Two different ways for reduction of fatigue test duration

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Abstract : Today, the safety rules of the automotive industry forbid fatigue failures which can affect mechanical structures. Because this phenomenon is not acceptable, fatigue tests are conducted to validate material behavior with standard spectrum on specimen and automotive components with spectrum signals measured on cars. But, those costly and time consuming tests don't always respect new development schedule targets. That's why, solutions to reduce test duration are investigated.
New technologies, and specially computer calculation of structure (CAD), allow the optimization of component design. Even if the number of tests is reduced with more and more simulation, fatigue tests are necessary to validate material behavior and components and to guarantee the reliability target. Consequently, it is necessary to accelerate fatigue tests by reducing loading signals without changing the fatigue life and the damage or by increasing the test frequencies.
In this paper we present a comparative study of two different ways to reduce fatigue test duration. One way consist to apply filtering method (integrating material parameters) on real service loads, this method can be used for multiaxial fatigue test on material specimen in advanced project phase and on component in validation project phase. The second way consist to increase frequency loading by using a piezoelectric fatigue system (ultrasonic fatigue frequency), this method can be used only for uniaxial fatigue test on material specimen in advanced project phase.
The study consists to identify strength and weakness of each method and to guide the test engineer towards the most appropriate and efficient form of testing for a variety of situations.

Key words : reduce fatigue test duration / filtering method / piezoelectric fatigue system / uniaxial and multiaxial fatigue test

1 INTRODUCTION

During these last fifteen years the duration of development of vehicles was divided by factor three according to competition between the car manufacturer .In the same time due to the growth of requirements in the market, reliability target of cars are considerably increased imposing to the car manufacturer to enhance the specifications of the life of materials and components. To sum up , manufacturers are under an increasing pressure to reduce the time-to-market for their products while assuring high reliability of these products .One way to achieve this target consist to use modern software tools to predict the fatigue life of materials, components and structure at the early stage of design cycle, and to help design optimisation in terms of reliability, taking into account practical loadings history. Nevertheless, reliability tests are still necessary for design verification or product sign-off. This part of the product developpment cycle is recognised as one of the most critical and time consuming activities.
In the test laboratory in recent past, the fatigue test consisted to apply for materials, standard method to determine fatigue limit at 10^7 cycles on hydraulic or electrodynamic test bench and for parts, uniaxial or multiaxial fatigue tests under service loads (variable amplitude) reproducing the original track measurement.
These methods have been widely used in different industries and allowed to represent the in-service behaviour for chassis and body parts but they were very long and diden't take into account reliability constraint on engine parts which involve modern fatigue limits 10^9-10^{10} cycles due to new specifications.

2 ACCELERATING TESTING TECHNIQUES

In front of the stakes described above the trial engineers were brought to propose a new test method by developing a new technology of machine to identify material behaviour increasing frequencies loading (ultrasonic fatigue technology) and by reducing the duration of the multiaxial signals of validation on component by using filtering method to delete non-damaging portions.

3 ULTRASONIC FATIGUE TECHNOLOGY

In this paragraph we focus on the principle of the method , the used domain , the following target and the facilities.

3.1 Testing methods

The S-N curve for metallic materials was almost considered to be asymptotic in horizontal axis when fatigue lifetime is over 10^7 cycles or predicted by using probabilistic method , and a few number of tests were carried out beyond 10^9 cycles to check the following existence of this asymptote(see Fig.1). High-performance materials (e.g. high-strength steel), which are particulary important for vehicle design are subjected to very high cycle fatigue loading during their working service. Thanks to the ultrasonic fatigue technology , we can know the usual life of a greater number of materials which arrive to 10^9-10^{10}cycles during its life on components. Besides the determination of the fatigue limit in the gigacyclic domain with time reduction, this type of machine can be also used under certain conditions and for certain material to accelerate the trials including megacyclic domain.

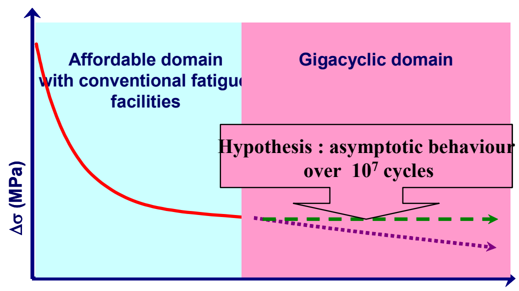

Fig.1

In 1950, Mason built the first 20 kHz piezoelectric machine, the design of Mason's machine has been used as the basis for most modern ultrasonic fatigue testing machines.
The ultrasonic fatigue technology have been developed and applied by many researchers in the world , because there have been no standards for testing procedure and testing machines, laboratories must developp their own machines and practical test procedures. We can find leading laboratories in this field in United states , Austria , France, China, Japan and Slovakia. Although ultrasonic fatigue test machines in these laboratories are not the same, some components are common to all machines. The three most important are : a high frequency generator, a transducer that transforms the electrical signal into mechanical vibration and a control unit (see Fig.1)

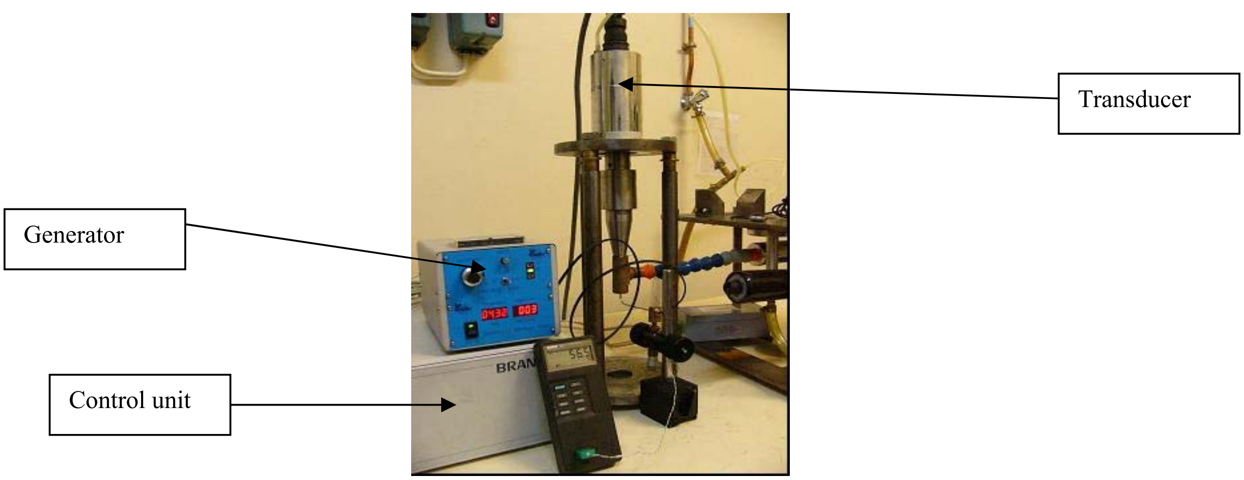

Fig.2

In this method a vibration is induced by a piezo-ceramic converter, which generates acoustical waves in the specimen through a power concentrator (horn) in order to obtain desired displacement and an amplification of the stress (see Fig.3). The resonant specimen dimension and stress concentration factor were calculated by FEM subject to 20 kHz. The dynamic displacement amplitude of the specimen extremity is controlled in order to keep the stress constant during the test, by the computer control and optical sensor. The test is automatically stopped when the frequency falls down to 19.5 kHz, that is because when the cracks is nucleated the frequency decrease until fracture.

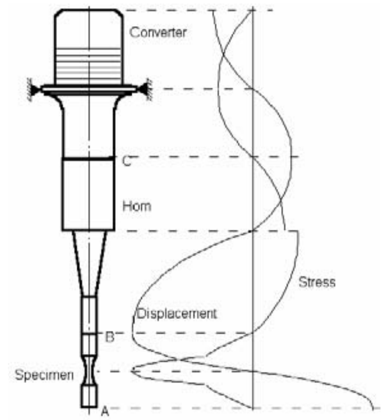

Fig.3

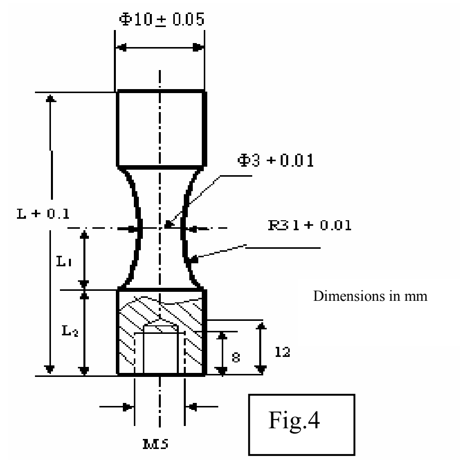

Fig.4

The dimensions of the ultrasonic fatigue specimen had been calculated to satisfy the resonance vibration condition at 20 kHz. The geometry is shown in Fig.4, the resonance length of the specimen can be calculated according to the material property (sound velocity and so on).Ultrasonic pulse and pause times were carefully controlled and compressed air cooling was utilized continually to minimize heating in the gage section. The use of this ultrasonic test bench for reduce test duration is essentially operated with constant amplitude loading on sample for uniaxial tension, uniaxial torsion and three-point bending.

To work correctly with the ultrasonic fatigue machines , stress calibration is necessary. The target is to verify the good correlation between the stress calculated by FEM and the stress measured. Among the important factors of concern , the variation of Young's modulus of the material due to high frequency is one of the most important. The method used by RENAULT consists in measuring working order the strain on sample by using strain gages.

The stress calculation is made with dynamic modulus ($\sigma_{dyn} = E_{dyn} * \varepsilon_{dyn}$) but also from a static calibration allowing to associate strain measurement to static stress (see Fig.5).

3.2 Principal results obtained

3.2.1 S-N Curves

The main materials studied by ultrasonic fatigue method are :

- Bearing Steel
- Spheroidal Graphite Cast Iron
- Aluminium Alloy
- Mechanical structural steel (martensitic, ferritic, bainitic, ferrito-perlitic)

A good agreement between tests carried out at high frequency (20 kHz) and classical fatigue data (30 to 100 Hz) is obtained on the most part of materials (see Fig.5, Fig.6,Fig.7).

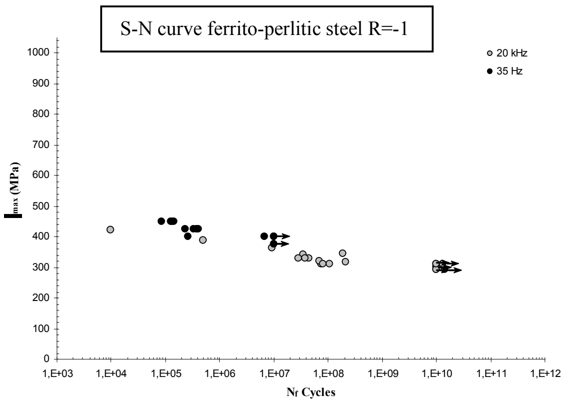

Fig.5

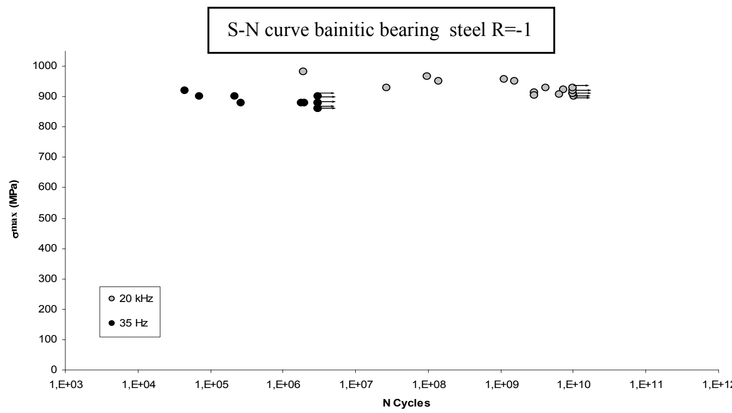

Fig.6

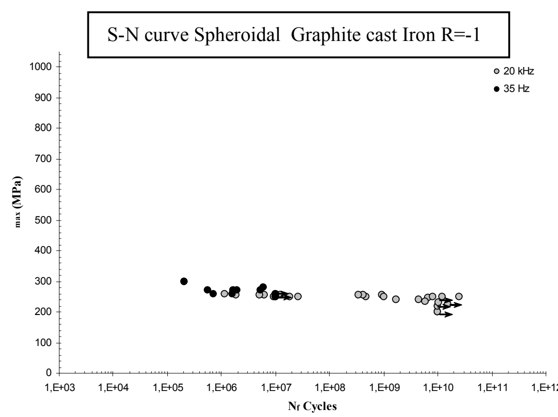

Fig.7

As for the results obtained (by high cycle fatigue limit) on the various microstructure, the interpretation is less easy. It seems nevertheless that the most homogeneous and\or finest microstructures (martensite, bainite, and perlite) don't show significant reduction of fatigue limit between 10^7 and 10^{10} cycles, reduction which is important for the heterogeneous ferrite-perlite microstructure (see Fig.8).

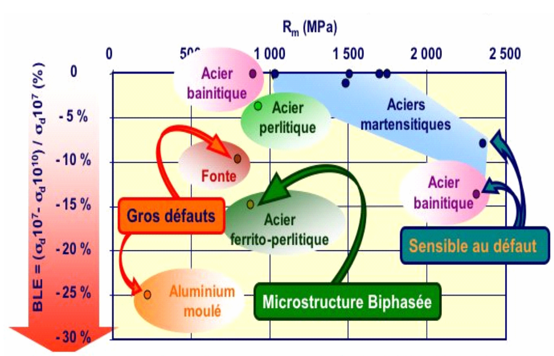

Fig.8

3.2.2 Fractography

SEM observations show that the fatigue crack initiation site for bearing steel (this material has value of example) was in two typical ruptures modes, in surface between 10^5 and 10^6 cycles, and over 10^7 cycles inside of the specimen principally located at non-metallic inclusions. As a result, the internal inclusion is the main rupture mode called “fish eyes” in the very high cycles regime (see Fig.9).

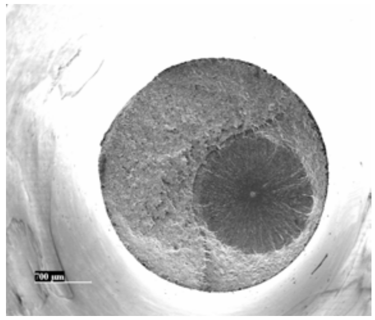

Fig.9

3.3 Strenght and weakness

The ultrasonic fatigue test method differs from the conventional fatigue test method which has frequency limited to 200 Hz with electrodynamic machine and 30 Hz with standard hydraulic machine. The frequency of ultrasonic fatigue testing ranges from 15 kHz to 30 kHz with current frequency being 20 kHz. With this new type of machine the time and cost to obtain a fatigue limit can be considerably reduced. For instance, the test time for 10^6 cycles is within few minutes by ultrasonic method , while conventional fatigue testing at 200 Hz will take one hour and one week at 30 Hz.

This time reduction allows to identify real fatigue limit to high number of cycles (gigacyclic domain) in harmony with project constraints (time and cost).In addition for material with small sensitivity to heating , ultrasonic testing machine can be used to provide result in megacyclic domain ($< 10^6$ cycles) with time reduction,often more economically and efficiently than other techniques.

Selection of material constitution for different batch is an other way to use this method on cast material especially on cast iron and cast aluminium which are difficult to produce without internal defects.

This method presents however some weak points which require additional works. Among weak points we can note stress calibration, operation for which we don’t have lead reference currently as required in the standard ISO9001 .SF2M workteam number 5 has been working on this point to propose a standard which is in agreement with industrial constraints.

An other weak point is the influence of thermal effect induce by high frequency. To measure this effect it’s necessary to carry out thermographic analysis with infrared camera. During the test, we observed a increase of the superficial temperature of the specimen (see Fig.10) depending of stress level.

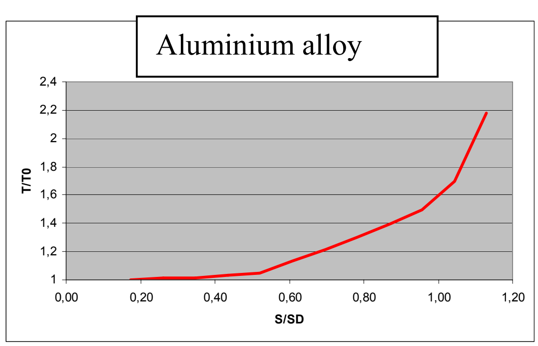

Fig.10

It can be difficult to control heat for certain microstructures and geometry of sample despite of cooling facilities. In the worst case the heat effect can affect mechanical properties and reduce fatigue strength.

The statistic analysis of the gigacyclic test results is also a weak point, because the usual models (Basquin , Bastenaire,……) used to determine fatigue limit from experimental results is not adapted to the shape of the curves. Indeed for steel with intermediary ultimate tensile strength (1500-1800 Mpa) we can obtained SN curves with three differents slopes (see Fig.11) corresponding to three differents failure mode (surface failure in megacyclic domain, no failure at the beginning of gigacyclic domain and internal failure in the gigacyclic domain).

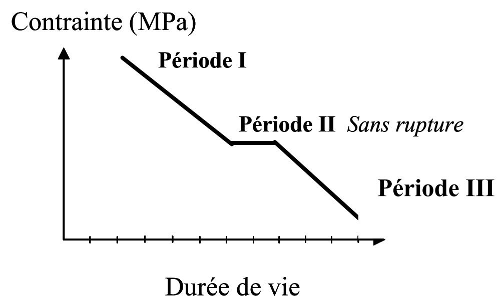

Fig.11

4 FILTERING PROCEDURES USED TO REDUCE VALIDATION TEST DURATION:

During validation project phases, components are validated on fatigue benches with multi axial spectrums representing the real car loading. In case of validation of the whole vehicle, the number of actuators can reach sixteen for this type of fatigue bench. As the test must be representative of the in service loading, the frequency test can't be increased. That is why, the only way to accelerate the test is to reduce the spectrum loading by removing the non damaging parts of the signal. This method is based on a damage calculation.

In this paragraph, a filtering procedure used to remove the non damaging parts of a validation signal is presented.

4.1 Principle of the filtering procedure:

A spectrum loading used to validate components or a whole vehicle is composed of different cycles that does not cause the same damage characterized by their amplitude and their mean value. All the cycle amplitudes or the damage caused by parts of the signal are compared to a filter. It is defined as the value under which the cycle does not create damage. That is why it can be removed. By eliminating the less damaging parts of the validation signal, its length is reduced. as the test duration. For that, filtering parameters as the level of the filter, the size of the window, the percentage of damage kept and the linking functions must be defined. All this parameters are presented in the next paragraphs.

4.1.1 Definition of the filter size:

In order to remove or not a cycle or a part of the signal, two type of filter can be defined. If the filter is defined as a value of the cycle amplitude, it is necessary to do a Rainflow counting of the signal. Each amplitude cycle will be compared to the filter (see Fig.12) to decide if the cycle is removed or not. The filter value is defined regarding objective of damage kept. It is obvious that the damage of the reduced signal decrease with the size of the filter.

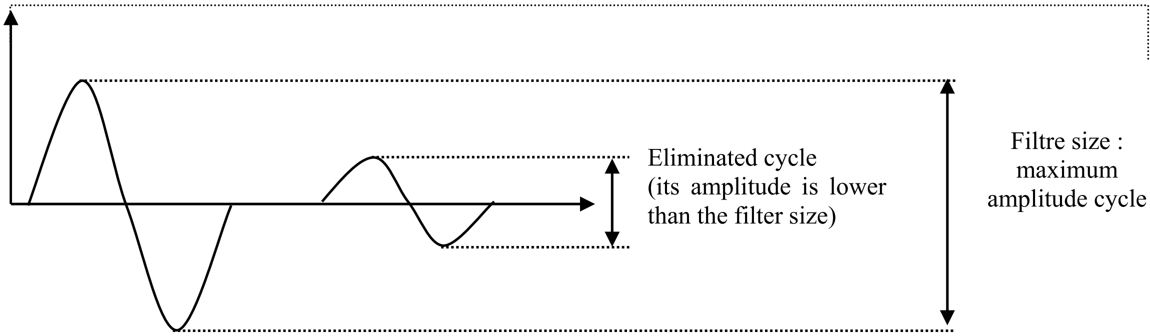

Fig 12 : Definition of the filter size

The filter can also be defined as a value of the damage caused by a part of the signal. In this case, a part of the signal is removed if the damage caused is under the value of the filter.

4.1.2 Definition of the window size

In order to keep the frequency content of the signal, several cycles situated before and after the signal are kept. It allows to have the same signal characteristics between the reduced and the non reduced ones. For that, it is necessary to define a length of a temporal filter called the window size (see Fig.13).

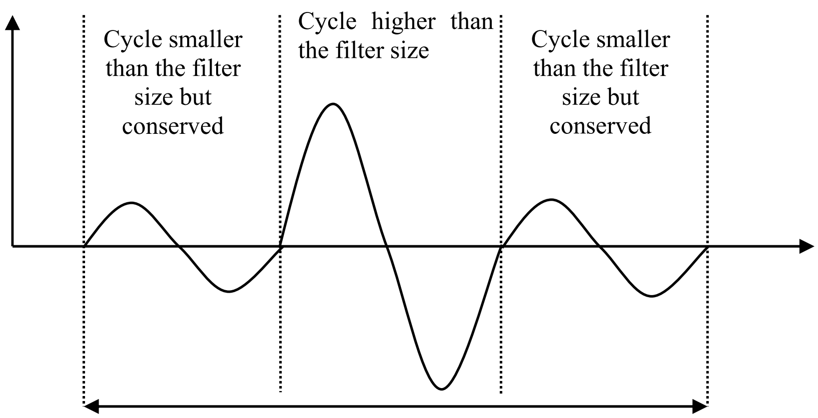

Fig.13

As shown on the figure 13, a cycle smaller than the filter can be kept because it is located just before or after a cycle conserved.

4.1.3 Definition of the couple "filter size – window size":

To evaluate the maximum of reduction rate, a study of sensitivity of the couple "filter size – window size" is necessary. It allows to determine the value of those parameters giving a maximum of reduction taking into account the specification of a reduced signal. It is important to verify that only the small amplitude cycles are removed by comparing the Rainflow counting of the original and the reduced signals.
Moreover, a spectral density analysis must insure there is no difference in the frequency content of the two signals.
The figure 14 present the results of a sensitivity study. The window size is called time slice and the filter size is represented by the damage kept. It is obvious that the higher is the filter size, the smaller the damage is.

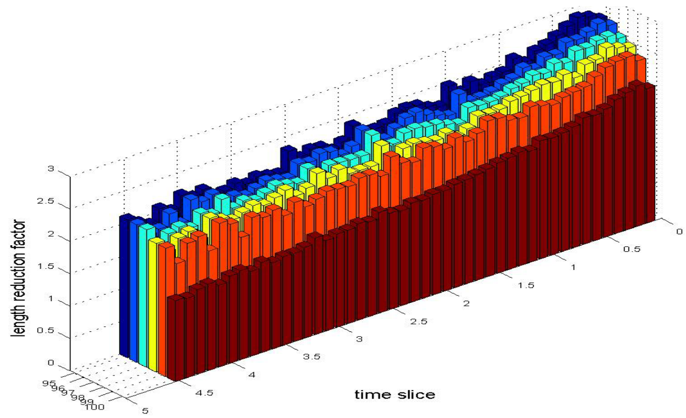

Fig.14 : Sensitivity study on a bad pavement signal

4.2 Application and objectives:

This reduction procedure is used on real multi axial loadings during the validation phase of automotive components or on a whole vehicle (Fig.15).

Fig.15 : Validation of a whole vehicle

The principle of the filtering procedure for multi axial tests is near the same as the principle described above for uni axial tests. Each canal is treated as explained in the 2.1 paragraph but to remove a part of the signal, you have to verify that at the same time and on all the channels, the signal is not damaging. In this case, it is possible to eliminate this part for all the signals.
With this procedure, it is possible to reach a time test reduction from 30% to 50%.

4.3 Inconvenients of this method:

Even if the filtering procedure gives the possibility to reduce the test duration and to respect the development schedule target, some points have to be checked before the treatment of the results.
Firstly, the same rupture mode (crack size and location) must be observed on the tests with reduced and original signals. If not, it means that the reduced test is not representative of the original one.
Secondly, all the damaging parts of the signal retained after the reduction are linked by a function to generate the reduced signal. This function must take into account the dynamic properties of the bench in order to obtain a signal that can be played.

4.4 Work orientation:

Commercial softwares propose reduction modulus based on the method described above. In this part, few tests on a suspension arm with reduced and non reduced signal and the way to improve the method are presented.

4.4.1 *Results on suspension arm:*

Commercial software allows to reduce validation test signals. At the Renault Technocentre, fatigue tests with multi axial spectrum loading (on X and Y directions) were carried out to evaluate a commercial filtering procedure. The application selected was on suspension arm represented during the fatigue test (see Fig.16).

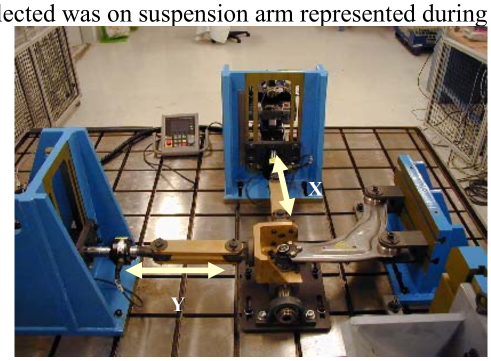

Fig.16 : Fatigue test on suspension arm

The sensitivity study of the filter parameters (LMS software) allows to determine the most adapted couple "filter size – window size" in order to reach a reduction of 50% of the signal length. It was verified that only the small amplitude cycles were eliminated and the frequency content were kept. With the reduced and the non reduced signal, the same rupture mode were observed near the point B (see Fig.17).

Fig.17 : Crack location on the suspension arm after fatigue test with reduced and original signal

4.4.2 *How to improve filtering procedures:*

Filtering procedures usually use a damage calculation based on a fatigue material properties. In the most case, a mean slope of the Wöhler curve is used for all components and for all the materials. One way to improve the filtering procedures is to introduce a material parameter (different for each application) in the definition of the filter value. The micro plasticity threshold or the fatigue limit can be chosen as material parameters.
At the Renault Technocentre, fatigue tests on seam welded structures (see Fig.18) were carried out to determine fatigue properties of the assembly and the filter size in order to generate a reduced spectrum loading.

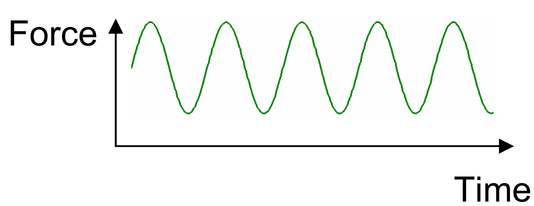

Fig.18 : Fatigue tests with constant amplitude loading

The results of fatigue characterizations with constant amplitude loading will be used to reduce a spectrum loading applied on the welded specimen and representative of a car loading. To validate the improved filtering method, fatigue tests with reduced and non reduced signals will be done on this specimen.

5 CONCLUSION

Filtering procedures used during the validation of automotive components are based on the elimination of non-damaging parts of the signal. To remove those parts, filtering parameters (filter size, window size) have to be defined. It must be verified that the characteristics of the original and the reduced signal are the same. For that, their Rainflow counting and spectral density analysis are compared. However, to validate the reduction procedure, the tests results must show the same rupture mode.

Fatigue tests on a suspension arm with reduced and non reduced signals show that a reduction of fifty percent of the signal length can be reached. But, the introduction of a material parameter in the definition of the filter size is explored to improve those filtering procedures.

Data acquisition in the very high cycle fatigue regime using conventional fatigue methods in not practical because it is prohibitively time consuming. Therefore, ultrasonic fatigue techniques allow to accelerated testing frequencies to save time in megacyclic domain or/and to identify fatigue limit in gigacyclic domain. The gigacyclic behaviour from the current study using ultrasonic fatigue method is in good agreement with the trend suggested by the data obtained at shorter lifetimes using conventional test techniques. Nevertheless, works are in progress to improve certain weak points of the method, especially on the try out (stress calibration) of the bench, on the effect of frequency and heat build up and on the statistical analysis of the results.

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