from the sampling of the load signal are removed and do not indicate the maximum or minimum values, which causes a decrease in the number of data by approximately 90% [12]. Further data reduction can be achieved by determining the value which is relevant to the subsequent analysis of the signal by removing cycles with an amplitude not affecting material fatigue (load amplitude with a range corresponding to 10-20% of the maximum amplitude [13]).

c) the method of grouping the load with a fixed value (Block Load Sequence - BLS) is a development of the PVE method and consists in grouping selected fragments of a signal from the load course with a similar value and combining them into measuring blocks. This method does not take into account the sequentiality of the load recorded in the original measurement signal. The combined measuring blocks include:

- cycles with maximum and minimum amplitudes, and their number,
- the range of cycles, their average values and the number of cycles,
- the range of cycles and the coefficient of cycles (the quantitative relation of cycles with the maximum amplitude to the minimum one) and the number of cycles,
- the amplitude and the number of cycles.
This method only takes account of the amplitude of the load, but it does not consider, for example, the phenomenon of accelerated development of the fatigue crack following directly the occurrence of the temporary elementary overload (crack retardation), which is a limitation of the damage accumulation linear hypothesis.

d) statistical distribution of load cycles (Statistical Exceedance Method - SEM) where the result is counted by load cycles, most often according to the level crossing algorithm, consisting in determining the number of exceedances of the determined value. Eventually, a histogram is obtained showing the load range as a function of the number of cycles, and the fatigue life of the component is estimated based on it.

e) the Increasing Load Frequency (ILF) method allows to speed up durability tests by increasing the load frequency, which, however, cannot exceed approximately 30-50% of the lowest natural frequency of the subassembly, so as not to cause dynamic (resonant) phenomena. This limits the application of the method to physical tests only, excluding virtual tests, and forces the analysis to determine the ranges of the occurrence of the lowest resonance frequencies [15, 16].

II. Methods for analyzing multi-axis loads:

a) the method of multi-axis reduction of measurement data to peaks and valleys (Multiaxial Peak Valley Extraction - MPVE) is a development of the PVE method [12]. It consists in taking into account parallel values of load in relation to the value of the measurement time, if at least one load value in any analyzed direction reaches the extreme value.

The time-correlated fatigue analysis (TCFA) method [11, 12] can be included among durability, determination and dynamic tests. It consists in counting load cycles in time windows, and in estimating fatigue life in these windows according to the adopted hypothesis. If the fatigue is negligibly small or does not occur in a given window (similarly as in the PVE method), the corresponding time interval is not taken for further analysis. The remaining windows are connected to each other so that the load signal values at the end of one and the beginning of the next window are comparable and do not generate artificial load amplitudes. This method also applies to multi-axis loads. The characteristics of the above determined methods used in the durability analyzes are presented in table 1.

| Method name | Considered loads parameters |
|-------------|-----------------------------|
| CAL         | Yes                         |
| PVE (MPVE)  | No                          |
| BLS         | No                          |
| SEM         | No                          |
| ILF         | Yes                         |
| TCFA        | Yes                         |

Table 1. Characteristics of determinate methods.

2.2. Random methods for fatigue life tests

Static one-axial methods for random estimation of durability include [5, 11, 12]:

a) the method for simple scaling of the power spectral density function of the load (Simple PSD Scaling), which consists in measuring loads at selected points of the component (assembly) as a response to the characteristic event loads. The obtained time courses are subjected to the Fourier transform in order to obtain the power spectral density (PSD) functions. One function that corresponds to the highest loads is selected from among the designated PSD functions, after that, the envelope is determined for it, which is then multiplied by the scale factor $w_s$ obtained, e.g. from the relation [12]:

$$ w_s = \frac{w_{max}}{w_{mean}} $$
where: \( b \) – the exponent of fatigue strength in the high-cycle range, \( RD \) – the assumed service time of the sub-assembly (real duration), \( TD \) – the test duration. The scaled characteristic used in further durability testing is obtained as a result of the multiplication.

Dynamic, stochastic methods of durability analysis may include methods based on a random function of power spectral density, which illustrates the distribution of load as a function of frequency [11, 12, 17-20].

b) the Shock Response Spectrum (SRS) method is determined from the pulse power spectral density function of the response to the impulse load. It was noticed that the mechanical system with many degrees of freedom in the range of resonance frequencies behaves as a system with one degree of freedom [11, 21-23]. The amplitude of the acceleration occurring at such a frequency of vibrations is approximately 10 times greater than at frequencies of non-resonating oscillations (the dynamic gain factor \( Q = 10 \)), assuming that the structural attenuation coefficient \( \xi \) is approximately 5%. Knowing the transition function describing the analyzed component (assembly) the system response expressed in displacement units can determined, which constitutes the input data for the stability analysis [11, 12, 14]. However, this method is characterized by low durability results, and is limited to the analysis of individual impulse loads (impacts) [24]. Miles proposed the method for determining the response acceleration values, taking into account resonance vibrations [25]. He presented the relation on the function of the power spectral density of the system's response in the form of the effective value of acceleration to a random load in the form of:

\[
PSD_{\text{sys}}(\omega_r) = \frac{\pi}{2} \omega_r Q \cdot PSD_z(\omega_r)
\]

where: \( \omega_r \) – the frequency of resonant vibrations, \( Q \) – the dynamic gain coefficient, \( PSD_z(\omega_r) \) – the power spectral density of the load signal in the form of acceleration for the resonant frequency. Assuming that the answer is a stationary random process with a normal distribution, it is possible to determine with 99.97% probability the highest amplitude of the response in the resonant frequency range by multiplying the resulting distribution by the value of 3 standard deviations [11, 12]. However, if the response is narrowband, which is typical for a system with one degree of freedom, it does not have a normal distribution. It is proposed then to apply the Rayleigh distribution [24].

c) the method for analyzing the highest amplitude of the response to the impulse load (Extreme Response Spectrum - ERS). The relation for determining the largest amplitude of the response of a system with one degree of freedom subjected to a random load in the form of the power spectral density of acceleration lasting for the period of time \( T \) is described by the equation [24]:

\[
ERS_{\text{sys}}(\omega_r) = \sqrt{\pi \cdot \omega_r \cdot Q \cdot PSD_z(\omega_r) \cdot \ln(\omega_r \cdot T)}
\]

d) the method for estimating durability based on the spectral density function of the acceleration (Fatigue Damage Spectrum - FDS) allows for determining the equivalent distribution of fatigue directly on the basis of the function of spectral power density of the load in the form of acceleration [24] based on the relation:

\[
FDS(\omega_r) = \omega_r \cdot T \cdot \frac{K^b}{Z_G^{m+2}} \left[ \frac{QPSD_z(\omega_r)}{2(2\pi \cdot \omega_r)^2} \right]^b \cdot \Gamma \left( 1 + \frac{b}{2} \right)
\]

where: \( K \) – the proportionality factor \( K = \frac{N}{S_m} \), \( m = \frac{-1}{b} \), \( b \) – the exponent of fatigue strength in the high-cycle range, \( Z_G \) – the point corresponding to permanent fatigue strength of the analyzed
subassembly material, $T$ – the load time period, $\Gamma$ – the gamma function. In a practical application, it is a great difficulty to collect a large number of input data characterizing the object being analyzed. Their determination is time-consuming; hence the method is applied to objects with a simple structure [24].

3. Pseudo-wear indicators

The methods presented above allow for relatively quick estimation of the durability of a component or an assembly, which is limited by fatigue strength. In fact, data sets containing hundreds of files in which data from several dozens or even several hundred measurement channels are stored are used to analyze the durability of a complex technical system. For a 4-wheel drive vehicle, a simple measuring system consisting of 8-12 acceleration sensors installed on and on the vehicle frame, several accelerometers installed on the cab, several on the load box and often several tensometers at selected measuring points is applied. This causes that such a measuring system consists of about 35-50 measuring paths, sending data for the analysis. Therefore, for practical reasons, a method for preliminary estimation of load effects for the entire technical system is useful, giving the result in a numerical form that is easy to use for comparative purposes and describing the impact of, for example, utilization or exploitation profile on the durability of a technical facility. Calculation of the so-called pseudo – wear is such a method. It is a combination of the Wöhler curve, the Palmgren-Miner damage accumulation hypothesis and the Rainflow load cycle counting. For the Wöhler curve, the Basquin equation is applicable:

$$N = \alpha \cdot S^{-\beta}$$

where: wear due to the loading cycle with the amplitude $S_i$ is $\frac{1}{N_i}$. The damage accumulation hypothesis can be presented in the following form:

$$D = \sum_{i=1}^{n} \frac{1}{N_i} = \frac{1}{\alpha} \sum_{i=1}^{n} S_i^{\beta}$$

In order to make the pseudo-wear parameter being determined partially independent on the constants characterizing the material, we can define them as:

$$d = \sum_{i=1}^{n} S_i^{\beta}$$

Fatigue wear is calculated from the relation:

$$D = \frac{d}{\alpha}$$

In the designated parameter $d_i$, $i = 1, \ldots, m$ corresponds to the individual measurement, and $j = 1, \ldots, n$ corresponds to the individual measuring path in the measurement. The values of the parameter $\beta$ are presented in table 2 on the basis of data contained in the literature, e.g. [26].

**Table 2. Values of the parameter $\beta$.**

| Parameter            | Welded joints (welds) | Steel elements (harsh surface) | Steel elements (smoothed area) |
|----------------------|-----------------------|--------------------------------|--------------------------------|
| Value $\beta$        | 3                     | 5                              | 7                              |

If the length of individual measurements is different, standardization $\tilde{d}$ can be carried out and then a normalized pseudo-wear parameter $\tilde{d}$ can be obtained. The value of the amplitude of the equivalent load is determined by virtue of the form of the result of setting the parameter $\tilde{d}$ value, which can be expressed in MPa units, however it is difficult to interpret from the engineering level. Such presentation of the estimation result provides a practical tool for evaluating, for example, the impact of the driver's driving style on the degree of vehicle wear, the impact of traffic conditions or the type of
road surface. The determined parameter of the equivalent constant-amplitude load is characterized by the constant amplitude of the load $A_e$ and the number of load cycles $N_0$. The equivalent wear coefficient takes the form:

$$D_e = N_0 \cdot \frac{1}{\alpha} A_e^\beta$$  \hspace{1cm} (10)

If it is additionally assumed that the target durability of the component or the entire vehicle is to be $D_{total}$, the following relation is obtained:

$$D_{total} = K \cdot \frac{1}{\alpha} d$$  \hspace{1cm} (11)

where: $K$ is the extrapolation factor determined by dividing the assumed target course by the length of the measurement section length. Assuming the equality of the parameters $D_e = D_{total}$, the relation is obtained as follows:

$$A_e = \left( \frac{Kd}{N_0} \right)^{\frac{1}{\beta}}$$  \hspace{1cm} (12)

The acceptance of the parameter value $N_0$ depends on the assumed component durability and may correspond to e.g. high-cycle fatigue strength ($N_0 = 10^5 - 10^7$) or, for example, low-cycle one ($N_0 = 10^2 - 10^4$). The obtained value $A_e$ can be referred to the value of the load recorded during the tests.

If the purpose of testing a component or a vehicle is to specify its durability limited by the influence of various operating conditions, the coefficient of the equivalent course $M_e$ may be determined:

$$M_e = \frac{d}{\tilde{d}_{ref}}$$  \hspace{1cm} (13)

where: $\tilde{d}_{ref}$ means the benchmark for the pseudo - wear of the component or the vehicle designated for the reference road section. The set value of the reference factor $M_e$ indicates whether the considered load conditions cause more or less wear compared to the reference conditions.

4. The selected test

The special high mobility wheeled vehicle was subject to road tests on the $8 \times 250$ m long road section. During the tests, load cycles were recorded for three different drivers to determine the initial spread of load values caused by different driving techniques. Examples of load courses are shown in figure 3. The values of the coefficient $d$ [MPa$^5$] were set when assuming $\beta = 5$, as shown in table 3.

| Driver number | 1 (5 1 1)     | 2 (5 2 1)     | 3 (5 3 1)     |
|---------------|---------------|---------------|---------------|
| Value $d$ [MPa$^5$] | 2.06E+11 | 2.21E+11 | 2.14E+11 |
| Ride time [s] | 91           | 82           | 84           |

It was assumed that the target total vehicle kilometers should be $P = 320 \cdot 10^3$ [km]. Hence the extrapolation rate is $K = \frac{320000}{2} = 160000$. Given the number of fatigue cycles $N_0 = 10^6$, the parameter $A_e$ was obtained (table 4):
Figure 3. Courses of loads during the test.

\[ A_e = \left( \frac{K \cdot d}{N_0} \right)^{\frac{1}{\beta}} \]  

(14)

Table 4. The value of equivalent amplitude \( A_e \).

| Driver number | 1 (5_1_1) | 2 (5_2_1) | 3 (5_3_1) |
|---------------|-----------|-----------|-----------|
| Value \( A_e \) [MPa] | 127       | 129       | 128       |

It can be read from the vehicle run enclosed to figure 3 that the largest amplitude of the load was about 165 [MPa].

In order to check the impact of driving style on the durability of vehicles, \( M_e \) values were determined by comparing drivers No. 2 and No. 3 to driver No. 1.

\[ M_e = \frac{d}{d_{ref}} \]  

(15)

The calculations prove that on the test section driver No. 2 will reduce the total vehicle kilometers by about 7% and driver No. 3 by about 4% compared to driver No. 1.

5. Conclusion

The above presented characteristics of selected methods of accelerated estimation of durability of assemblies and subassemblies may apply to high mobility vehicles. The two given indexes: pseudo-wear and equivalent load amplitude can be effectively used to pre-assess the durability of the selected component and to evaluate the impact of selected traffic conditions on the component durability limited by fatigue strength. This enables the estimation of the impact of operating conditions on an object compared to the conditions considered as reference.
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