Effect of Rainflow Cycle Number on Fatigue Lifetime of an Arm of a Vehicle Suspension System

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***Abstract*—Fatigue is considered as one of the main cause of mechanical properties degradation of mechanical parts. Reliabilities methods are appropriate for fatigue analysis using uncertainties that exist in fatigue material or process parameters. Current work aims the study of the effect of the Rainflow cycle number on fatigue lifetime of an upper arm of the vehicle suspension system. The major part of the fatigue damage induced in suspension arm is caused by two main classes of parameters. First parameter characterizes materials properties and a second one describes equivalent force generated by road excitation and passenger's number. Therefore, representative sampling of Young's modulus and equivalent loading are selected as input parameters to conduct repetitive finite elements simulations by Monte Carlo (MC) algorithm. Strain-life approach based on Manson-coffin and Ramberg-Osgood equations is used in order to determine fatigue lifetime of each combination of input parameters. Thereafter, response surface is built according to preselected performance function. A PYTHON script was developed to automatize finite element simulations of the upper arm according to a design of experiments. Preliminary results show Rainflow primary cycles to have significant effect on obtained cycle's number to fracture. Load generated by excitation road have a remarkable quasi-linear inversely proportional effect on fatigue lifetime.**

***IndexTerms*—Monte Carlo, Response surface, Rainflow cycle, Performance function, Fatigue, Suspension system.**

I. Introduction

Fracture in industrials parts causes usually significant financial losses and dangerous accidents. Workers and users of such parts are the first victims of these parts when fail occurs. Fatigue is considered as one of the main undesirable phenomenon contributing to the material degradation. The number of loading cycles involved in the process has a major role in the degradation of material. Several fatigue approaches are available in literature to predict cycle's number and fatigue lifetime of mechanical parts. These approaches are numerical, experimental and empirical based mainly on stress and strain life methods. Only one of the methods, the strain-life, is studied in this work. Accuracy of fatigue lifetime prediction is inversely proportional to the number of process, interface and materials parameters. Errors and imprecisions of fatigue estimation results are enhanced especially when statistical variation of parameters is considered. In practice, designers frequently allow oversized structures and a very high material quality choice. According to these considerations, it is important to identify the main parameters governing fatigue behavior. A sensitivity analysis of a set of preselected parameters allows the identification of those that have the highest impact on fatigue lifetime prediction. Design of experiment plans are often used in order to ensure an efficient sensitivity in reduced time. Fatigue is modelled basing on theoretical, numerical and experimental methods.

Literature on the design and selection of fatigue characteristics of vehicle suspension systems can be found for generic vehicle model. However, a few works are available on the assessment of the suspension arm fatigue. Breytenbach and Schalk Els [1] conduct a mathematical minimization analysis to optimize suspension characteristics ensuring a best isolation of the vehicle structure from road. The proposed optimization problem is based on the cumulative fatigue damage method considering a hydro-pneumatic spring static gas volume and a damper scale factor as two design variables. Nadot and Denier [2] proposed an experimental analysis and multiaxial criterion to study fatigue for nodular cast iron automotive suspension arms. They validated results using a multiaxial endurance criterion based on the Dang Van model.

In this work, Monte Carlo algorithm is used to conduct repetitive simulation of a finite element model of an upper arm of suspension vehicle. Strain-life method is then adopted to predict fatigue lifetime using Manson-coffin and Ramberg-Osgood equations. A developed script allows automatizing repetitive simulations, extracting and saving (in independent database) strain energy density for each converged simulation. Rainflow cycles are counted by MATLAB software according to a saved strain energy density. Commercial FEA software ABAQUS is used to perform dynamic simulation of finite element model of upper arm. On the base of preliminary sensitive analysis, it is shown that the major parameter influencing fatigue failure are road excitation and Young's modulus.

II. NumericalApproach

The proposed numerical approach based on road profile model development and numerical finite element model are a

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modified version proposed first by the authors [11, 12] of this work.

A. Cumulative fatigue damage

Under cyclic stress or strain, a permanent amount of damage D will occur in micro-structure of an upper or lower arm of an automotive suspension system. This cyclic loading is due to irregularity of each kind of road. Rate of fatigue damage will be strongly dependent of the nature and frequency of this damage. The damage cumulating is one of the important tools of fatigue lifetime prediction of components made from A375 aluminium alloy. Damage D can be deduced from each D_i $(i=1,\ldots,N)$of$N$sources and given by :

$$\sum_{i=1}^{N} D_i = D \tag{1}$$

This leads to equivalent following equation:

$$\sum_{i=1}^{N} \frac{D_i}{D} = 1 \tag{2}$$

Where D_i/D define the fractional damage caused by each cycle. In our cases, cycles refer to road excitation levels and they will be identified by Rainflow counting algorithm. It is reasonable to predict number of cycles to failure N_i respectively for all stress/strain levels. Thus, fractional damage D_i/D can be replaced by n_i/N_i and rewritten according to Palmgren-Miner [4] :

$$\sum_{i=1}^{N} \frac{n_i}{N_{fi}} = \frac{n_1}{N_{f1}} + \frac{n_2}{N_{f2}} + \cdots = 1 \tag{3}$$

Where n_i is the number of cycle and N_i is the number of cycles to failure at a selected stress/strain level.

Loading cycles are usually affected by noise when measured by electronic transducers such as strain gages. These cycles are recorded and stored in a numeric database. Then a filtration process is used in order to isolate primary loads from noise. Some algorithms are developed to realize the filtration and counting main loading cycles. Cumulative fatigue damage will be proportional to the number and counting methods of cycles. Cumulative damage was estimated by adding each fraction of fatigue lifetime according to the corresponding Rainflow cycle. This is considered as the most common method to expect failure when the sum of these fractions reaches 1 (100%).

B. Road profile model development

Vehicles driven on irregular roads profile are subjected to random excitations. In order to make a reliable lifetime prediction of the arm, it's essential to take into consideration a real and complete excitation profile. In this study, the road excitation cycles are described by the power spectral density (PSD)[5]. This excitation is due to the irregularity of the profile of the floor as a random function. Figure 1 shows displacements versus time for a three road roughness classes obtained by PSD. The excitation spectrums of the road through the tire, the spring reaction and the shock absorber are calculated from the enslavement relationship between the suspended and unsuspended mass (m_u).

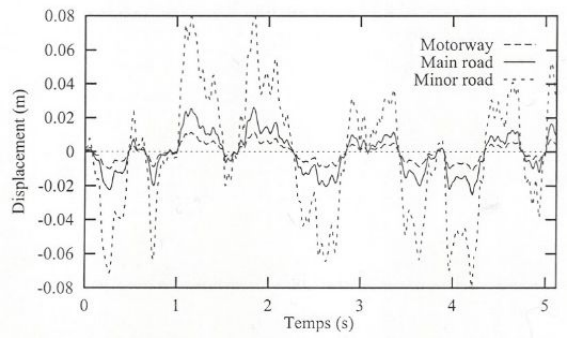


Fig. 1: Road Profile In Time Domain For Three Road Types [11,12]

The excitation caused by main road profile is calculated analytically from the PSD acting on the upper arm suspension of a vehicle through a tire of constant stiffness K_t where the return chain is made up of a linear shock absorber and a linear spring. The motion equation of mass m_u is [11, 12]:

$$m_u\ddot{x}_1 + k_t(x_2 - x_1) = 0 \tag{4}$$

Where x_2 is calculated from PSD formulation. This type of second order ordinary differential equation (ODE) can be transformed into a system of two first-order ODEs that can be solved numerically with fourth-order Runge-Kutta method.

Fatigue model: the uniaxial criterion equivalent to the multiaxial case is used as suggested by Elmarakbi *et al*. [7]. Since the aluminium alloys present a plastic rather than an elastic behaviour[6], the nonlinear profile is given by the Ramberg-Osgood equation as :

$$\varepsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{1/n'} \tag{5}$$

where $K' = {\sigma_f}'/{\varepsilon_f'}^{n'}$is the coefficient of the endurance limit, $n' = b/c$the cyclic hardness exponent, ${\sigma_f}'$ the coefficient of the fatigue strain, c the exponent of the fatigue ductility, b the fatigue strain exponent and $\varepsilon_f'$the coefficient of the fatigue ductility.

In the present study the three-dimensional elastic finite element analysis of the model was used. The value of the strain energy density obtained from the analysis in three-dimensional finite element method (FEM) is equalized to the strain density energy of the uniaxial case that makes up the plastic and elastic deformation energy. The total uniaxial strain energy per unit of volume obtained by an exact integration, is represented as :

$$U_a = U_{ae} + U_{ap} = \int_0^{\varepsilon_a} \sigma_a d\varepsilon_a = \frac{\sigma_a^2}{2E} + \frac{\sigma_a}{n'+1}\left(\frac{\sigma_a}{K'}\right)^{\frac{1}{n'}} \tag{6}$$

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The resolution of Eq.6 gives the necessary constraint to produce the same energy density as in the uniaxial case. Replacing the stress value in Eq.5 gives the corresponding deformation. Knowing the deformation, fatigue lifetime can be predicted by using the Manson-Coffin relation as in Eq.7:

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma'_f}{E}(2N)^b + \varepsilon'_f(2N)^c \quad (7)$$

The equation of the plastic-strain is :

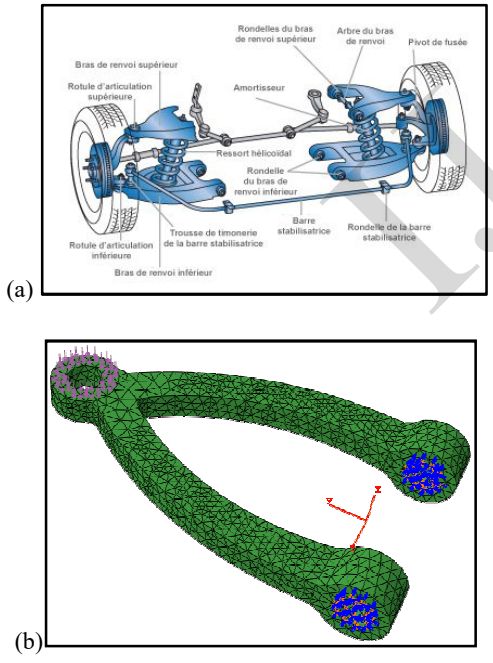
$$\frac{\Delta\varepsilon_p}{2} = \varepsilon'_f(2N)^c \quad (8)$$

The equation of the elastic-strain is :

$$\frac{\Delta\varepsilon_e}{2} = \frac{\sigma'_f}{E}(2N)^b \quad (9)$$

C. Finite element model

The developed fatigue model is applied to an upper suspension arm of a vehicle (Figure 2). Two main random variables are chosen for the reliability study: the applied load (number of passengers in a vehicle) and the Young's modulus of this piece. In fact, these two variables directly affect the lifetime of several vehicle pieces. Thus, it's necessary to characterize these mechanical pieces using quality limitations in order to produce a confidence interval and to secure the vehicle.



(a)

(b)

Fig. 2: Upper suspension arm. (a) Suspension system of a vehicle showing the upper arm [8] (b) Finite element model

All material properties and process parameters are given in Table 1. The prediction of fatigue lifetime follows three steps. In the first one a parametric finite element analysis of dynamical model of upper suspension arm of a vehicle was developed. The most important objective of a parametric model is to facilitate successive change of chosen design variables.

Table I: NUMERICAL PARAMETERS USED FOR A357[3]

Mean Young's modulus		70.754 GPa
Poisson's ratio		0.3
Density		2700 kg/m³
Mean load		2488 KN
Fatigue coefficients	σ'_f	1466 MPa
	ε'_f	0.262
	b	-0.143
	c	-0.619

In the second step, a PYTHON script was developed to conduct and post-process repetitive simulations of the parametric FE model according to Monte Carlo algorithm. Third step allow establishing an empirical fatigue model based on multiaxial strain energy density (SENER) criterion [9]is used. Figure 3shows the developed generic simulation approach and how it's implemented by computer.

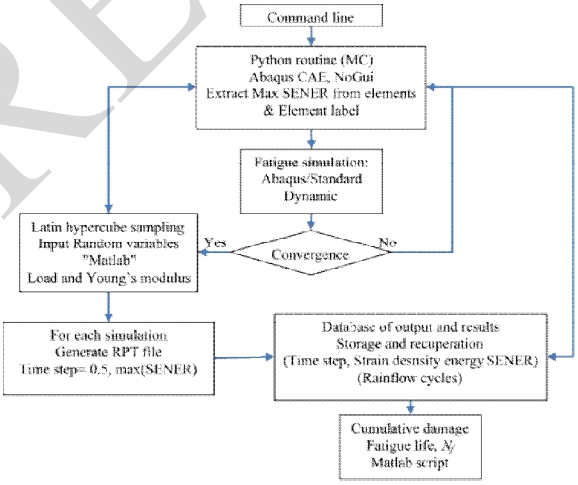


Fig. 3: Flowchart of the proposed generic approach

In this study, the Monte Carlo technique simulation coupled with dynamical model of upper suspension arm of a vehicle is used. An empirical fatigue model based on multiaxial strain energy density criterion equivalent to the uniaxial one [7] is used. The main steps which characterize this study are:

- Generating random variables each drawing material parameters of the mechanical part.
- Studying the distribution of loading.
- Calculating the strain energy density in the upper arm of the suspension system of a vehicle subjected to random excitation described by the power spectral density (PSD).

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- Filtering the results and identify the critical elements.
- Calculating the lifetime according to Manson-Coffin and Ramberg-Osgood equations.
- Describing the lifetime in a response surface.

III. Results and Discussions

The strain energy density (SENER) is extracted from each ABAQUS deterministic finite element simulation to store it in a database using PYTHON script. Figure 4 shows strain energy variation according to N_{MC}Monte Carlo simulations.

After identifying N_{RF} Rainflow cycle's number from one deterministic simulation (Figure 5), it will be possible to extract (N_{MC} x N_{RF}) Rainflow cycles and store them in an independent database.

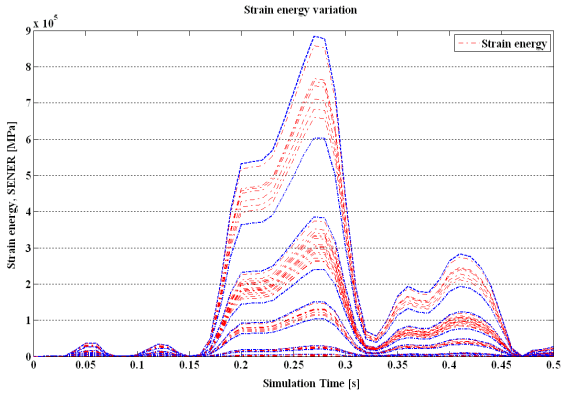


Fig. 4: Strain energy variation for a half-time simulation (N_{MC} simulations)

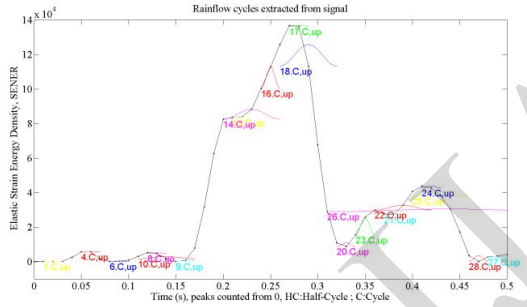


Fig. 5: Extracted Rainflow cycles from signal: peaks counted from 0

RainflowMarkov algorithm leads to the determination of 10 basic cycles defined by the maximum and minimum values of SENERat each cycle as shown in figure 6. Time corresponds to each cycle does not change for each Monte Carlo simulation. However, corresponding value of the SENER changes at each simulation.

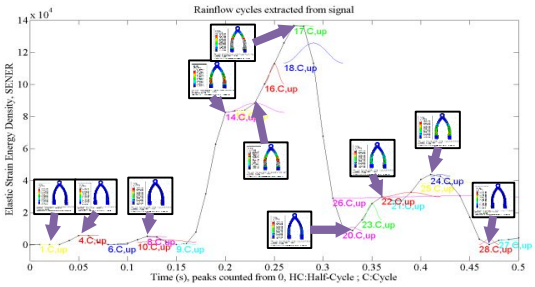


Fig. 6: SENER distribution 10 basic Rainflow cycles

The used Rainflow cycles counting method ignores cycles order. Basic cycles are ordered by descendingamplitude. This method should be used with carefullywhen we evaluate cumulative fatigue damage (equ. 3) which considers the order of road excitation in time. Strain energy related to each Rainflow cycle is shown in figure 7. From the figures it appears that the maximum values of SENER are attended respectively for cycles 4 (1.98 E5 MPa), 5 (3.23 E5 MPa) and 8 (1.039 E5 MPa).

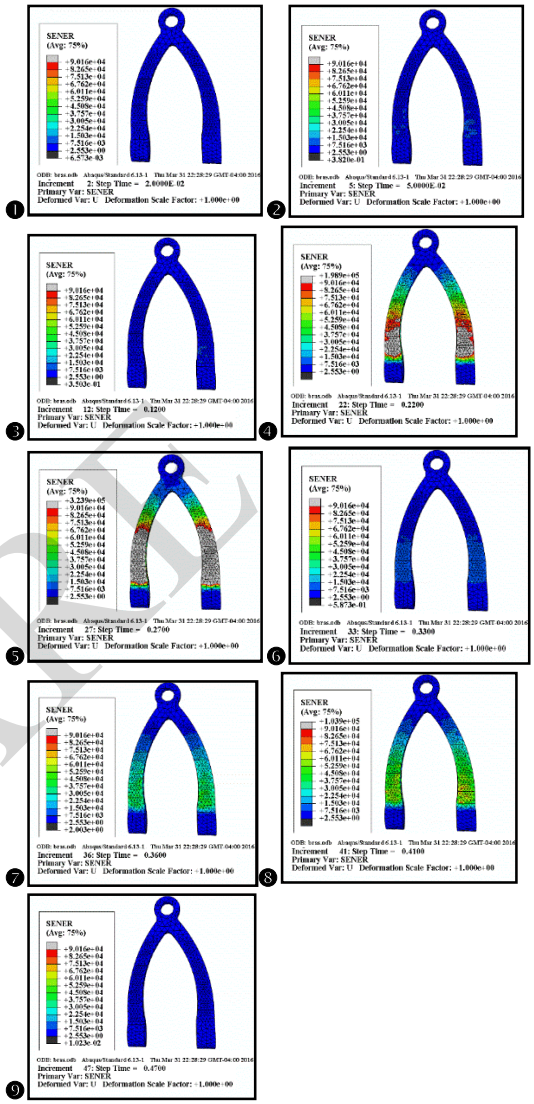


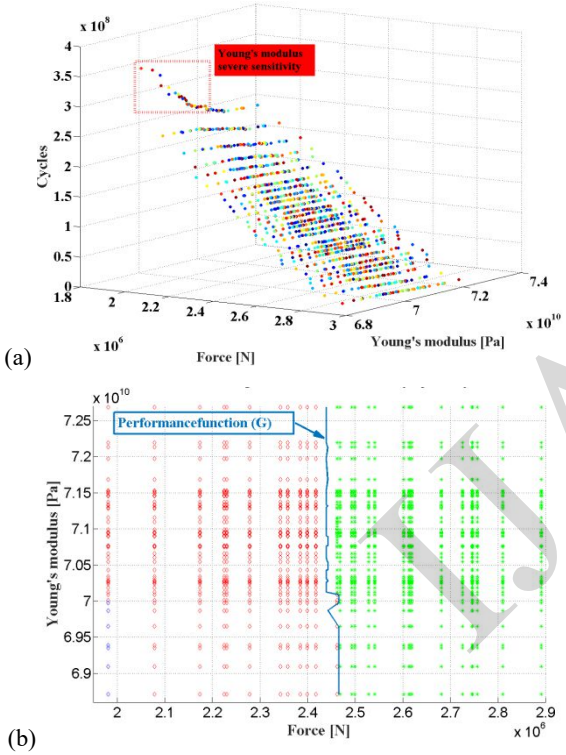
Fig. 7: Strain energy density profile associated to 9 Rainflow cycles

A performance function is chosen according to some theoretical observations on acceptable fatigue life. In the present case, possible failure modes must be avoided. The parameters involved in numerical simulation model are based on a regular use of the vehicle (road excitation, passenger's number ...). This lead to a secure choice of the cycle's number N_f applied to the upper arm. The performance function can then be written as:

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$$\text{Performance function} \equiv G(\text{young, load}) = \begin{cases} 1 \ , \ for \ N_f \geq 1.25\ E8\ cycles\ (success) \\ 0 \ , \ for \ N_f = 1.25\ E8\ cycles\ (failure) \\ -1 \ , \ for \ N_f < 1.25\ E8\ cycles\ (failure) \end{cases}$$

Figure 8 show response surfaced constructed according to the performance function in physical space. The failure probability P_f is calculated by : $P_f = P[G(young, load) \leq 0] = 0.46$, thus the reliability probability P_r is equal to P_r = 1-P_f = 0.54. It can be shown that the fatigue life is strongly dependent on force amplitude. Fatigue life decreases from 3.6283e8 to 5.0038e4 cycles inversely proportionalrespectively for forces which vary from 1.981 KN to 2.891 KN. High Young's modulus values have a negligible effect on fatigue life. However, an important effect was identified in the top-left zone of response surface (figure). At this zone, fatigue life reaches its maximum values (Nf > 2.44 E8) respectively for force under 2.1 MN and young's modulus under 7 MPa.



◊:N_f>2.44 E8◊ : N_f ∈ [1.25 E8 ; 2.44 E8]

* : N_f<1.25 E8

Fig. 8: Response surfaces of the fatigue life as a function of the Young's modulus and vehicle load; (a) 3D view, (b) 2D view - performance function

IV. Conclusions

Basing on parametric fatigue simulations of an upper arm of vehicle suspension system under tow random variables, the following conclusions can be drawn :

1. From the comparison of the obtained fatigue life response surface it appears that the load has a direct and important effect. While the used range of Young's modulus values is provided a negligible variation of fatigue lifetime. However, a severe sensitivity was noticed for Young's modulus and forces under 70.91 GPa and 1.9 KN respectively.
2. Proposed model based on the strain energy density parameter depends strongly on the obtained Rainflow primary cycles number.
3. Large scatters of the fatigue life caused by very high loading exceeding the regular used values.
4. Secondary Rainflow cycles have a negligible effect on lifetime prediction. Otherwise, the respective strain energy value is very low.

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