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Železniške naprave - Metoda načrtovanja osi

Railway applications - Axle design method

Bahnanwendungen - Konstruktionsverfahren von Radsatzwellen

Applications ferroviaires - Méthode de conception des essieux

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Railway applications - Axle design method

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Bahnanwendungen - Konstruktionsverfahren von Radsatzwellen

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European foreword

This document (CEN/TR 17469:2020) has been prepared by Technical Committee CEN/TC 256 “Railway applications”, the secretariat of which is held by DIN.

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Introduction

The first railway accident due to the fatigue failure of an axle occurred on 1842, May 8th, in France, near Meudon, on the Versailles-Paris line.

In those days, the fatigue phenomenon was unknown. This failure initiated numerous studies including German Engineer August WOHLER works on wheelset failures at the end of XIX century.

In the middle of XX century, M. KAMMERER, an engineer working for French railways, established the bases for the calculation of wheelset axles.

At international level, the report ORE B136 RP11 « Calculation of fret wagon and passenger coaches' wheelset axles » was edited in April 1979, using in particular the French approach.

This document allowed editing on 1994, July 1st of UIC leaflet 515-3 «Railway rolling stock – Bogie – Running gears – Axle calculation method».

The first edition of the European Standards about design of axles occurs on April 2001 (EN 13103 for non-powered axles for powered axles).

The ongoing European standardization has allowed the merging of EN 13103 in only one standard (EN 13103-1 Railway applications – Wheelsets and bogies – Part 1: Design method for axles with external journals) and the creation of a new Technical Specification about internal journal (CEN/TS 13103-2 Railway applications – Wheelsets and bogies – Part 2: Design method for axles with internal journals).

All these documents, including M. KAMMERER's work up to EN 13103-1 and CEN/TS 13103-2, use the beam theory calculation method. The stresses taken into account are then the nominal stresses. The fatigue limit is determined from full scale tests in which nominal stresses are taken into account. Concentration factors are defined from tests to consider the local geometry and to increase the nominal stress locally. The method is quite simple, with no need of sophisticated calculations or dedicated software.

On another hand, in the middle of XX century, the need in mechanics to have a tool to calculate complicated parts lead to the development of the finite element method.

Along with the theoretical study of this method, the use of new mathematical objects and the growth of calculation capacities of computers, the finite element method raised to a large and common use in design.

The stresses then calculated are local stresses, and not anymore nominal stresses, and the fatigue limit to be applied with this methodology are based on local stresses.

In the Euraxles project, the objective was to propose the use of a new assessment method based on load measurements, finite element method, experimental fatigue limit and new safety concept for the design of axles in particular for axle designs requiring more complex geometries. This design procedure is different from today's proven methods given by the EN standards and not in a status to substitute them. Nevertheless, it was considered interesting to gather the Euraxles project results inside this Technical Report. The content should be considered as partial and only for informative uses at this stage. For example, the reliability of the input data, the variability of parameters, boundary conditions and the confidence in the partial results should be assessed at full extent.

Where relevant, CEN TC256/SC2/WG11 comments and responses to preliminary enquiry inside the community were inserted for additional use for the reader, as Observations of CEN/TC 256/SC 2/WG 11. Besides, a general recommendation of use has been drafted by WG11 members in chapter 9.

This new method is described in this Technical Report in order to allow the possibility for wheelset designers to apply it and to collect return of experience for further improvement.

Work Program summary

Clause 4 deals with the definition of a new fatigue design method which enables to assess the in-service reliability of axles with regards to fatigue failure. The proposed approach, based on the “Stress Strength Interference Analysis” (SSIA) and the “Fatigue-Equivalent-Load” (FEL) methods, aims at estimating the probability of axles’ fatigue failure by characterizing the variability of in-service loads and the scatter of the axles fatigue strength.

First of all, the main lines of the SSIA method are recalled. This method aims at evaluating the in-service reliability of components for their design or their homologation. In the second part, the fatigue load analysis method that is proposed for railway axles is described. It starts with a post-processing of an axle load measurement: from a time signal of forces applied to both wheels fitted on the axle, fatigue cycles of bending moment applied to the axle are identified and transformed into a cyclic equivalent load, Meq, which is a measurement of the severity of the initial variable load. Then, virtual but realistic load spectra are generated, thanks to a classification operation followed by a random draw of elementary load data that considers the operation and maintenance conditions of the axle. All the spectra are then analysed with the FEL method in order to build the distribution of in-service load severities. This distribution gives a picture of the stress to which the axles are submitted. In the third and last part, the methods are applied to real data of SNCF. Sensitivity analyses are performed in order to quantify the effect on Meq of variations of parameters and to verify the convergence and robustness of the process. Finally, results obtained for a passenger coach are given. The comparison between the distribution of load severities and the normative load, defined as according to standards EN 13103-1, shows that, for the studied axle, the normative load is very conservative. Finally, using the axles fatigue limits identified on full-scale tests, a Stress Strength Interference Analysis is performed to calculate the probability of failure of the axle.

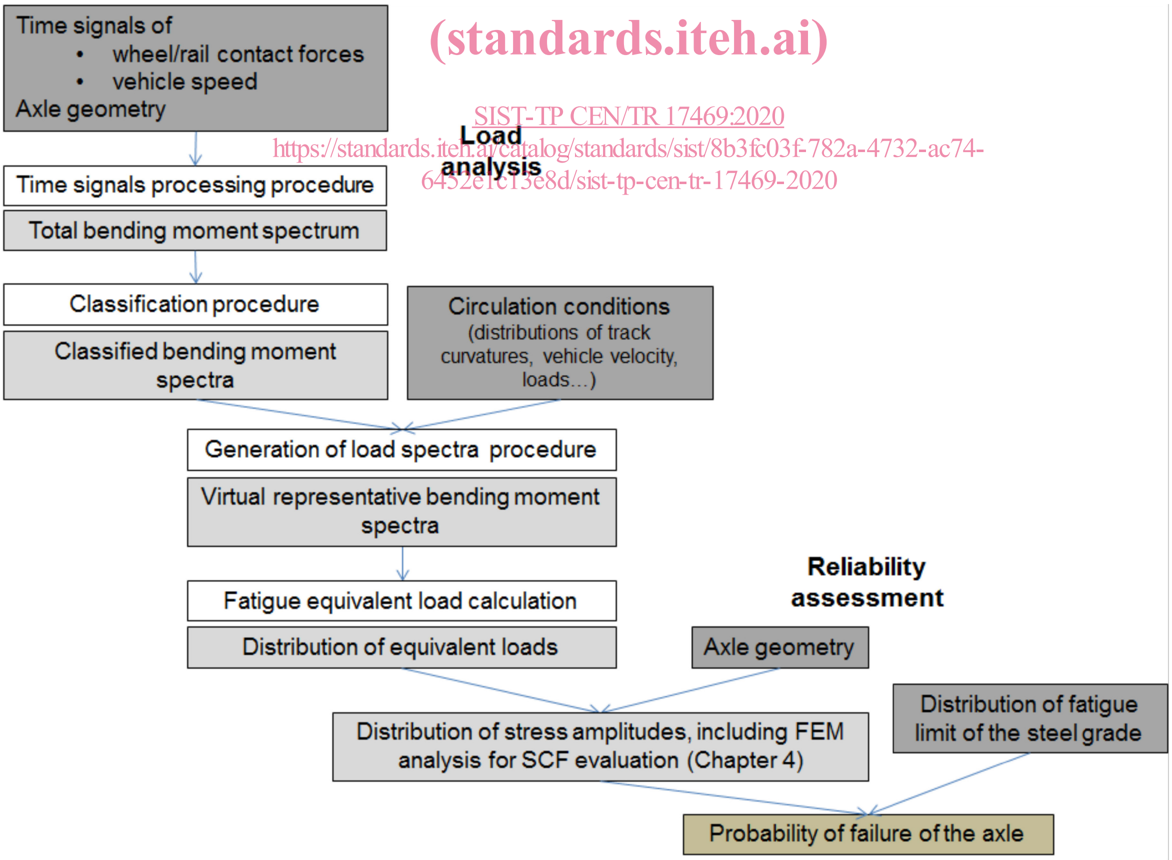


Figure 1 — Flowchart for load analysis and reliability assessment

Clause 5 concerns the mechanical modelling of an axle and defines a procedure to obtain local stresses from the applied loads.

The characteristics of the finite element models to be applied to railway axles are analysed in terms of element definition, convergence analysis, boundary conditions. A parametric analysis was performed to assess the applicability of the models. The numerical models generated were validated through the comparison with experimental results coming from full scale fatigue tests. Finally, a methodology to design axles using modelling tools as a complement to current European norms is proposed looking for a compromise between the computational effort and the results obtained.

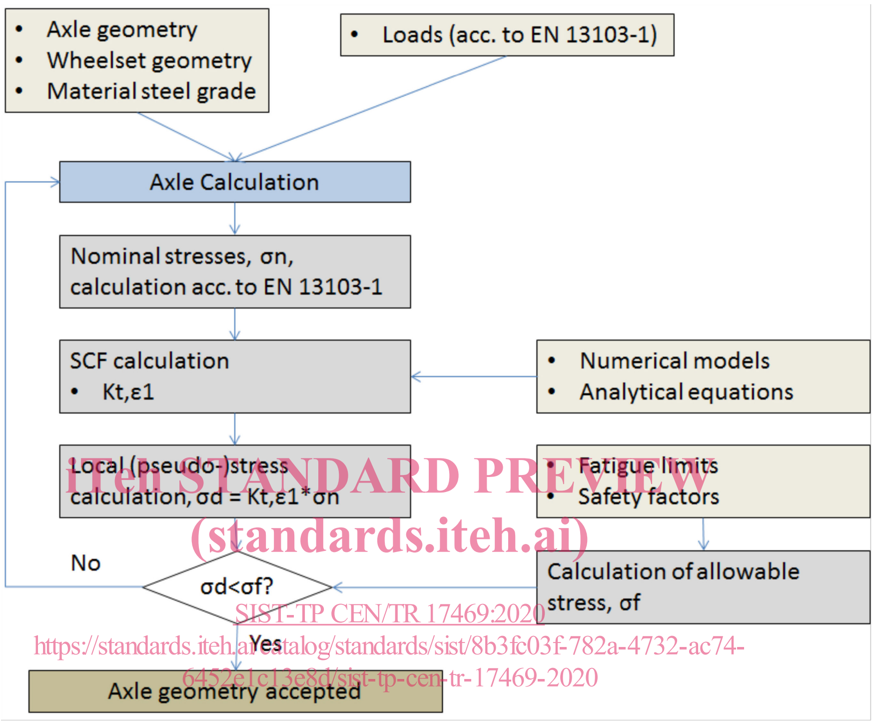


Figure 2 — Flowchart for modelling

The main scope of Clause 6 is to provide the fatigue limits for standard steel grades considering also the effect of surface conditions that may be different from the normal newly machined axles, like surface corrosion that can appear during the service or surface blasting as a method to improve paint adhesion.

The areas of the axles considered were the free body transitions or groves and the wheel seats where at high bending rates relative micro slips take place generating the so called fretting fatigue phenomena.

The paper provides in the conclusions a comparison with the fatigue limits that are today included in the European Standards.

Another aspect that is treated in this work is the stress concentration effect that takes place along the transitions where the body fatigue limit is verified. These parameters were measured by strain gauges during each test and used inside the Euraxle project to validate their estimation through FE model calculation.

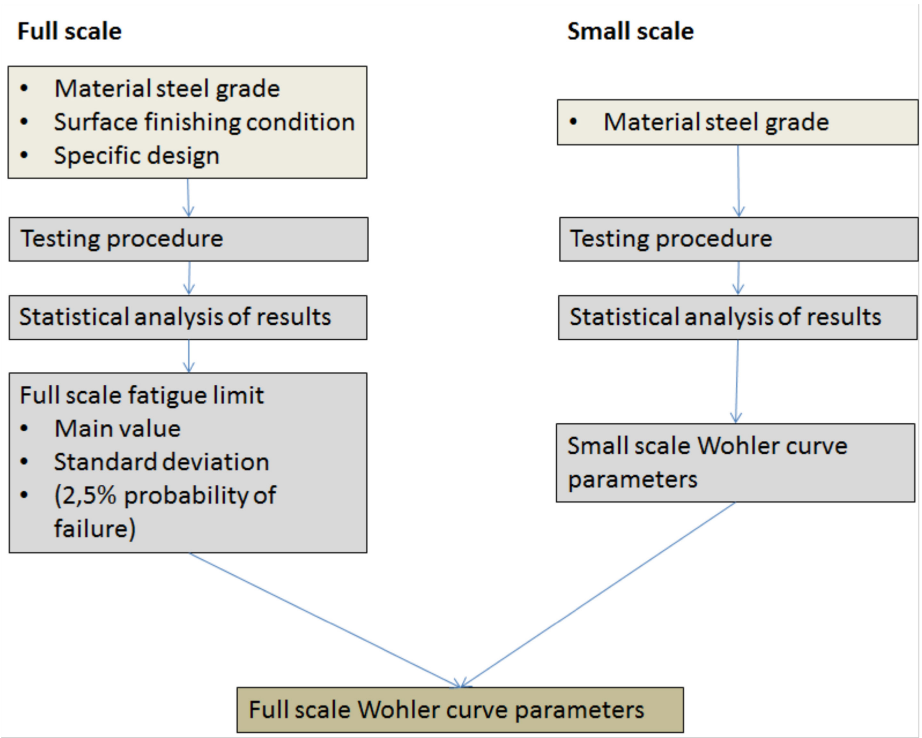


Figure 3 — Full-scale and small-scale fatigue tests

1 Scope

This document presents the stage of knowledge resulting from the Euraxles project about the design of the axle, and further steps to be taken.

It is the support:

- to define the loads to be taken into account;

- to describe the stress calculation method using finite elements and the validation processes associated;

- to specify the maximum permissible stresses to be assumed in calculations and the safety factors to be used.

This technical report is applicable for:

- wheelset Axles defined in EN 13261 as "pure wheelset";

- other axle designs such as those encountered in particular rolling stocks e.g. with independent wheels, variable gauges, urban rail…

This document has not for aim to replace EN 13103-1 and CEN/TS 13103-2 but to present a complementary method to the existing ones.

2 Normative references

There are no normative references in this document.

3 Terms, definitions, symbols and abbreviations

3.1 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at https://www.iso.org/obp/ui

3.2 Symbols and abbreviations

FEL	fatigue equivalent load method
SSIA	Stress Strength Interference Analysis
KMR	Consequent Miner Rule
FEM	Finite Element Method

Nomenclature is given in Table 1.

Table 1 — Nomenclature

$Y_1(t)$, $Y_2(t)$	lateral force applied to both wheels
$Q_1(t)$, $Q_2(t)$	vertical force applied to both wheels
P1, P2	Vertical loads applied on the journals
C_{min}	Minimum transition length
F	Fatigue load
F_{eq}	Fatigue equivalent load
F_n	Severe representative load that can be defined for test and simulation validation
x, y, z	Longitudinal, axial, vertical direction of wheelset reference axis
$M_x(y)$	Bending moment applied to the y-section of the axle in the x direction (train circulation direction)
M_x	Bending moment applied to the most critical section of the axle in the x direction
$M_{x,eq}$	Equivalent bending moment applied to the most critical section of the axle in the x direction
$M_{x,EN}$	Normative bending moment
MR	Resultant bending moment
P	Probability
P_f	Probability of failure
P_n	Probability of having a more severe load than F_n
E	Young modulus
K	Stress correction factor
K_t	Stress concentration factor
K_f	Fatigue stress concentration factor
$K_{t,s}$	Stress concentration factor based on strain measurements
D	Total fatigue damage
d_i	Partial damage generated by the ith class of a load spectrum
n_i	Occurrence of the ith class of a load spectrum
N_i	Number of cycles for a crack initiation for the ith class of a load spectrum
CV_X	Coefficient of variation for the X variable
m	Slope of the S-N diagram when using a one single slope curve
k	Slope of the S-N diagram for $S > S_D$
k’	Slope of the S-N diagram for $S < S_D$
N_D	number of cycle for the knee of the S-N diagram
S	Stress load
S_D	stress amplitude for the knee of the S-N diagram
K_{ref}	total mileage of an axle

σ_f	Allowable fatigue stress
σ_d	Calculated dynamic stress
σ_{VM}	Von Mises stress
σ_h	Hydrostatic stress
τ	Shear stress
σ_1	Principal stress
ε_1	Principal strain
σ_n	Nominal stress
D/d	Diameter ratio (diameter of wheel seat divided diameter of nearby body)
D_N	Outer diameter of hub
d	Diameter of the axle shaft
r_{max}	Maximum value of the radius of the transition r
F1	Full scale axle body fatigue limit
F4	Full scale axle seat fatigue limit

4 Loads

4.1 Reliability analysis based on the Stress Strength Interference Analysis method

Fatigue is known to be a damage phenomenon which is very dispersive. The sources of variability are linked to the material properties that depend on its composition but also on the manufacturing process, the geometry of the structure, loads, usages, environment, etc. To ensure safety, margins applied to the specified loads and the prescribed fatigue limits, associated to a stress calculation method were defined in standards EN 13103-1 [21] for the design and validation of railway axles. They were established in the past decades, based on experience of railway experts and experimental and modelling works. Today, they enable to guaranty a high level of safety for the European railway sector, as feedback from operation shows. But, to gain competitiveness, it can be very useful to measure the available margins in order to ensure that when a new design or a new technology is introduced, the level of safety is maintained.

For that reason, it would be beneficial to switch little by little from conservative approaches towards reliability approaches. Maximalist approaches ensure safe designs by defining safety factors that make the load specifications more severe and underestimate the allowable fatigue limits. The consequence is that optimized solutions can’t be found. Moreover, when a significant change occurs in the system, it is difficult to evaluate its impact on reliability. In reliable approaches, the aim is to have a “just necessary” design associated to a target probability of failure. For safety critical components, the probability of failure during the lifetime generally vary from 10^{-5} to 10^{-8}. In the example given in [4] on an automotive engine part, the target probability is 10-6. For railway safety applications, if one considers that the number of accidents due to mechanical failures is rather small, a target between 10^{-6} and 10^{-7} sounds reasonable.

Observations of CEN/TC 256/SC 2/WG 11: The target value quoted (10^{-6} to 10^{-7}) is a failure rate per axle during its whole life. It is approximately in line with the 10^{-9} failure rate per operational hour defined in the CSM (EU regulation 402/2013) for technical systems for which a functional failure with immediate disastrous consequences is assumed.

Reliability approaches have been developed for many years in various industries. The methods always *consist* in characterizing the variabilities of the system to be designed and in calculating its probability of failure by propagating the uncertainties in a deterministic modelling, as shown in Figure 4.

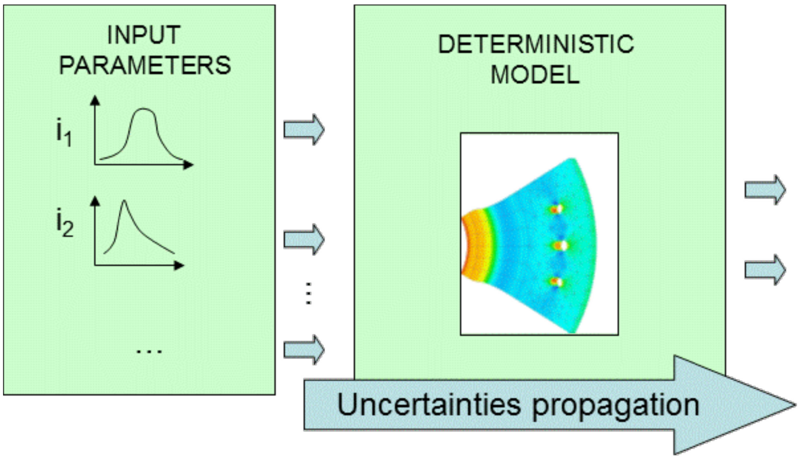
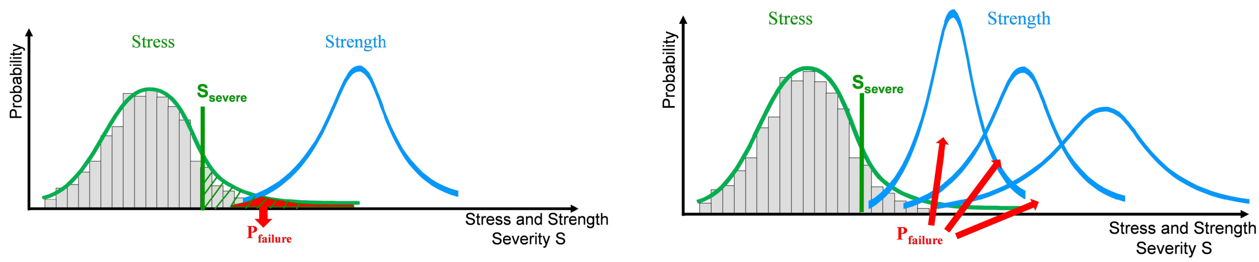


Figure 4 — Reliability approaches

The SSIA (Stress Strength Interference Analysis) is one of the reliability methods. It is widely used in industries, due to its simplicity. Within this approach, only two global parameters are used to characterize the variability of the problem: the load severity - referred to as STRESS - and the component strength - referred to as STRENGTH. These two parameters are chosen so as to be comparable (for instance, local stresses vs fatigue limits). Once the distributions of the Stress and the Strength are identified and modelled, a probability of failure can be easily calculated, by means of analytical expressions or numerical resolutions, as explained for example in [1][2][3][4]. The SSIA is therefore often used in the validation process of a new component. But it is even more powerful in the design process: from a pre-defined target probability of failure Pf, for a given distribution of Stress, the Strength distribution (mean value and scatter) can be specified. Let's notice that there is not a unique solution to this problem, as shown in Figure 5.



a) SSIA for the validation process **b) SSIA for the design process**

Figure 5 — SSIA approach

To apply the SSIA approach, it is necessary to characterize both distributions. The distribution of Strength can be identified thanks to laboratory fatigue tests. To have a good estimation of its distribution and not only its mean value, a sufficient number of tests is necessary. In the Euraxles project, new tests were performed for steel grades EA1N and EA4T. They are described in [17] and in Clause 4 of the report. For the Stress distribution, measurements of loads shall be carried out in various operating conditions in order to capture the variability of the behaviour of the component, as described in 4.2.3. Using complementary information on the variability of usages from an axle to another, a distribution of in-service load severity S can be generated. Accordingly, a representative and severe load can be defined as a specification to be used in the numerical and experimental design and validation process. This severe load is defined by its probability of occurrence $P(S > S_{severe}) = P_{severe}$ as shown in 2. This probability is a parameter that needs to be chosen by the industry and depends on the application. The idea is to define a severe load to accelerate the physical fatigue tests, but not to define a solicitation that would induce a damage process that is not the one that is studied. Typical values vary from 1/100 to 1/50000.

4.2 Fatigue load analysis method

4.2.1 General

The method for the axle fatigue load analysis is described in this part. The first step is the load signal post-processing: from a time signal of forces applied to the both wheels, elementary fatigue cycles applied to the axle are identified. Then, by calculating the total damage induced by all these elementary load cycles, a cyclic equivalent load, F_{eq}, which is as damaging as the initial variable load, is calculated. Its amplitude is taken as a measurement of the variable load's severity. The second step of the method is the generation of virtual load spectra which are realistic and representative of real usages of axles. To do so, information from operation and maintenance are used (total average number of kilometres before the axles reach the acceptable wear ratio limit, the way the axles are changed in a whole train during maintenance, the characteristics of the tracks on which the axles circulate, etc.). A strategy to generate those load spectra is described. The third and last step is the processing of all these virtual spectra with the FEL method which enables to build the distribution of in-service loads severities ("Stress" in the SSIA) to be compared to the standard load.

4.2.2 Load signals processing and Fatigue-Equivalent-Load

In mechanical high-cycle fatigue, Wöhler works showed that the main parameters that affect the lifetime of a material under a cyclic one-dimensional load are the amplitude and, to a less extend, the mean value of the load. To estimate the total damage induced on a component by a load with variable amplitude, it is necessary to identify all the elementary cycles included in the load signal and finally cumulate the partial damages induced by all these cycles. When defined by their amplitudes and their mean values, the elementary cycles can be identified thanks to a Rainflow counting method, as explained in [6]. When the mean values variations of the elementary cycles are small, one can consider that only the amplitudes of the cycles have to be considered in the fatigue analysis. Hence, a simple cumulative damage law, as the linear Miner rule [7], can be used to calculate the total damage. Finally, a cyclic equivalent load, called the F_{eq}, producing the same total damage, can be easily calculated, using Wöhler curves. Its amplitude is taken as the parameter of load severity. The whole process is explained in details in [1] and is presented in Figure 6, where F(t) is the initial load time signal and F_{eq} is the amplitude of the final cyclic equivalent load.