From Fatigue Behaviour of Materials to Fatigue Life of Machine Elements or Structures

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Abstract: Fatigue failure remains a major concern in the design and performance evaluation of machine components and structures as it accounts for a significant proportion of mechanical failures. This article presents a fatigue evaluation methodology based on SN (stress-cycles to failure) curves to understand and predict the fatigue behavior of components under various loading conditions with widely varying device geometry and dynamics. In order to accurately interpret and utilize the SN curves, the paper outlines key factors influencing material fatigue, including stress amplitude, mean stress, stress concentration, environmental effects, and surface finish. The integration of these factors into the SN curve-based assessment is discussed to tailor fatigue evaluations to specific machine components and structures. To demonstrate the practical application of SN curves in fatigue assessment two case studies of machine components and structures are presented. The paper ends with a summary and conclusions, the most important of which is that the greatest impact on the design fatigue life has accurately estimated stresses resulting from the load conditions and the dynamics of the structure.

Keywords: Fatigue assessment; Machine components; Structural fatigue; SN curves

1 Introduction

Fatigue analysis is an integral part of the design of machine elements and structures subjected to variable load. It is carried out at the design stage and during the improvement of the structure with the use of basic fatigue information of materials. These are mainly fatigue stress or strain characteristics, so called fatigue curves, that are performed in the laboratory under simple loading conditions such as axial push-pull or reverse torsion [1–4]. In order to use information about materials to predict fatigue life, an algorithm should be developed that takes into account all aspects affecting the fatigue life of machine and structure components. Typically, the following elements are considered [5–8]:

Load Analysis: The algorithm should incorporate an analysis of the applied loads, including both static and dynamic loads. This involves understanding the magnitude, frequency, and distribution of the loads that the machine elements or structures will experience during their service life.

Stress and Strain Analysis: The algorithm should account for the stresses and strains generated in the machine elements or structures due to the applied loads. This involves performing stress analysis and calculating the stress and strain amplitudes at critical locations. It is crucial to account for the response of the material to variable loads by employing suitable hypotheses for the accumulation of fatigue damage such as Miner's rule or other more advanced models based on the specific application. Additionally, the algorithm should address the multiaxial nature of the stress state.

Material Properties: It is crucial to consider the material properties, such as yield strength, ultimate tensile strength, fatigue strength limit and finite fatigue strength. These properties

determine the response of the material to cyclic loading and are essential for accurate fatigue life prediction. This data is typically represented by an S-N curve, which relates stress amplitudes to the number of cycles to failure.

Environmental Factors: The algorithm should account for environmental factors that can affect fatigue life, such as temperature, corrosive conditions and exposure to other potentially damaging agents.

Scale and Stress Concentration Effects: If the machine elements or structures contain notches, fillets, or other stress concentration features, the algorithm should incorporate methods to assess their impact on fatigue life. This may involve applying appropriate stress concentration factors and combine them with finite element analysis (FEA) to model local stress concentrations. The scale effect should be considered if the volume of material subjected to fatigue stresses is not comparable with laboratory samples.

Validation and Calibration: It is important to validate and calibrate the algorithm against experimental data or real-life case studies to ensure its accuracy and reliability. This may involve performing fatigue tests on representative samples or comparing the algorithm's predictions with known fatigue failures.

Bearing in mind the above factors affecting fatigue life, new and more accurate algorithms for determining fatigue life are being developed. These algorithms are built to take into account all factors, creating a universal way of solving the problem. Nevertheless, each case is different and even the most universal algorithm needs to be adapted to the current case. The reason for using the algorithm for current needs is primarily the speed of calculations and their accuracy. A decision should be made regarding:

- durability estimation methods i.e. the stress or strain approach,
- domain in which the calculations will be performed, i.e. in time or frequency,
- whether adjustments to the impact of notches on fatigue life will be necessary,
- whether "pure material" fatigue or fatigue of joints, such as welds or bolted components, determine durability,
- whether the influence of external factors such as temperature change or corrosive environment should be taken into account,
- from where they will be taken or by what method stresses or strains will be determined.

In order to present the complexity of this issue, two cases of determining the fatigue life of structures are presented below, which differ significantly from each other and the basis for their determination are classic stress fatigue characteristics, i.e. SN curves for basic material.

2 Case studies

Two case studies are presented. The first concerns the compressor mounting bracket in passenger cars and the second concerns the device for transporting motorcycles. In both cases, the SN curve is known, however, the degree of complexity of the shape of the element and load conditions complicate the process of determining the fatigue life and requires a different computational path. Therefore, appropriate algorithms for fatigue assessment were constructed for both cases and presented in subsections 2.1 and 2.2.

2.1 Fatigue assessment of the compressor mounting bracket

2.1.1 Background

This case involves suspension system with nonlinear dynamic behaviour caused by collisions among suspension subcomponents during operational loading and vibration tests. The structure consists of a vibrating mass, functioning as a compressor for car air suspension system, which is securely attached to compressor brackets. To isolate vibrations, the structure is suspended on vibration isolators that include springs, rubber, and a lower bumper. Additionally, the entire assembly is fastened to a rigid frame that serves as the upper bumper for the rubber (Fig. 1).

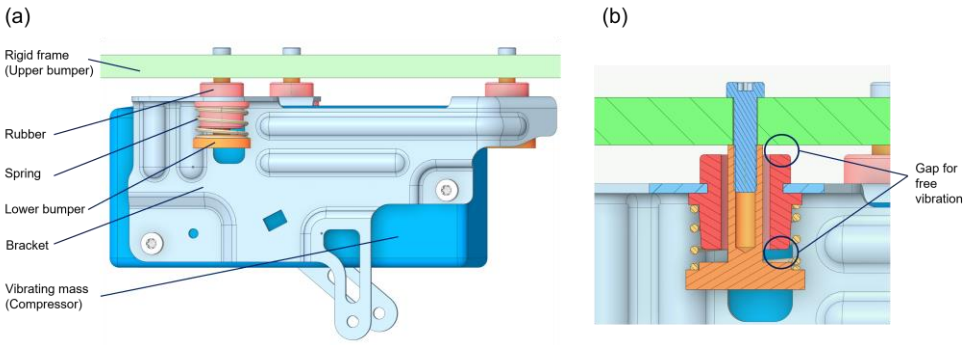

Fig. 1 (a) Simplified scheme of suspension system of compressor. (b) Vibration isolator cross section.

During working conditions, the structure operates close or at its natural frequency which leads to the rubber-bumpers collisions even under low level excitation. Collisions are realized double-sided, occurring both between the rubber and the upper bumper, and between the rubber and the lower bumper. As a consequence, the fatigue life of the compressor brackets is significantly affected.

Effective methods for vibration fatigue calculations called spectral methods are performed in frequency domain [9,10]. Frequency response analysis in Finite Element Method (e.g. Nastran SOL 111 or ANSYS Harmonic Response) are used as an input for the spectral methods. Obviously, this are linear solvers which do not consider structure nonlinearities like collisions in the described system and cannot be used directly for stress history prediction. To overcome this limitation, an adaptation was needed to make the linear response of the structure compatible with the real nonlinear dynamic caused by collisions.

2.1.2 Proposed solution

Due to the occurrence of collisions the main problem in the algorithm for determining the fatigue life is the correct determination of stresses in the points of interest. In order to use efficient linear FEM solvers for stress calculations the method is proposed where, vibration test was conducted to obtain dynamic response of the structure under collisions conditions. The idea is to modify in FEM simulation the excitation input to obtain response of vibrating mass which will be in line with registered in the test. The modified PSD input for FEM simulation can be obtained from Eq. (1), where PSD_{otput_test} is power spectral density based on accelerations recorded in the test, and $S(f)$ is the transfer function of the system.

$$PSD_{input_modified} = \frac{PSD_{output_test}}{S(f)^2} \quad (1)$$

The system was excited on electrodynamic shaker in vertical direction using PSD profile with RMS acceleration of 1g (see Table 1). Fig. 2 displays the graphical representation of the PSD input. The shape and test frequency range of the defined PSD input is based on automotive standards like DIN EN 60068-2-64 "Environmental testing; Part 2-64: Tests; Test Fh: Vibration, broadband random and guidance" or DIN EN 60068-2-47 "Environmental testing; Part 2-47:Tests; Mounting of specimens for vibration, impact and similar dynamic tests".

Table 1. Vibration test profile used in the test.

Point	Frequency [Hz]	PSD [g^2/Hz]
1	5	0.0250
2	10	0.0300
3	20	0.0300
4	200	0.0004
RMS acceleration	1.02g	

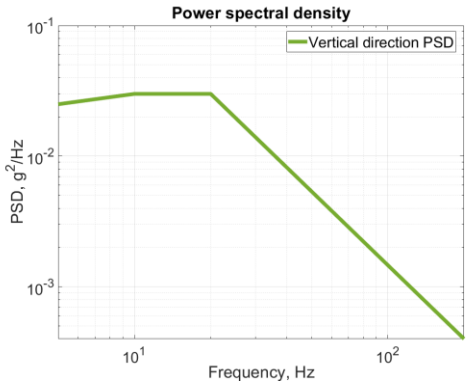

Fig. 2 Vibration test profile according to Table 1.

Two acceleration sensors were installed on the test rig. The 1st one close to shaker table to control the input PSD signal, and the 2nd sensor is mounted on the vibrating mass (compressor) to control the system PSD response required for further FEM simulation (Fig. 3). The structure was excited for 100 s using sampling rate 1 600 Hz.

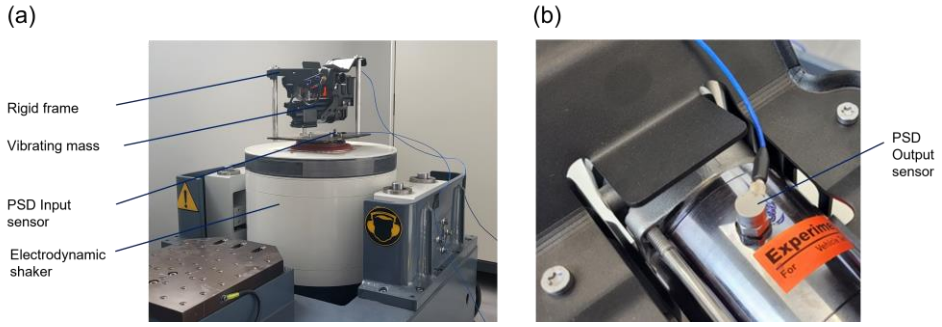

Fig. 3 (a) Test rig for compressor dynamic response measurement. (b) Response measurement point (compressor).

2.1.3 Results for loading PSD

The test aimed to measure the dynamic response of the vibrating mass (compressor) in the suspension system, following vibration test profile presented in Table 1. Registered results are presented in Fig. 4. To obtain the PSD function, the acceleration time history data on the compressor (Fig. 4a) was subjected to analysis through the Welch method [11], resulting in the presentation of the PSD function in Fig. 4b.

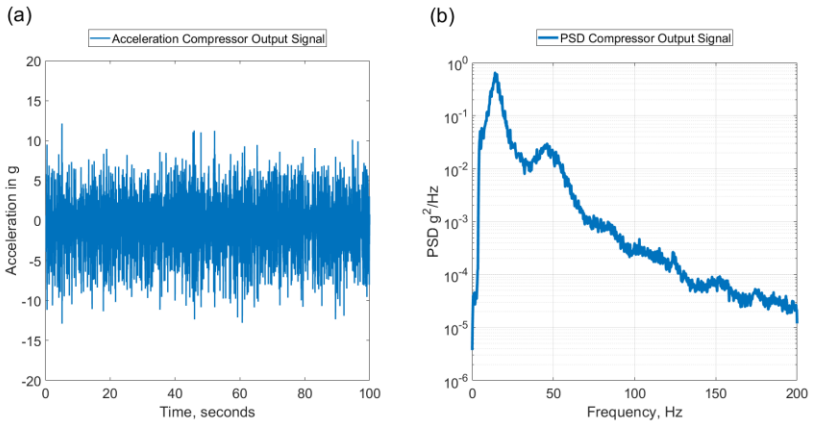

Fig. 4 Response of the compressor in accordance to the input shown in Table 1. (a) Response acceleration in time domain, (b) response in frequency domain.

The acquired results were utilized to adjust the fundamental PSD input for finite element method simulation. In place of the vibration profile detailed in Table 1 and Fig. 2, a modified PSD input was calculated using Eq. (1) and visualized in Fig. 5.

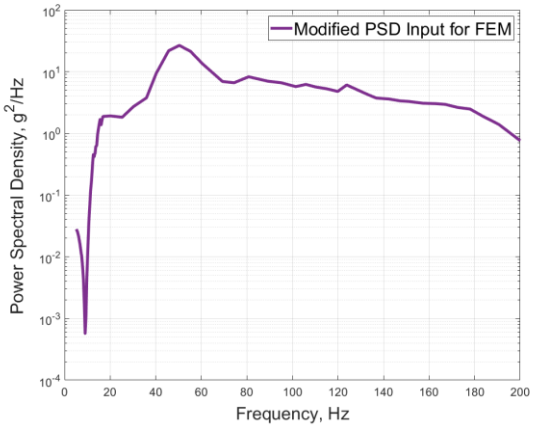

Fig. 5 Modified PSD input signal for FEM simulation.

Fig. 6 shows the difference between RMS stress results on the compressor bracket when collisions are disregarded (Fig. 6(a)) and when they are taken into consideration (Fig. 6(b)).

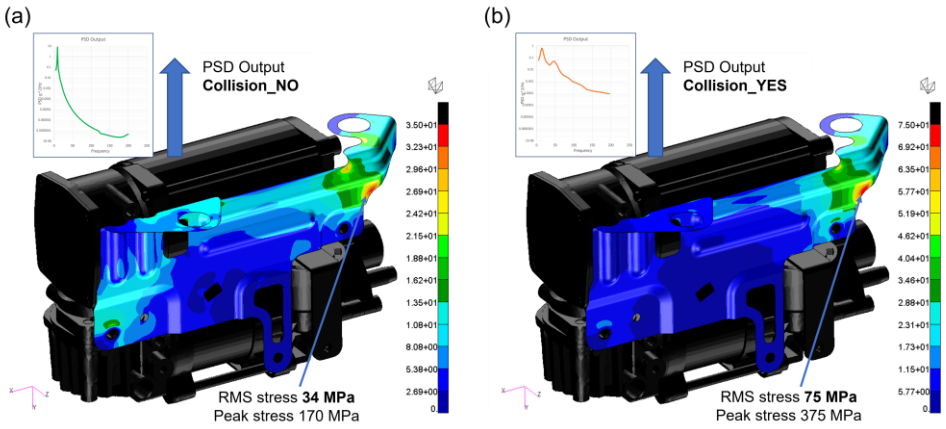

Fig. 6 Von Mises stress results during random vibration test: (a) results when collisions are not included, (b) Results with modified PSD Input – collisions included.

The PSD functions for both the model with collision consideration and the model without collision consideration were extracted from the bracket notch area, where fatigue cracking is anticipated. These functions are presented in Fig. 7.

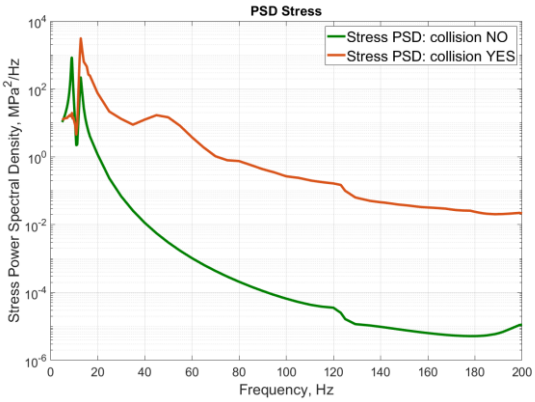

Fig. 7 Von Mises stress results during vibration test: (a) results when collisions are not included, (b) results with modified PSD Input – collisions included.

The bracket material is specified as fine-grained steel suitable for cold-working. S-N curve was derived based on the fatigue limit σ_{af} = 185 MPa and the corresponding number of cycles $N_0 = 10^6$ at which this limit was initially observed. The curve slope, represented by the parameter *k*, is determined to be 5. Following that, fatigue calculations were conducted employing the methodologies proposed by Dirlik and Tovo-Benasciutti [12–14]. The outcomes of these fatigue calculations are presented in Table 2.

Table 2. Bracket vibration fatigue calculation results.

Stress PSD	RMS, MPa	Peak stress, MPa	E[P], 1/s	According Dirlik, days	According Tovo-Benasciutti, days
Without collision	34	170	12.34	467.6	495.4
With collision	75	375	50.38	3.22	3.33

2.2 Fatigue assessment of the motorcycle transport device

The second case study focuses on analysing a transportation system consisting of a motorcycle transport device, an automobile, and a motorcycle. This device is mounted on the car's hitch, as shown in the Fig. 8. During transportation, it is subjected to random vibrations originating from the road surface over which the movement takes place [15]. While the S-N curves (fatigue strength) of the materials used in the device's construction are well-known, the exact loads and excitations acting on this device remain unknown.

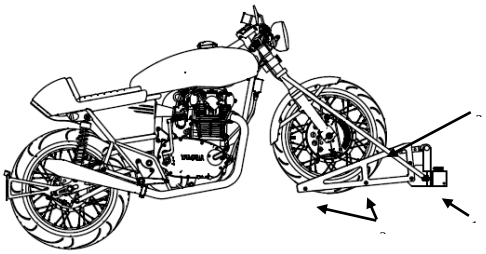

Fig. 8 Transport device according to patent PL 224395 B1; 1. Mounting element (for tow hitch); 2. Wheel base; 3. Stabilizing strap

In the context of the discussed system, which is related to the field of automotive engineering, there is an opportunity to reference the characteristics of excitations – standardized Power Spectral Density (PSD) functions that are commonly used in fatigue calculations within the automotive industry [16]. However, the presented system is exposed to specific excitations resulting from interactions with the suspended mass on the car's hitch. To precisely analyse these excitations, real acceleration measurements were conducted directly on the device at the hitch mounting location (Fig. 9). These measurements were conducted on two distinct road surfaces: asphalt roads and unpaved roads. The device underwent these measurements while being subjected to a full load during the transportation of a motorcycle (Fig. 10)

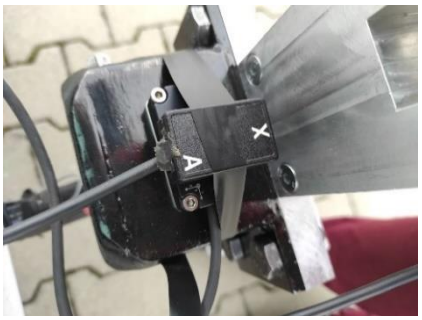

Fig. 9 Measurement point for acceleration in three axes.

Fig. 10 The device with a motorcycle attached.

Based on the measured accelerations, utilizing MATLAB tools, particularly the PWELCH function, the power spectral density function was determined for both the asphalt (Fig. 11) and non-paved road (Fig. 12) routes. The obtained PSD characteristics constitute significant input data for further analysis. To comprehensively assess the impact of these excitations on the device's behaviour, a numerical simulation was employed using the FEM within ANSYS software.

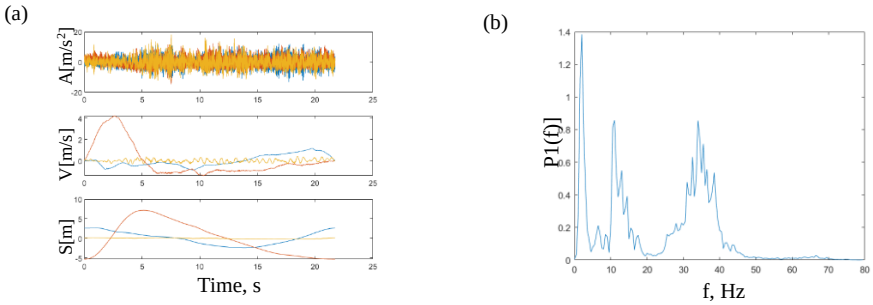

Fig. 11 Asphalt road: (a) raw recorded signal, (b) determined PSD function.

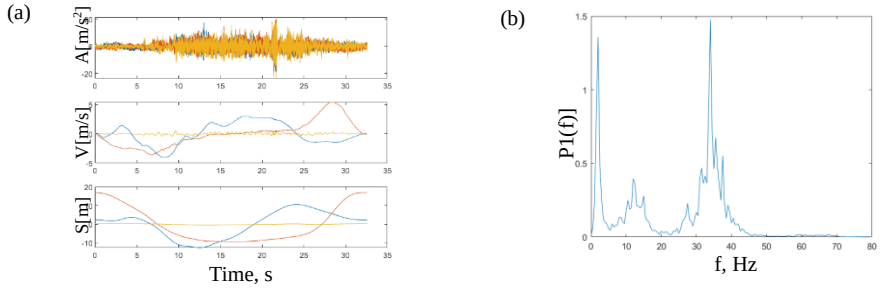

Fig. 12 Unpaved road: (a) raw recorded signal, (b) determined PSD function

The incorporation of PSD excitation characteristics in the computer simulation allowed for the replication of a realistic dynamic environment in which the analysed device operates. Such an approach facilitated a detailed assessment of stresses, deformations, and potential critical areas with regard to material fatigue. Comparing simulation results with previously known S-N curves of materials will enable an evaluation of safety and durability for the designed structure under real operating conditions.

After constructing a simplified computer model of the analysed system, a detailed simulation was initiated using the Ansys software (Fig. 13). As part of the basic strength analysis, a node most susceptible to potential damage was identified. This pivotal node is located within a triangular support where significant loads and stresses are present.

To conduct a more advanced analysis, Ansys Random Vibration tools were employed, enabling the modelling of interactions caused by random vibrations. These simulations were conducted while considering boundary conditions, which were selected in accordance with the research carried out in the publication by Mazurek and Mamala [17]. The device's mounting location was modelled as a fixed support, the rear car wheel as a cylindrical support, and the entire motorcycle system with a mass of 200 kg was appropriately considered. For the purpose of representing real-world conditions, an excitation in the form of PSD was applied to the fixed support point.

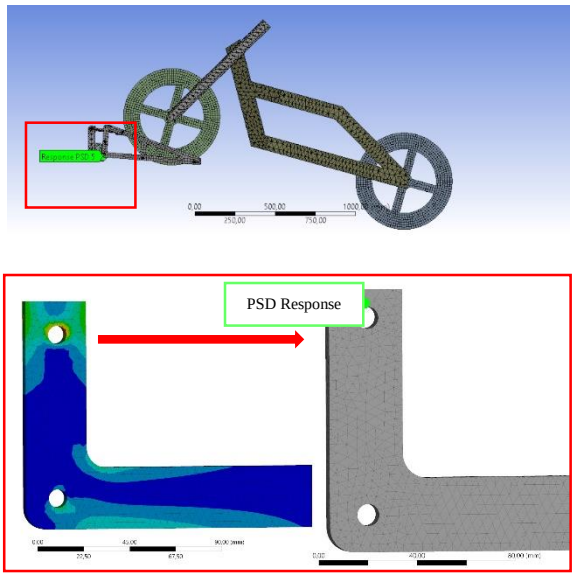

Fig. 13 Determination of the PSD response reading location.

Conclusion and Summary

Fatigue characteristics of materials in the form of SN curves are only the basis for fatigue calculations. Equally important here are all elements of the fatigue life determination algorithm, in particular stress determination and consideration of factors influencing fatigue, such as scale factor, stress concentration effect, average stress, amplitude distribution and sequence, and environmental factors. At the forefront of factors influencing the fatigue life is the correct determination of stresses, on the basis of which the analysis is carried out. In real elements subjected to operating loads, it is difficult to assess the actual state of the load. Therefore, this element is burdened with the greatest uncertainty.

For fatigue calculations in real conditions, the most suitable is the spectral method, which statistically reflects the load. This is a well-known method and is often referred to as vibration fatigue method.

The influence of the notch on the fatigue life is usually expressed by an increase in the stress value. In the spectral method, if the notches are not sharp, their influence is taken into account in the FEM calculation, also by increasing the stress near the notch. Of course, the scale factor for the volume of loaded material should not be neglected.

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