# Predetermined Stress Loading Wav-File Generation for a Servohydraulic Fatigue Testing Machine

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Thesis

**SAVONIA UNIVERSITY OF APPLIED SCIENCES** **THESIS**
**Abstract**

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| Abstract<br><br>The purpose of this Thesis was the study of Fatigue Test through a realistic vision using actual test specimen. The classic Fatigue test are done by standards waves or lineal Data, but that is not what happen in an actual world, therefore, we are using here wav-files as our data waves, which give us similar results as we can find in the real world.<br><br>The thesis consists of a theoretical and practical part. During the Theoretical part we are going to understand all of Theory involved in this Thesis and will explain better the practical part, which is done using a computer Software and the Servohydraulic fatigue Testing Machine Type LFV 500-HH | | | |
| Keywords<br>Fatigue,Test,Test Specimens,Young Module,Stress | | | |
| Public | | | |

# Forewords.

I appreciate the trust Mr. Tattu Westerholm and Mr. Anssi Suhonen gave me to do this work during my Erasmus in Finland, and for their patient with me, it was a really interesting experience, learning how engineers work in different parts of Europe.

I would like to thank Mr. Lauri Alonen for his help with the programming and explanations about how to work in the laboratory.

Express my gratitude to my parents, for letting me go to Finland and supporting me in every decision I have made during my life.

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Kuopio 18 Decemeber 2015

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## NOMENCLATURE

| | |
|---|---|
| **PCM** | Pulse-code modulation |
| **f** | Frequency, Hz |
| **F** | Force, kN |
| **L** | Length, mm |
| **W** | Wide, mm |
| **D** | Diameter, mm |
| **H** | High, mm |
| **We** | Weight, Kg |
| **V** | Voltage, V |
| **C** | Electric Current, Amp |
| $S_e$ | Stress e |
| **N** | Number of Cycles |
| **S-N** | Stress-Number of Cycles |
| **LCF** | Life Cycle Fatigue |
| $\xi - N$ | Strain-Number of cycles |
| $\sigma_{max}$ | Maximum tension |
| $\sigma_{min}$ | Minimum tension |
| $\sigma_m$ | Mean tension |
| $\sigma_A$ | Alternative component |
| **b** | Basquin Slope |
| **LEFM** | Linear-elastic fracture-mechanics |
| **FFT** | Fast Fourier Transform |
| **FPI** | Free programmable interface |
| **DION7** | Test software |

# 1 PREFACE

The purpose of this Thesis is to perform Fatigue Tests into Test specimens in order to Determinate Their Fatigue Life in an actual World.

To carry out this work, we are using wav-Files data due to the accuracy of the results if we compare them with the classic data.

First of all, to do this Tests we have to create the wav-Files and we have to be able to understand all the results, some of the software used to do this task have been Maplesoft and Matlab, with them we can create wav-files with the correct sample frequency, analyze them using the Fourier Transform or the Rain Flow Method and we can take a look into the representation of the waves.

After that, the Testing Machine Type LFV 500-HH is responsible to do the Tests, it can analyze only wav-files with a specific Frequency Sample, which is 8106.128 Hz and in a PCM format through the PCS8000 controller and using the Software DION7

At the end, the results can be evaluated by software in order to understand and determinate the Fatigue Life Cycle so we can compare them with the actual situations in the different scenarios.

# 2 BACKGROUND

## 2.1 MACHINE DESCRIPTION

### *2.1.1 TECHNICAL INFORMATION*

Servohydraulic Test Machines perform static, dynamic and fatigue testing of materials, components and structures through the use of Test specimens. There are many different configurations available in order to imitate the different scenarios that can be found in real work situations.

The Type of the machine used for this work is a servohydraulic fatigue Testing Machine LFV 500-HH (Locking Hydraulic) with the next parts:

| | |
|---|---|
| Load Cell Type 1248EAW 500KN, no. 492814 | |
| Manifold Platen mounted direct onto the actuator | |
| Servo valve moog Type G761-3025B,no. 5161 | |
| Servo valve moog Type G761-3025B,no. 5134 | |
| Set of dynamic rated connections | |
| Set (2 pcs) of dynamic rated Hydraulic non-shift wedge grips Type WGR-H 500 | - Set(4 pcs) of inserts for flat specimen 0-21 mm, wide 100 mm<br>- Set(4pcs) of inserts for flat specimen 20-41mm,wide 100 mm<br>- Set(4pcs) of inserts for flat specimen ∅ 5-12 mm<br>- Set(4pcs) of inserts for flat specimen ∅ 10-21/24 mm |

Table 1: Parts of the Machine

We can take a better Look into the different parts of the Machine in the Figure 1 and Table 2 which follows.

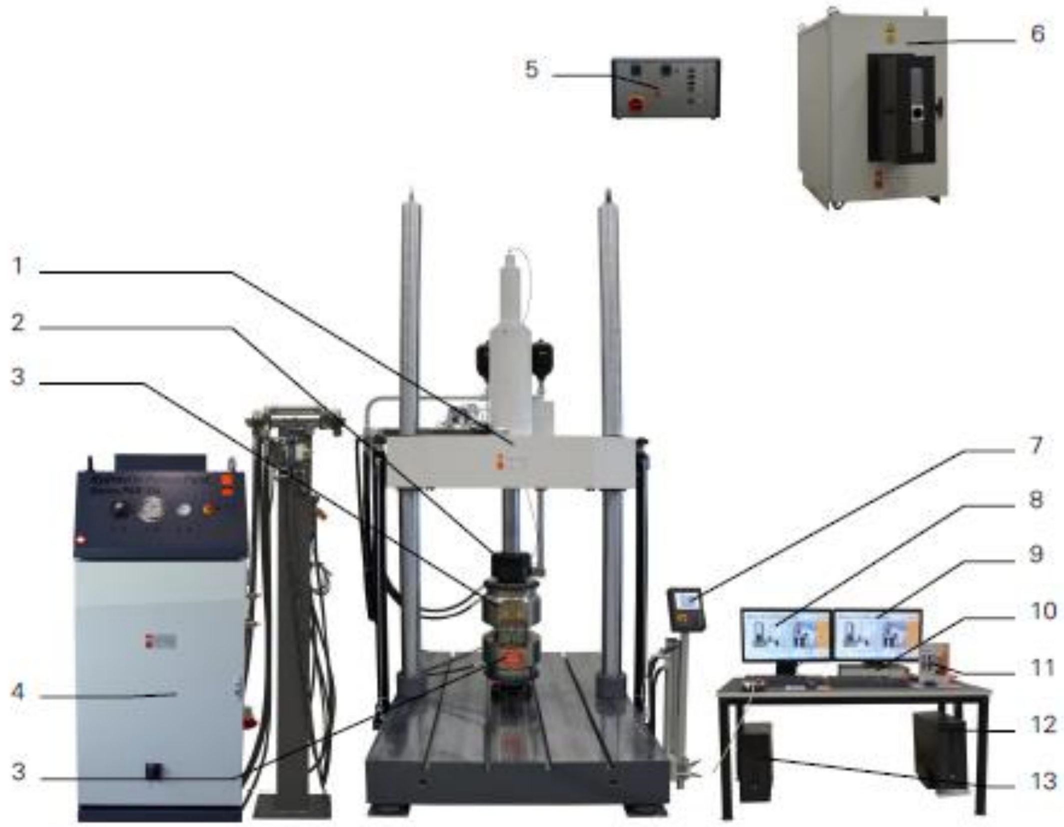



Figure 1. Machine Picture

| |
|---|
| **1.** Servohydraulic fatigue Testing Machine Type LFV 500-HH |
| **2.** Load Cell Type 1248EAW 500 kN |
| **3.** Dynamic rated Hydraulic non-shift Wedge Grips Type WGR-H 500 |
| **4.** Hydraulic Power Pack Type PAC-134 |
| **5.** Furnace Controller |
| **6.** Environmental Chamber Type ETC 460-1 |
| **7.** Multifunctional Remote Control Hand Set Type HB 8000 |
| **8.** Screen Type HP Z23i Videoextensometer System Type VEX 50 |
| **9.** Screen Type HP Z 23i |
| **10.** High Resolution Digital Material Testing Control System Type PCS 8000 |
| **11.** Software DION 7 |
| **12.** PC Type HP Elite Desk 800 G1 |
| **13.** PC Type Elite Desk 800 G1 for Videoextensometer System Type VEX 50 |

Table 2: List of parts

The power pack is a freestanding unit and can be placed in a separate room. The machines can be equipped with integral T-slot platen suitable to fix components, specimens or manufactured assemblies. The machine can be configured with climatic chambers, high temperature furnaces, testing devices and other accessories to suit your specific testing needs.

To meet the wide variety of testing needs, the LF (SV) is offered in different configurations. All options as: Extended test space, other actuator strokes, protection device for operators safety, additional low force transducers a.s.o are available. The LF (SV) test system is modular constructed and can be configured with a variety of grips and fixtures, extensometers, different software packages and other accessories to suits the specific testing needs. The precision load cell, which is mounted on crosshead, is overload protected. In combination with the high resolution digital controller class 0.5 according to ISO 7500-1 and other international standards can be reached.

To perform this Fatigue Tests, the machine has the Technical data represented in the Table 3, Table 4 and Table 5.

| | |
|---|---|
| Force max. | 400 kN dynamic / 500 kN static |
| Testing height between Grips | 80 - 2050 mm |
| Load measuring | Load Cell Type 1248EAW 500 kN |
| Measuring accuracy from 2.500 to 500.000 kN tension/compression | Grade 0.5, ISO 7500-1 T2 |
| Piston stroke | 400 mm |

Table 3: Performance Attributes

| | |
|---|---|
| Dimensions W x D x H | 2000 x 1925 x 5080 mm |
| Weight (with grips) | approx. 10000 kg |

Table 4: Dimensions and Weights

| | |
|---|---|
| Power supply | 3 x 400V+N+PE |
| Current | 150 Amp. |
| Electrical pre- fuse | 200 Amp. |

Table 5: Supplying, Interface, Connections

### *2.1.2 MACHINE EQUIPMENT*

These servohydraulic machines count with different parts which allow to develop proper tests with the characteristics that we are looking for. In order to understand better this, the concepts Load Frame, Actuator, Load Cell and Hydraulic Power Supply have to be explained.

**Load Frame:** It is designed for an accurate Testing for a wide range of applications. The LFV 500-HH test machine counts with two rigid column construction which offer axial, superior and lateral stiffness giving a consistent loading to the test specimen. To facilitate the repositioning, the upper crosshead of the test machine can be adjustable which allows also a good cleaning and more hours of work with it.

**Actuator:** It is responsible of the movement and control of the test mechanism. In this LFV test machine, it is a double ended with an equal area construction allowing the generation of an equal axial force in tension and compression. Due to the Hydrostatic bearings, the fiction during the test is really low, therefore the results are more accurate and one more time, the life working time is longer.

**Load Cell:** It gives more precision to the force developed. It is mounted on upper crosshead.

**Hydraulic Power Supply:** When one if these test are performance the dynamic part is done by an oil flow and pressure. In this case, the actuator on crosshead is available to give a power supply of 8l/min oil flow, but it can be increased to 500l/min with power packs, this packs include more hydraulic parts, electrical parts and operation parts, it includes also some coolers for water and oil to keep the quality and reliability of the process.

### *2.1.3 MAINTENANCE*

As every machine, and more important in Test Machines where the results must have the best precision possible, the maintenance of the machine has to be the best possible, in the case of the model LFV- 500 HH , the maintenance and inspection work has some intervals that have be followed to preserve the good conditions to develop the tests. Also this model counts with some locks and keys that must be switch or remove before the maintenance, which guarantees the safety conditions to carry out the maintenance.

The intervals of the Machine Maintenance are:

**14-days:** In this case it is a basic maintenance with a general cleaning, oil level checking and visual control of the parts, looking for some fractures.

**Monthly:** Every month the bearing areas of the specimen have to checked and cleaned, as the electrical wires and plug connections.

**Yearly:** Every year the installation state and calibration of the machine are recommended, where some aspects are checked as the oil level and pressure, hydraulic filters have to be changed and the rest of the filters have to be replaced or cleaned and more visual inspections. In case that during the year the hours of work were more than 5000, the oil must be replaced for a new one.

In our case we count with a Certificate from Ilac-Mra, a Swiss accreditation service with the date of calibration 19.06.2014 at 24ºC with the serial number 1722.The recommendation of maintenance says that a new calibration should take place every year, but in this case the test machine has not been used enough time to need a new one.

The calibration results are under the ISO-7500-1 Metallic materials -- Calibration and verification of static uniaxial testing machines. The reported of calibration is stated as the standard uncertainly of measurement multiplied by the coverage factor K=2, which for a normal distribution corresponds to a coverage probability of approximately 95%.

# 3 THEORY

## 3.1 INTRODUCTION

Many of the machine elements such as shafts, springs or pipes are under varying loads. The behavior of the materials under this kind of loads is different that the behavior under static loads, one machine part can support too much effort from a static load but the same part can break under a varying load if this one is repeated many times. This is because this kind of loads tend to create fissures that expand after a number of cycles, when this happens, the facture for fatigue appears and the piece breaks. Therefore the design of the elements which are under varying loads have to be developed by a theory that controls this kind of fissures and how they can expand after a number of cycles, that theory is named Fatigue Theory, and one of the important concepts of that Theory is the relation between stress and life.

This kind of fracture was discovered during the XIX century, when the wheels of the trains started to fail only after a short working life even when they were manufactured with one of the best steels possible, it was because a brittle fracture that means it happened suddenly and they could not prevent the result because this wheels were calculated under Static stress Theories.

The engineer and mathematician Jean-Victor Poncelet was the first one who described this failure due to varying Loads in 1839 and a few years later, in 1843, Rankine studied this Train wheel problem, but it was not until 1867 when after 12 years of work, the German engineer August Wöhler, who during an exposition in Paris, showed his results of the Fatigue Theory, talking for first time about number of cycles. Wöhler also found the Fatigue Limit for steel. He worked on fatigue marks and he developed the S-N curves, also known as Wöhler curves, which characterize the fatigue behavior of materials

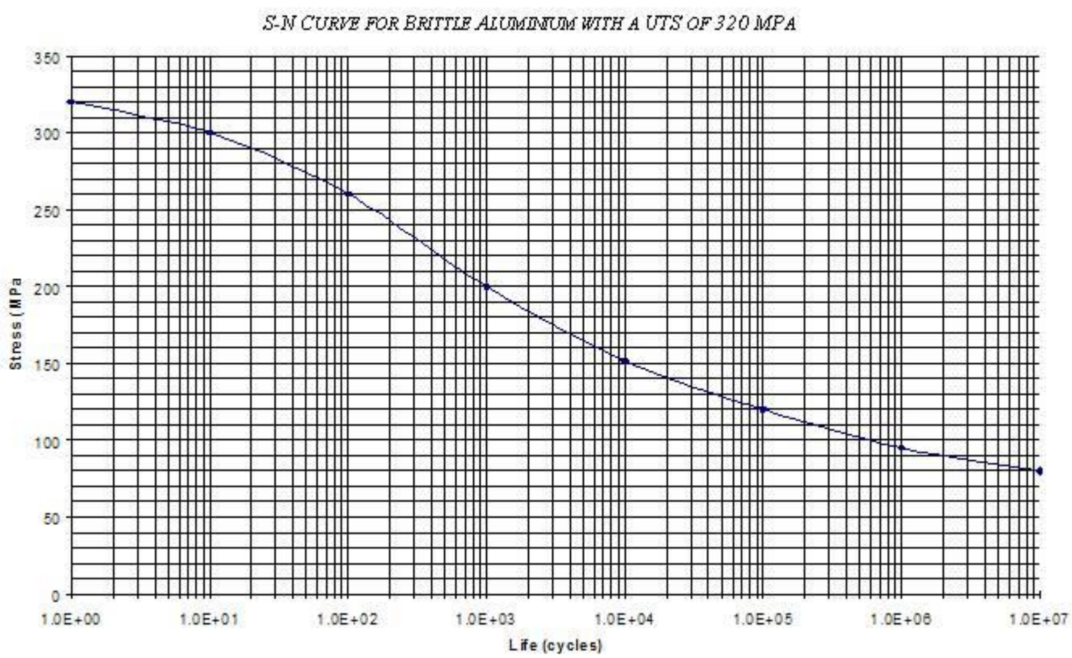



Figure 2. Wöhler curves

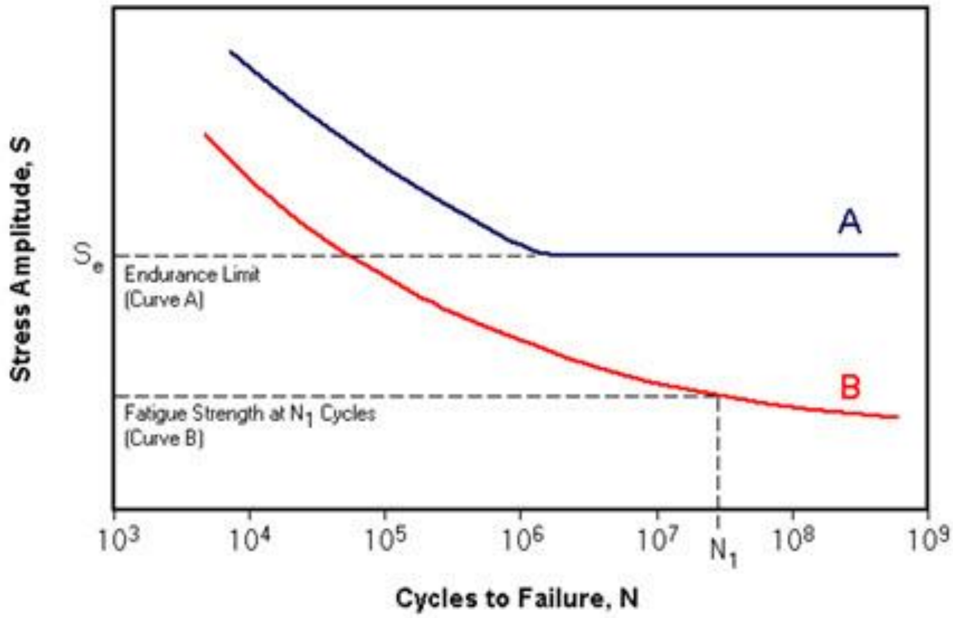



Figure 3. S-N Wöhler curves (2)

If we take a look into the Figure 3, we can check that if the stress in our Machine part is lower than “$S_e$”, our piece will not fail and his work life will be infinite, but if you exceed that limit, the part will fail after “N” cycles, in case of the curve B it will break at “$N_1$” cycles and will never be able to work forever.

In 1903, Ewings and Humphries observed that if the limit of a static load is surpassed, some internal planes get displaced so our material experiments deformation, moreover, when the stress increases some lines appear where this displacements begin, with more stress more lines, when the number of lines is large enough, this causes the fracture of the material.

However this Ewings and Humphries Theory could not explain why some test specimens did not break under some limits, right like Wöhler observed.

In 1910, the American scientific Bastin, develops the first equation which join the number of cycles with the infinite material´s life Wöhler talked about.

In 1920, Hanson and Gough studied that materials get stiffen when displacements starts inside the pieces, only when the stress is not high enough to break this piece. This explained Wöhler Theories and why under a number of cycles the life of the piece is infinite.

## 3.2 FUNDAMENTAL BASIS OF FRACTURE MECHANICS

There are only four basic failure mechanisms: overload and fatigue, corrosion, wear and depending of the use of our mechanisms or piece, the design of them will vary. The factors that most influence in the fracture of materials are also important, they are the selection of a wrong design or material, but there are also other factors as wrong manufacturing process or changing the final use it was not designed for, varying the work conditions, therefore it cannot support these new forces.

### *3.2.1 FAILURE ANALYSIS*

Failure analysis during service is very important because through it we can know the actual stress that pieces can work with during their lifetime and it also allows to choose the correct factors to design the mechanisms, however, this analysis during service is very complicated to carry on because very often the work conditions can change and the reality of the failure has nothing to do with the actual work it was proceeding.

### *3.2.2 FAILURE CLASSIFICATION*

A failure is defined as the termination of the ability of an item to perform a required function. When this function is not performed as well as it was expected is because this item has suffered a failure, these failures can be because of many reasons and they are reunited in groups, here I am going to explain two of them.

#### *3.2.2.1 Type Of Loads*

Failures can be classified depending of the Load Type and how it is applied on the item, there are two different types of loads, static loads and variable loads.

- Static Loads: this kind of loads may be due to internal pressure, bending, torsion, tension or a combination of them, as result of this loads the fracture is also static and the variation of temperature affects too much to the lifetime of the piece.

- Varying Loads: varying loads are the result of the force application in cycles, so the number of them must be measured because the amplification of the wave changes.

#### *3.2.2.2 Type of Fracture*

Another classification is by the type of fracture the piece has suffered, there are three different levels: atomic level, microscopic level and macroscopic level.

- Atomic Level: the material behavior can be studied by the Dislocation Theory, it explains that dislocations introduce imperfections into the internal structure of the piece decreasing the yield stress value expected. Although this Atomic Level does not give us really useful information about actual cases, it is important to study how planes behave and how this dislocations move through the structures, because depending of this planes preferences, the fracture may change under different work conditions.

- Microscoscale: this fracture happens because internal grains of the material get displaced by the stress, moreover grains can suffer ductile deformation in their surfaces.

- Macroscale: it is divided in smaller groups.

  *Ductile by static load;* this implies plastic deformation, this kind of fracture absorbs too much energy, that means that the size of the piece get larger than it was in the beginning.

  *Brittle by static load;* this kind of fractures begins from small fissures, then the deformation moves across the piece. The material does not suffer plastic deformation.

  *Fatigue;* It occurs due to the piece is under cycles of forces, other factors as corrosion or temperature are also important in this Fatigue Fracture.

### *3.2.3 FRACTURE MECHANISMS*

We can summarize this mechanisms in two, Brittle Fracture and Ductile Fracture, the main difference between them both is the amount of energy (plastic deformation) they can bear without breaking, we can see this in the figure 4.

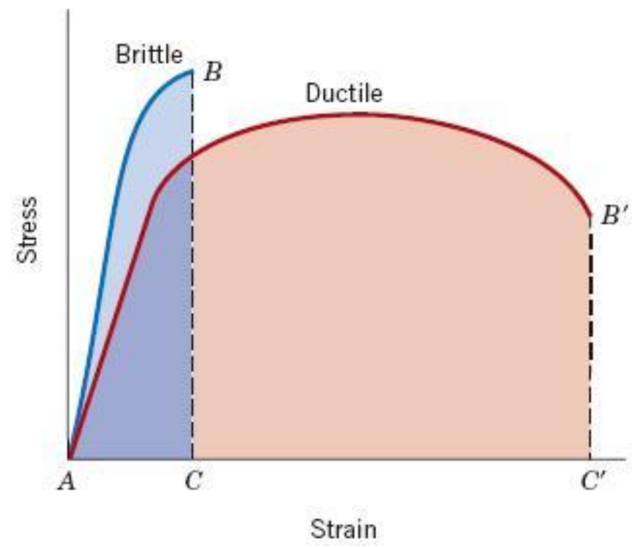



Figure 4. Stress-Strain Diagram

The kind of fracture is also distinct if we compare both systems, it also depends on the whether the force application is torsion compression and etc… we can see the difference looking at the Figure 5.

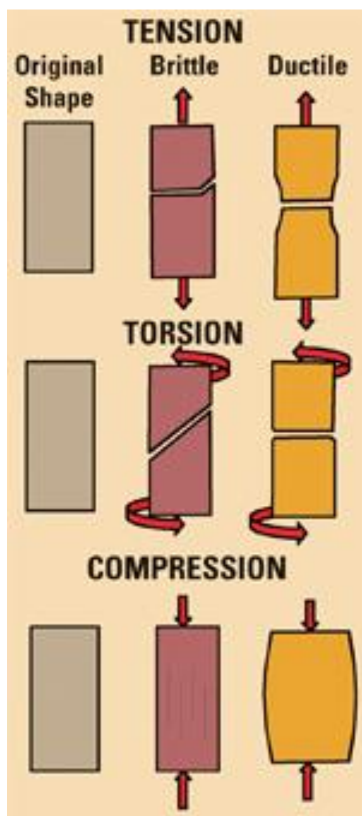



Figure 5. View of the different fractures depending of the material

#### *3.2.3.1 Brittle Fracture*

Brittle fracture is a suddenly failure in a stressed material. The fissures usually go so fast that it is impossible to tell when the item is about to break, that means the piece does not absorb too much energy, there is not plastic deformation. In most cases this is the worst type of fracture because you do not know the piece is in bad conditions until it is too late.

Brittle Fracture has the characteristic that the cracks run near to perpendicular applied stresses planes and there are two types of Brittle Fracture to explain this, Trasngranular Fracture and Intergranular Fracture.

- Transgranular Fracture: the fracture runs through the grain of the material, this means that this fracture changes its direction every time it changes grain, this can be observed by naked eye looking at the surface of the broken piece.

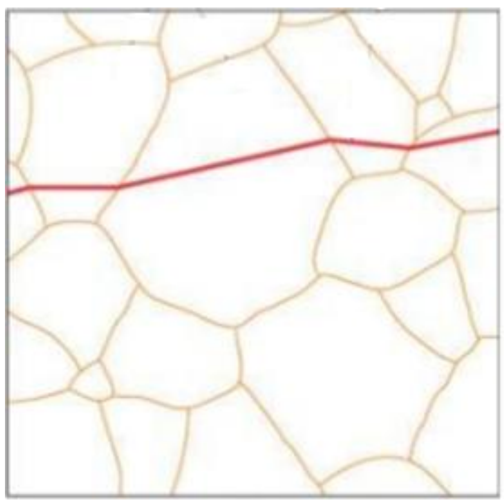


Figure 6. Transgranular Fracture

- Intergranular Fracture: the fracture runs along the grain boundaries, it does not cross the actual grains, this type of fracture is common when the phase in the grain boundary is weak.

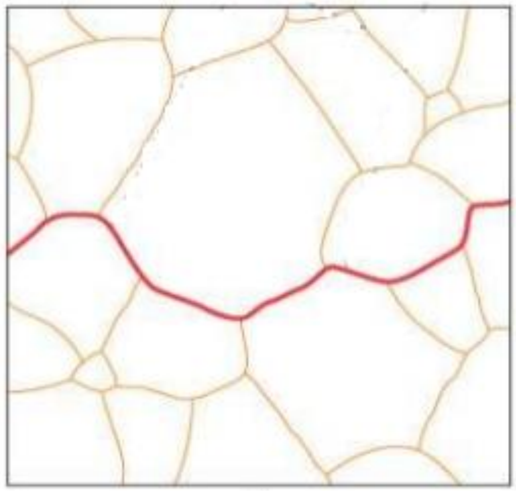


Figure 7. Intergranular Fracture

### *3.2.3.2 Ductile Fracture*

The Ductile Fracture is accompanied by significant plastic deformation, that means that it is possible to observe the deformation before the specimen breaks therefore this Ductile Fracture is usually more desirable than Brittle Fracture because you can prevent the failure before it is too late. In very high purity materials may result a large plastic deformation with nearly the reduction of all the area of the specimen, however if the material contain impurities it can fail with lower strains.

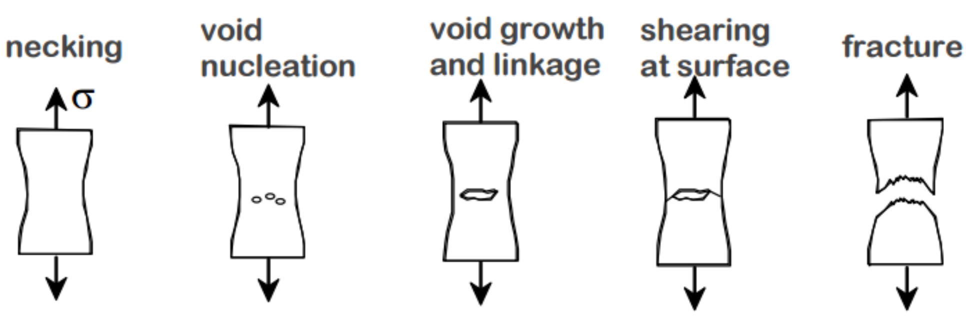



Figure 8. Ductile Fracture Mechanisms

#### *3.2.3.3 The Ductile-Brittle transition*

I have explained both type of fracture but they are general terms which sometimes work together, that is why the ductile-brittle transition has to be described in order to understand the actual cases. There are two important factors here, the temperature and the dislocation density.

- Temperature determines the amount of ductile or brittle fracture that take place in a material, in general we can say that with higher temperatures we obtain a ductile fracture, on the other hand, with lower temperatures the fracture tends to be more brittle, and therefore at moderate temperatures materials use to have both types of fracture.

- Dislocation Density theory explains that when dislocations are not able to move very far fractures are more brittle because the plastic deformation decreases.

### *3.2.4 CRACK MODES*

There are three different crack propagation modes:

- Mode I is called opening
- Mode II is called in-plane shear
- Mode III is called out of plane shear

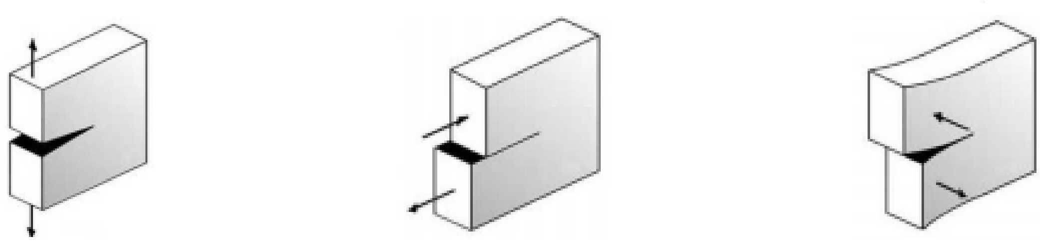


Figure 9. Crack modes I-II-III in order

In actual cases the item can be under any of these modes or a combination of them three, being the Mode I the most common because of in Brittle materials, cracks tend to break through the plane which needs less stress to do it.

## 3.3 FUNDAMENTAL BASIS OF FATIGUE

The concept of Fatigue explains why a piece which is under varying loads can broke with a lower amount of stress than the same piece which works under static loads.

Fatigue can be explained as the process in which damage is accumulated due to the repetition of load application that might be well below yield point.

### *3.3.1 FATIGUE CRACK CHARACTERISTICS*

The origin of the fatigue crack is a stress concentrator point in the piece, but this fracture has to be studied because many times it gives us information about the work conditions and why it broke.

Here we got an example of a shaft fracture:

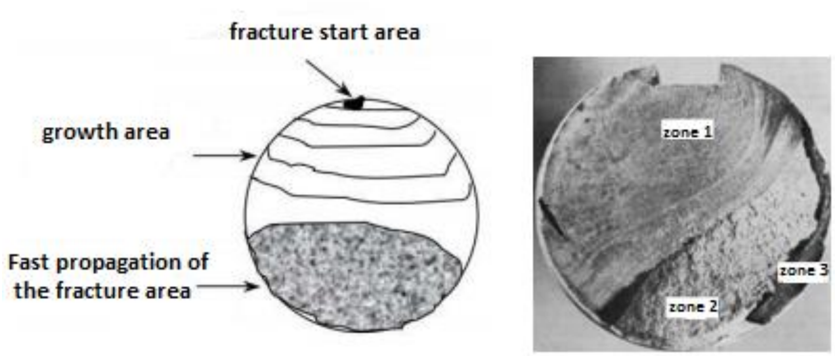



Figure 10. Propagation of the crack on a shaft

- Zone 1: it is the biggest zone, the crack propagation is slow and its surface is even, it can be possible to see the propagation lanes.

- Zone 2: the crack propagation in this zone is fast, with an irregular surface.

- Zone 3: finally the section of the piece is so small in this part that it cannot resist the stress anymore and therefore it breaks.

*3.3.2 VARYING LOADING*

In real cases, the amplitude items have to work with, are usually variable, hence it is important to represent this loads correctly in order to predict the lifetime or to have an accurate measure of the loads than appear during work.

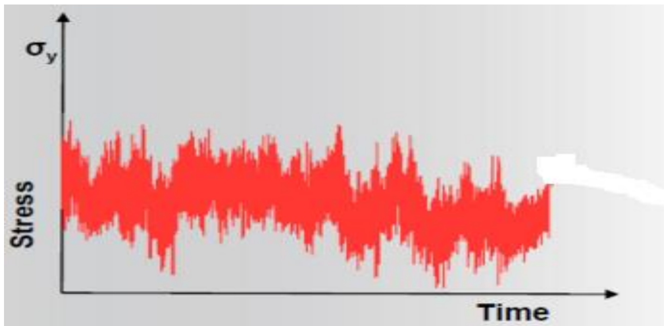



Figure 11. Varying loading representation

To measure this load data, transducers are used to translate physical information into data that can be read by computers, this transducers are attached to the critical areas of the items. Data may be filtered to prevent mixing primary loads and noises after the recording, they are also summarized or compressed using some methods that I will explain later, otherwise the amount of data will be too large to work properly with computers.

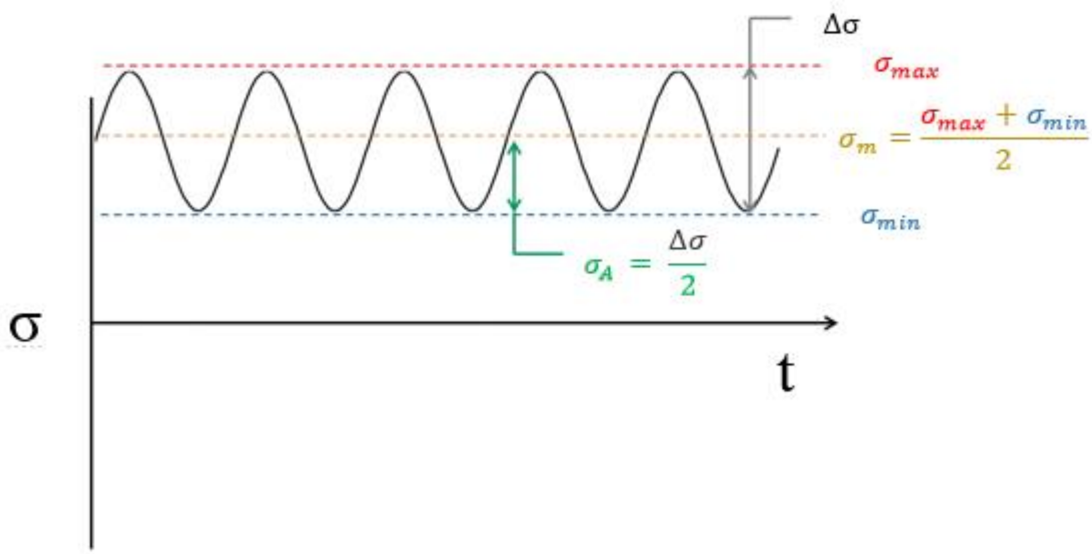



Figure 12. General varying loading representation

In Figure 12 we have a general varying loading representation, where the mean load is not zero, this mean load can be also negative values, for example in cases such as bridges where pretensions (compressions) are used or zero. The meaning of the variables are:

- $\sigma_{max}$ = Maximum tension
- $\sigma_{min}$ = Minimum tension
- $\sigma_{m}$ = Mean tension
- $\sigma_{A}$ = Alternative component

### 3.3.3 CUMULATIVE DAMAGE

Cumulative damage refers to the fatigue effects of loading events by cycles, the damage increases when loads are applied in cycles in a cumulative manner which can lead to failure and fracture.

One important concept here is the "fraction of life", also known as "cycle ratio", the energy accumulation leads to a linear summation of cycle ratio:

$$r_i = \frac{n_i}{N_i}$$

$r_i$ = cycle ratio

$n_i$ = number of cycles

$N_i$ = number of cycles to break

When the cycle ratio is 1, the fracture is about to happen. Because of this simplicity is the most common measure of damage, but it is not the only one, there are others as crack population or crack length.

#### 3.3.3.1 Cumulative Damage Theories

There are different cumulative damage theories, we can differentiate between linear and non-linear theories.

- Linear Theories: the most used theory is the Palmgren & Miner Theory, also known as Miner´s Theory, it is based in two principles:

i) The damage produced by n such cycles is :

$d_i = \frac{n_i}{N_i}$ $n_i$ is the number of cycles we use

$N_i$ is the number of cycles until failure

ii) The failure will happen in the next case:

$$D = \sum_{I} d_i = \sum_{i} \frac{n_i}{N_i} \geq 1$$

However this theory can lead to wrong results due to it does not take care of the application order of the cycles that is why some factors have been introduced in such us changing the number one for another value previously studied, in order to make results more realistic.

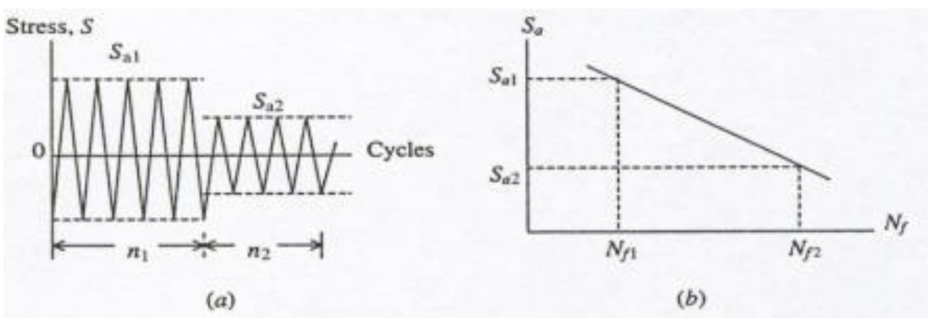



Figure 13. Representation of linear Cumulative Damage Theories

- Non-Linear Theories: in the case of non-linear theories, the representation of the S-N diagram is no longer a line, now it is a curve so it comes for different kind of equations, one of the most important theories in this area is the Manson & Halford Theory, developed in 1981.

### *3.3.4 LIFE ESTIMATION*

The cumulative damage theories that I have just described have to go with some estimations of the life, here I am going to explain the most common: S-N approach, and the ξ-N or LEFM approach.

#### 3.3.4.1 S-N approach

Stress-Number of cycles approach represents both variables in a diagram

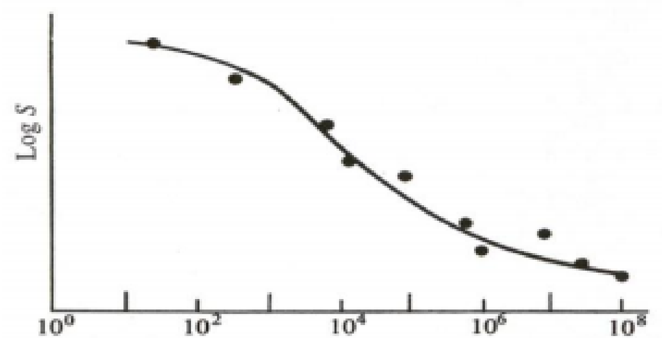



Figure 14. S-N diagram

This S-N curves are obtained under load-control test conditions, this is the easiest approach model and it is design for infinite life work, preventing crack initiation with a high strength criterion so we are always working under a particular value we previously set up. Although is one of the most used life estimation models, it is the least accurate method for LCF (life cycle fatigue) and it is not useful for low cycle fatigue because it cannot describe it due to plastic deformations, it cannot describe the crack growth fatigue neither.

If we take a look again on the figure 4. We can see the typical S-N curve where the curve “A” (steel´s behavior) can have an infinitive life if it works under proper stress conditions and the curve “B” (Alloy´s behavior) cannot.

In some cases the concept safe stress designs is used. It is a process in which some elements such as nitrogen or carbon are mixed with the original material, preventing premature failures, we have to understand than in many cases only 10% of the greatest ranges will do more than 90% of the damage.

- Power Relationships: a power law equation can be used to define de S-N relationship

$$N_1 = N_2 \left(\frac{S_1}{S_2}\right)^{\frac{1}{b}}$$

Where b is the Basquin slope, it is a value that must be set up previously:

$$b = \frac{-(logS_1 - logS_2)}{logN_2 - logN_1}$$

Solving both equations we can calculate the cycles to failure for a known stress amplitude.

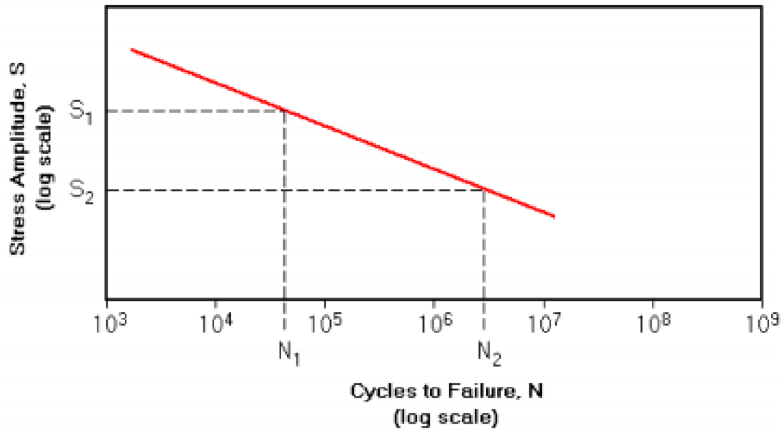



Figure 15. S-N representation

This top values (peaks and valleys) are taken out from a plot and converted to nominal stress ranges and means, to work with them later. Some typical values of this design line are:

Ferrous Metals → $1x10^3$ to $5x10^6$ cycles

Non-Ferrous Metals → $1x10^3$ to $5x10^8$ cycles

- Fatigue Ratio: through the experience, some ratios between fatigue and stress have been developed, so they are very useful when we do not need perfect accurate results because it simplified the problem.
  This is the ratio between the endurance limit "$S_e$" and the ultimate strength "$S_u$" and its value is from 0.25 to 0.60. As an example the Steel has the next values:

  - $S_{e,steel} = 0.5S_u$ for $S_u < 1400$ MPa
  - $S_{e,steel} = 700$ MPa for $S_u > 1400$ MPa

  With a stress level for 1000 cycles is:

  - $S_{1000,steel} = 0.9S_u$

  So its representation would be:

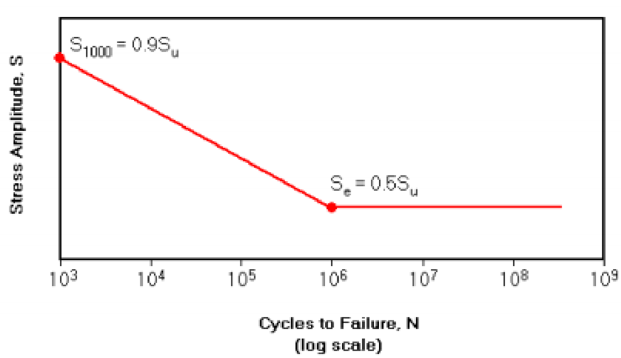



Figure 16. S-N curve for steels

#### 3.3.4.2 ξ- N approach

This method is strain based and accurate for crack initiation and damage standpoint, the main difference with the S-N approach is this one is used for low range cycles but on the other hand it is more complicated to use and it requires too much computational calculation.

#### 3.3.4.3 LEFM approach

linear-elastic fracture-mechanics describes crack propagation and predicts remaining life using non-destructive tests, it is also used for low range cycles as the ξ – N approach and is complicated to carry out in the same way as this one, it is also very sensitive to accuracy of stress intensity factors.

### 3.3.5 CYCLE COUNTING METHODS

Cycle counting methods are used to summarize cycles of loads with various amplitudes occur, a cycle is a load variation from two (maximum and minimum) values. Cycle's counts can be made for Forces, stress, strains etc…

The Cycle counting objective is to compare what are the effect of variable amplitude loads histories in fatigue tests and simplified the data which are obtained by experiments, but depending of the work, different methods may be used because results might vary significantly depending of which one we are using. Although different methods lead to different results, all cycle counting methods must count cycles with its range from the highest peak to the lowest valley, and look for other values which belong to different ranges.

#### 3.3.5.1 Rainflow Counting Method

The Rainflow Method is used in fatigue´s analysis so as to simplify the spectrum of varying stress of a wave, it is the most used counting method because it allows the application of Miner´s rule that I just have described.

It was described by Tatsuo Endo with the help of M. Matsuihi in 1968. Jonge´s (1980) algorithm is easier to implement and ASTM algorithm (1985) is the one which is recommended nowadays, but it was not until 1987 when a mathematical definition appeared, described by I.Rychlik.

Rainflow method separates small and uninteresting oscillations from the others which are important to study, this is interesting because in fatigue damage calculation, these small oscillations do not cause cracks. Therefore, the purpose of Rainflow Method is that cycles can be summarized and simplified in several ways.

The Endo´s Algorithm follows the next steps:

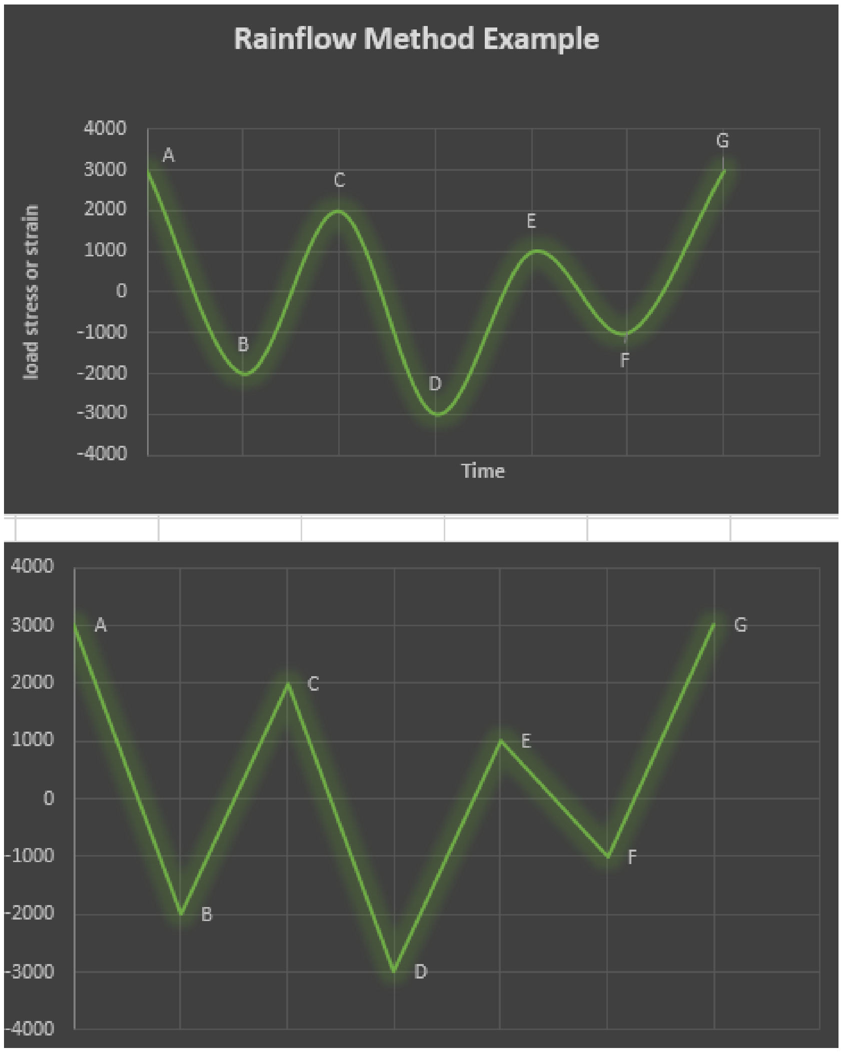



Figure 17.Signal Example

1- Turn the signal around by 90º and make water flow from their highest peak, and go down to the next reversal, this "rain" will flow down until either a roof extends opposite beyond the vertical of the starting point, or the flow reaches a point is already wet. (Figure 18)

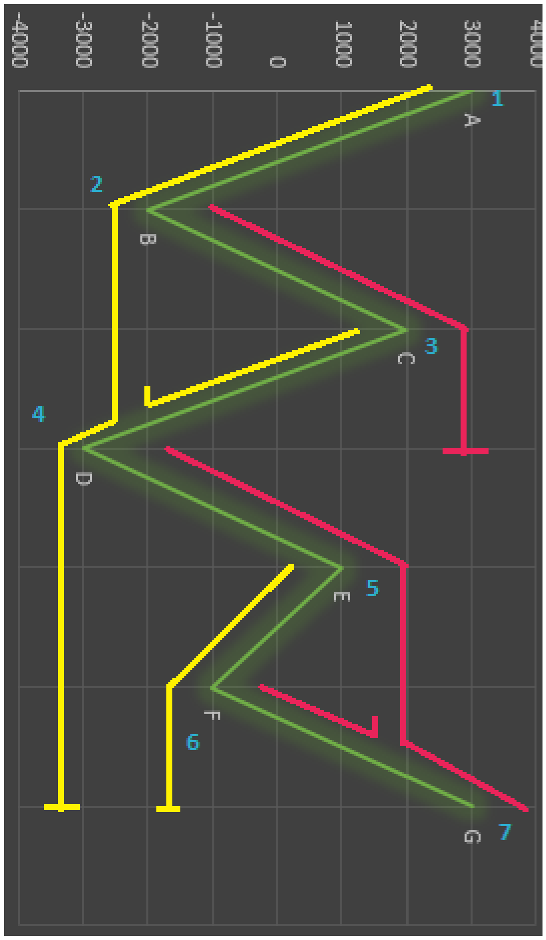



Figure 18. “Rain” flowing in the Rainflow method

2- Each time we do this a half-cycle is defined, so the most of cases them can be paired into full cycles, in this example every half-cycle is repeated twice, so they form one full cycle.

| Range | Cycles |
|---|---|
| *1000* | *0* |
| *2000* | *1* |
| *3000* | *0* |
| *4000* | *1* |
| *5000* | *0* |
| *6000* | *1* |

Table 6. Range and cycles counting

3- Table 6 can be condesed in a bar graphic in order to observe the results.

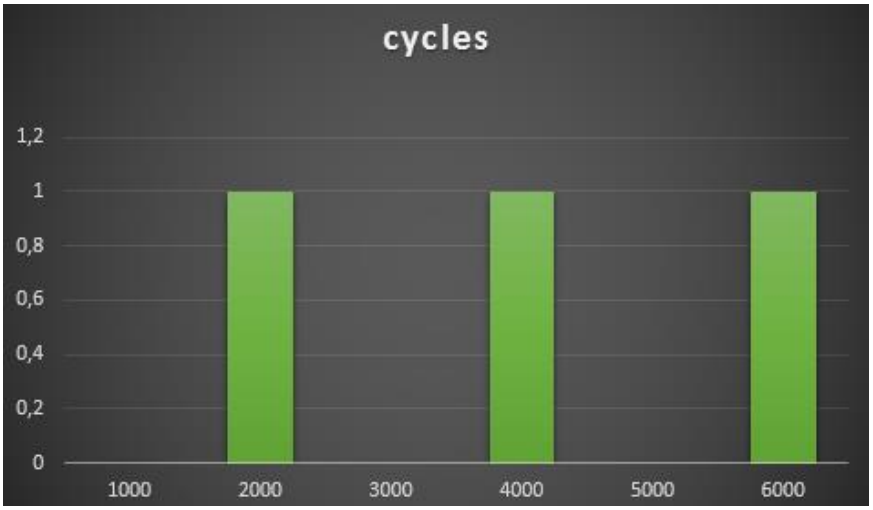



Figure 19.Bar plot of Rainflow counting

### 3.3.5.2 <u>Racetrack counting method</u>

Although the Rainflow counting method is the most common used, there are other counting methods that are important, In the case of the Racetrack counting method, only when the inclination of the direction changes we start a new cycle range, using the same example as we used for the Rainflow method, I´m plotting here using the Racetrack algorithm.

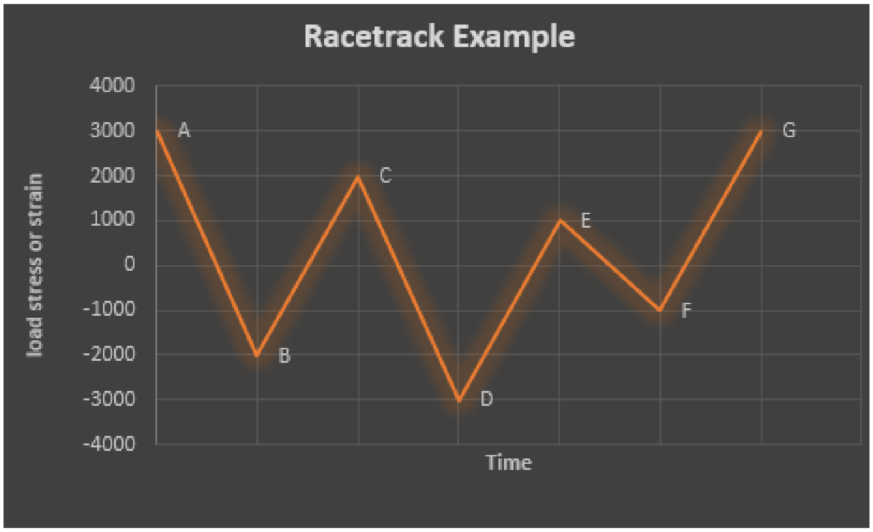



Figure 20. Wave example for Racetrack Counting Method

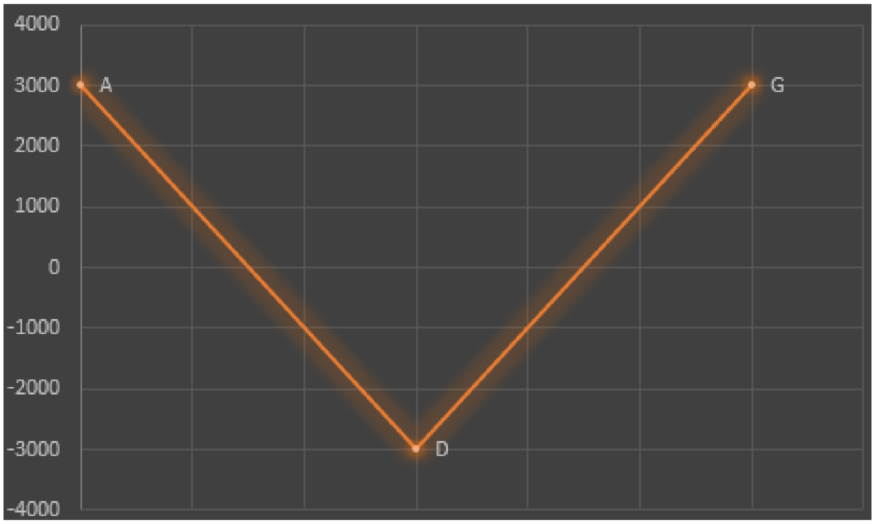


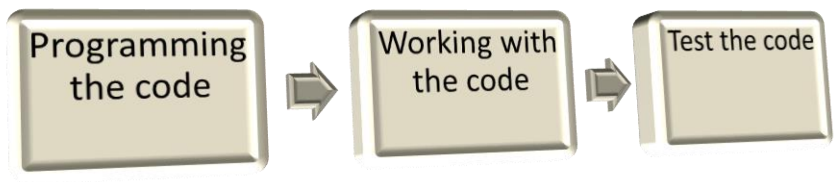

Figure 21. Racetrack count

This method is useful for condensing histories to those events when only a small part of the cycle is important and the rest can be considered useless, this method accelerates testing and computation and it permits to focus the attention on the important events.

# 4 COMPUTER PROGRAMMING

## 4.1 PREVIOUS CONSIDERATIONS

The software selection to develop this work is very important because not all software have the necessary tools to carry out the task. The main part of the work consists in:




As we can see the purpose of this software programming consists in developing a code, creating wav files with the correct format and characteristics and use some methods such as the Rainflow method or the Fourier Transform to obtain valuable information.

We selected first as our software, Maple Software, the problem was it has not all the functions we needed, that is why later we changed to Matlab which is more international and complete compared with Maplesoft, Although Maplesoft has not all the functions we need, it is an easy software and the creation of waves and graphic plotting is an easy task, that is why I am going to include some code in this work.

Our LFV 500-HH Test Machine, has not many options to work with wav files,

The wave-file must fulfill some properties to work fine on the controller:

- Supported data formats are wave type 1 (PCM integer Data 8 Bit unsigned, 16 Bit signed or 32 Bit
signed) and wave type 3 (PCM float data (32 Bit IEEE float).
- The wave file can have 1 or two channels. However, the second channel will be ignored if existing.
- Because the synthesizer reads the next value of the wave-file each control cycle, the sampling frequency of the wave-file must correspond to control cycle frequency if real-time generation of the set value is important. That frequency is 8106.128 Hz.

## 4.2 MAPLE SOFTWARE

Start working with MapleSoft is an easy task because it does not need extra files to run, so executing “Test.mw” file is enough to start working with it.

MapleSoft is a really delicate Software, this means that the commands have to be written exactly as the manual says, otherwise it would not be executed, capital letters, spaces between words etc… cannot be changed.

I am going to talk about the Maple file added .Although MapleSoft does not need extra files to run, it is necessary to load some commands in the beginning, they give us extra tools we may need during the work.

| | |
|---|---|
| To work with Audio | with(AudioTools) |
| To plot | with(plottools) |
| To work with signals | with(SignalProcessing) |

The main problem of this software is the way it creates sin wav files. First it is necessary to create the sin expression, and then the wave, the problem here is this sin wave is not created with a particular wave frequency, and our Frequency ranges is only from 0.2 HZ to 22 Hz. (see appendix A.1)

Other problems are for example, that MapleSoft does not allow to use Fourier Transform with arrays, which is the way the data from the wav files are represented, if this happen with this Fourier expressions, it will also happen with other future functions we might be interested to use here. The final problem I found using Maplesoft is I could not program a cycle counting method such as the RainFlow method.

However, Maplesoft still has some easy commands that can be useful in some situations such as reading wav files, plotting them or getting the array data from the wav file. With the command getdata(FileName) we can DoubleClick on the matrix (Figure 22) to get the information of the wave in a matrix format that we can export to excel for example.

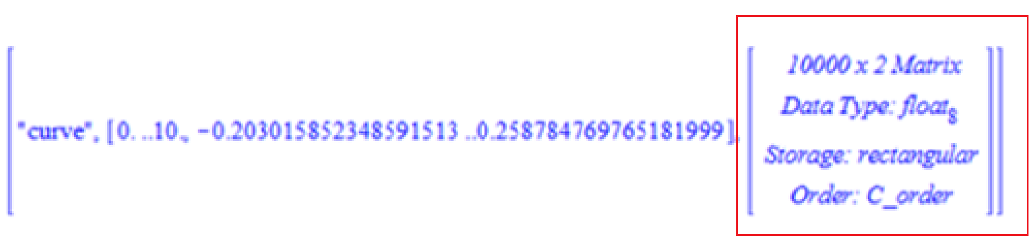



Figure 22. Matrix Data of a wave.

- Explanation of the main commands:

- To save the result from a command, the expression is: *name:=*
- If you let a space between mathematical expressions it has the same meaning as the equal function.
- Writing directories, we have to separate each subdirectory with double slash “\\”

## 4.3 MATLAB SOFTWARE

Matlab is a powerful tool which allows us to develop almost everything if you have a proper knowledge about it, I have develop here how to create wav files, how to work with them and their analysis using FFT , Rainflow method or Miner´s cumulative damage method.

### *4.3.1 SIMPLE WAVES*

Simple waves is the name of the file where the waves programming are included. One example, the Test File, it is the one we used to carry out the real test with our fatigue machine.

The Machine´s Software counts the wave cycles, not the number of times our wavfile is repeated, this means that to have clear information, we have to define the duration of our wavfile as the period of the wave, otherwise, we will not know the exact number of complete cycles before it breaks.

Here we have some plot examples of this Simple Waves

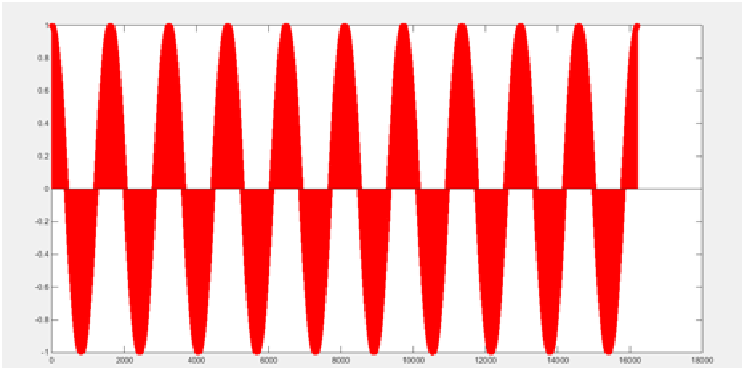


Figure 23.Cos wave, 5Hz Frequency

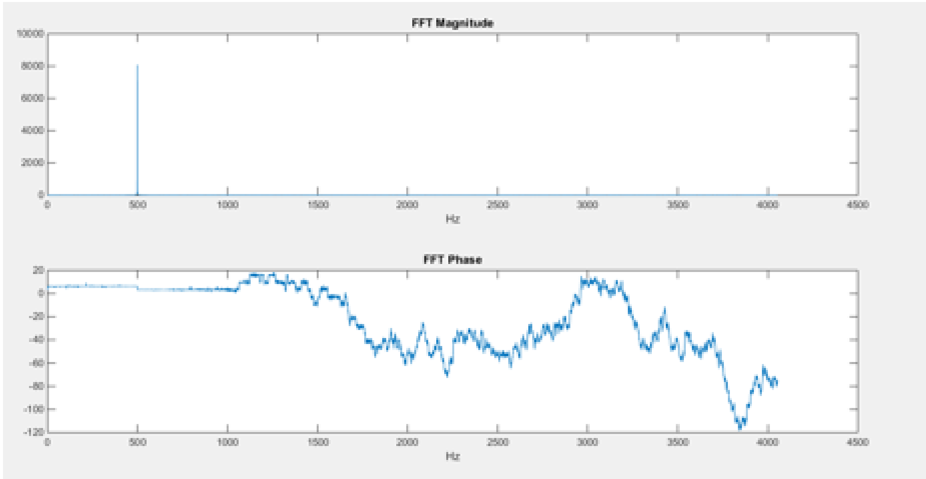



Figure 24. FFT analysis, 8106 Hz sample, 15Hz Frequency sinewave

In this case we are working with 16 bits, otherwise our machine´s software cannot read with the properties we want to, but if we create a 32 bits wave file with 2 sin waves, this FFT transformation is more obvious.

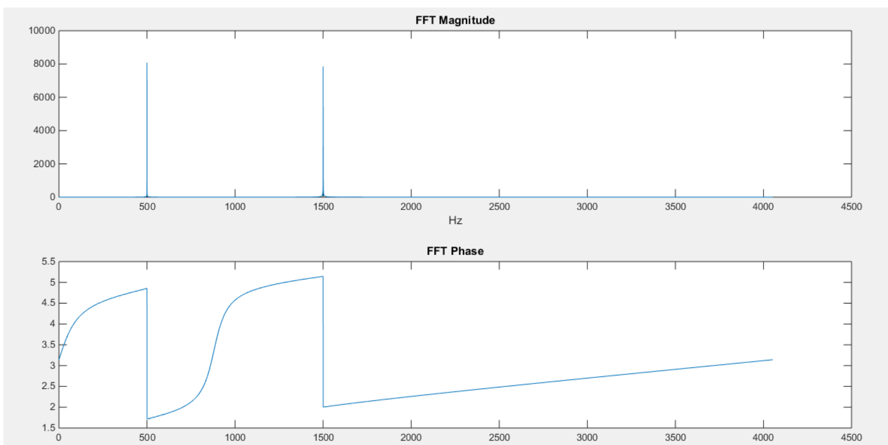



Figure 25. FFT analysis, 32 bits wave

### *4.3.2 RAINFLOW*

In this Rainflow part there are two different codes:

- Wave to Rainflow: this code graphics the number of cycles grouped, the way to use it is executing the "Plotting_rainflow.m" file,the rest are support files.

- Rainflow to wave: this code ,“loadingarrays.m” has to be executed to work with it, the rest of files are support files. It allows to load excel files or ASCII files and create wav files from it with the correct characteristics to work with our machine. Depending on what are we looking for we have to comment or uncomment part of the code, it also plot the Number of cycles and values.

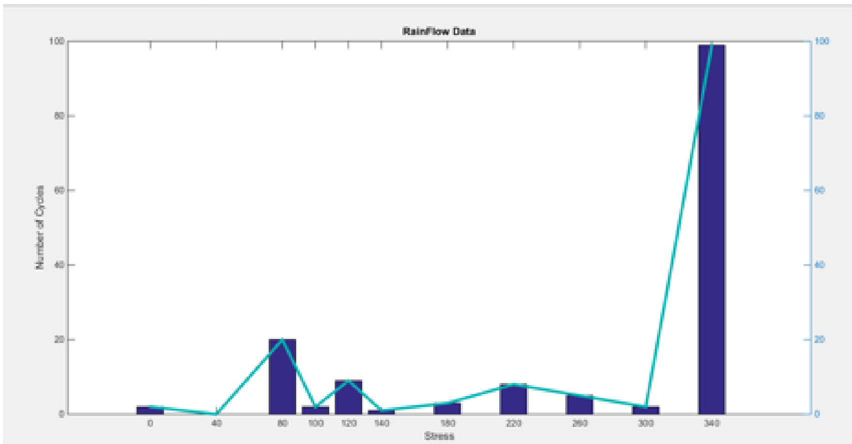



Figure 26. Rainflow plotting Data from an example

### *4.3.3 VIBRATIONDATA*

This is the best code of the collection, is not written by me, the author is a NASA scientific Thomas Irving who let me use it here. This part requires some instructions to follow every step so I am going to explain them here.

Vibrationdata File has more than 1300 Files, but all of them can be used from one, I recommend to use the file searcher of the File writing its time: “vibrationdata.m”

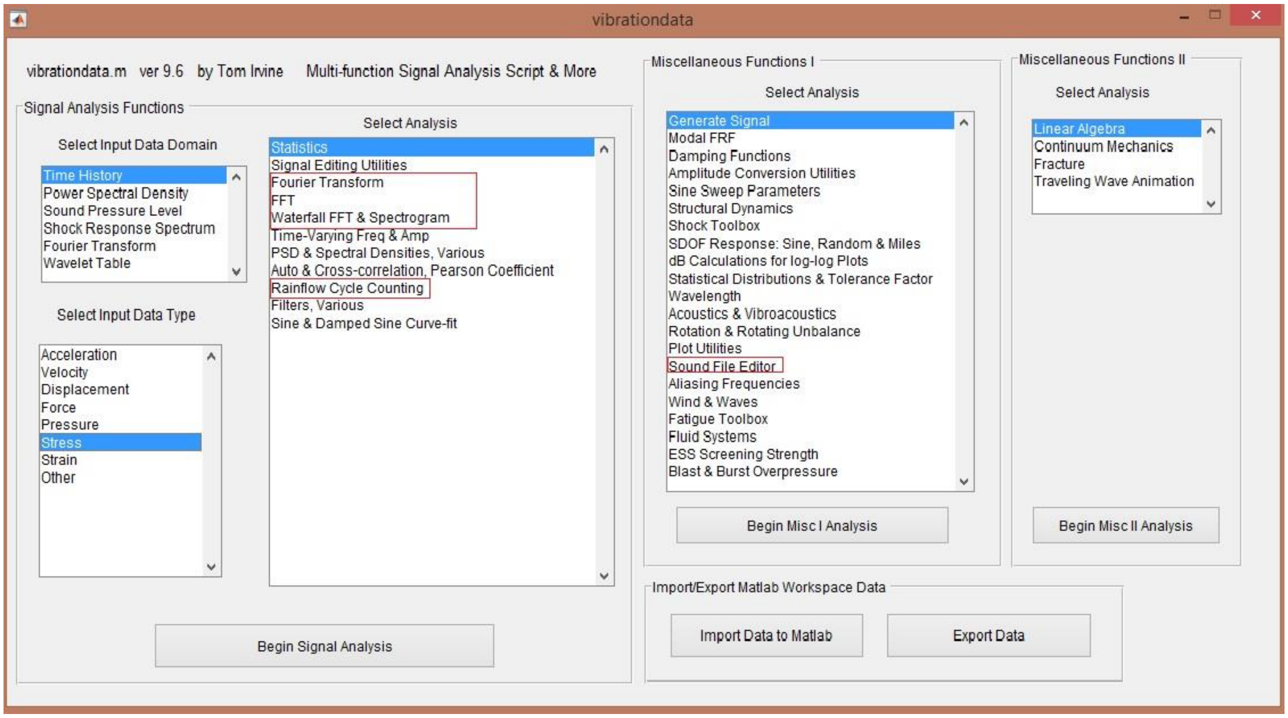



Figure 27. Vibrationdata Main menu

Here we can see the functions we are interested in, I recommend to take a look in the rest of them, they are also very interesting.

#### 4.3.3.1 Sound File Editor

An important function is the Sound File Editor. Clicking on it (see Figure 27.) and then in Begin Misc | Analysis this menu will appear:


Figure 28.Sound File Editor Menu

Here we can read wav File, see Figure 29

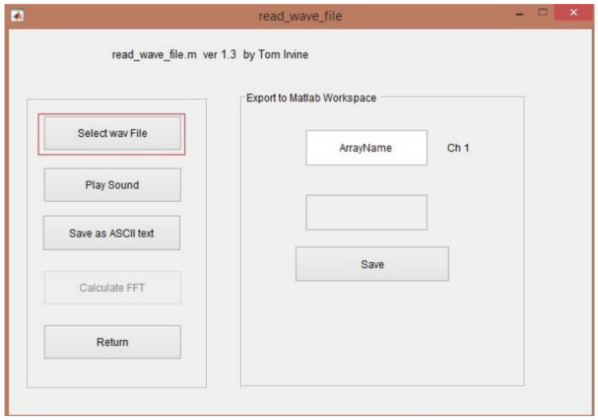



Figure 29. Read wav File menu

We can select here a wav file, for example one of the sin wav file we created previously and name the array data in the box, as an example I wrote ArrayName, saving it into the Matlab workspace, we can back to the previous menu by return button or the cross in the corner.

In the main menu (Figure 27) we can export now our array information by the function "ExportData". We can chose here the export format and we have to write the name of the Array we previously loaded into Matlab worksheet (Figure 29), there is also the function "Import Data to Matlab" in case we already had the data.

#### *4.3.3.2 Fourier options*

The "Fourier Transform" or "FFT" functions, are simple to carry out, just picking them and clicking on begin signal Analysis and following the stepts. It returns the same information as the "simpleWaves" Matlab Files I have talked about in the point 4.3.1, and in the Figure 30 we can see its return plot, as we can see it is the same as the other one.

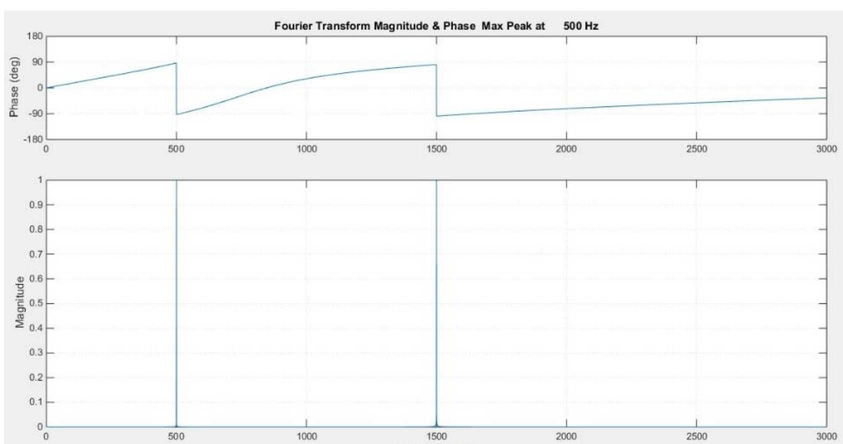



Figure 30. Fourier return plot

The “Waterfall FFT & Spectrum” shows a 3D image of our FFT Transform.First we have to load an Array and setting up the time and frequencies, then click on view processing options:

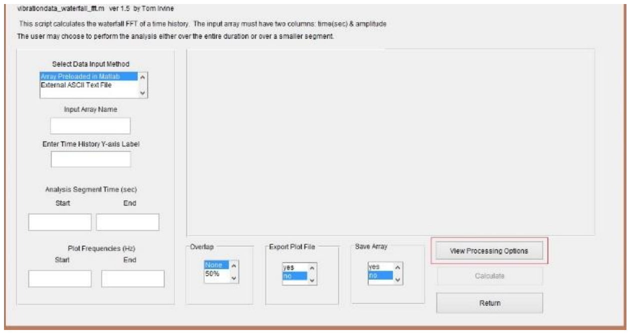



Figure 31. Waterfall FFT main menu

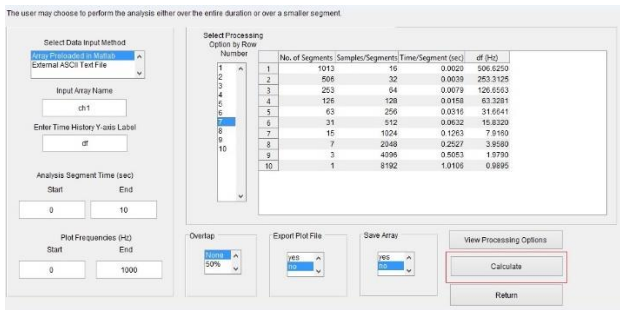



Figure 32. Waterfall FFT main menu-2

A good point to plot is around 40-60 segments, in this case number 5 or 6 would be a good option, after that, we can click on calculate:

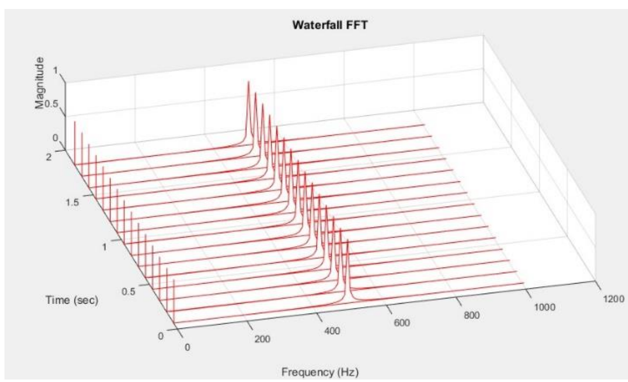



Figure 33. Waterfall FFT representation

#### 4.3.3.3 Rainflow Cycle Counting

The last Function I have used from here, is the “Rainflow Cycle Counting” Function. (see on Figure 27)

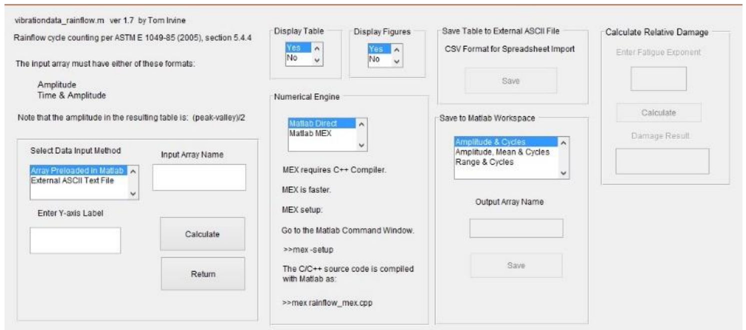



Figure 34. Rainflow cycle counting main menu

In this menu (Figure 34) we have to load the input Array name, and press on calculate, It will return a plot and a table with the Rainflow information, see figure 35.

| Lower Range | Upper Range | Cycles | Ave Amp | Max Amp | Min Mean | Ave Mean | Max Mean | Min Valley | Max Peak |
|---|---|---|---|---|---|---|---|---|---|
| 2.77 | 3.08 | 999.5 | 1.5 | 1.54 | -0.0275 | -2.93e-06 | 0.0274 | -1.54 | 1.54 |
| 2.46 | 2.77 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2.16 | 2.46 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.85 | 2.16 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.54 | 1.85 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.23 | 1.54 | 2000.5 | 0.711 | 0.734 | -0.842 | 0.000151 | 0.842 | -1.54 | 1.54 |
| 0.924 | 1.23 | 0.5 | 0.535 | 0.535 | -0.927 | -0.927 | -0.927 | -1.46 | -0.392 |
| 0.616 | 0.924 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.462 | 0.616 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.308 | 0.462 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.154 | 0.308 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.077 | 0.154 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0.077 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Figure 35. Rainflow information returned

Now we can calculate the relative Damage giving a Fatigue Exponent (Figure 36.) Or to save the information into an Array, (Figure 37) and the Miner´s cumulative Damage Calculation option appears:

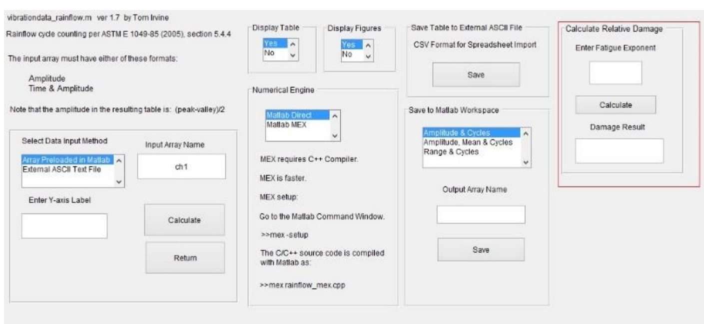



Figure 36. Relative Fatigue Damage


Figure 37. Miner´s Cumulative Damage Option

Now we can set up the data we want such as the material or units, loading our Stress Array we just have to press calculate to get the cumulative damage information, (Figure 38)

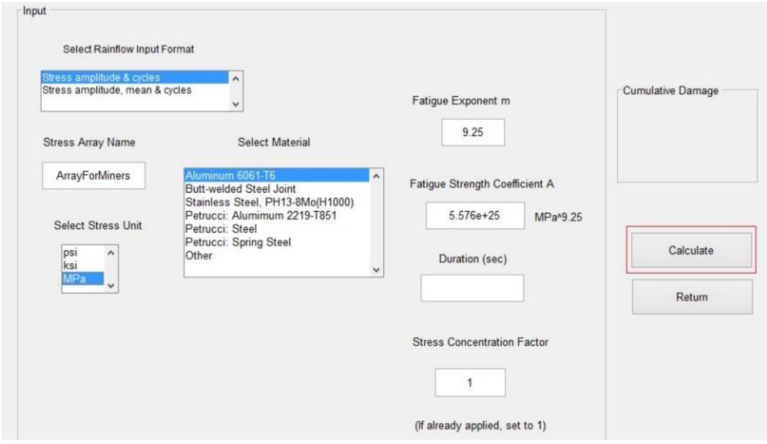



Figure 38. Miner´s Calculation menu

## 4.4 LFV 500-HH SOFTWARE

The LFV 500-HH software is called DION7, it is a software developed by the same company as the machine, (Walter-Bay), it only has one option to work with Wav files, but once the wav file is loaded, the way to work with it is the same as every wave we can create with the software as a "regular way". The only condition is that it has to have the characteristics explained in "4.1 PREVIOUS CONSIDERATIONS" topic.

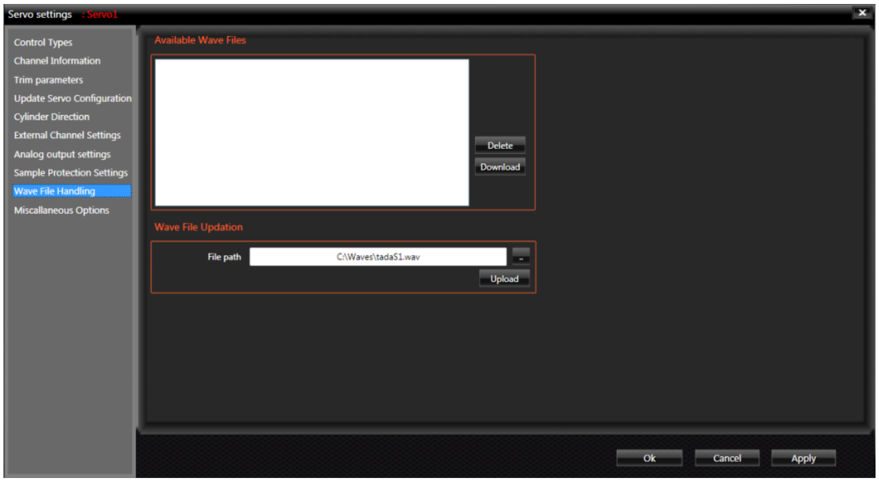



Figure 39. Dion7 software, wave load menu

We can follow the steps in the manual, DION7 FPI part, taking care of considerations such us the saving criteria, the structure of the FPI editor or the break criteria.

# 5 RESULTS

This work has two different parts, the programming part and the fatigue test part, I have been focused on the first one, only testing if the code works with the fatigue machine. We did not have any problem with it and we were able to carry out the tests properly, always taking care of the safety recommendations when we worked at the laboratory.

The programming part was especially delicate in this case, using two different software, finally we could work with wav files in a specific format and with special attributes, graphic them and going from wav files to arrays and vice versa. I have been also, with the help of some private code, able to improve our code programming offering more plot options and cumulative damage calculations.

The code is included with this memory paperwork and can be used for future tasks.

# 6 CONCLUSIONS

When I started working on this Thesis I was very scared because the background knowledge I had about the fatigue was only the fundamental theory, I only had worked with the basics topics of this area, in addition to this, I never worked with Matlab or similar software so my work was to learn how to use them. In the beginning I started with Maplesoft because we thought it could do the work easier, but then we had to switch into Matlab because Maplesoft had not enough functions for us, this made me lost a great amount of time, because after some time learning Maplesoft I had to start also learning Matlab. However I am glad about what I have learned, I have learned new knowledge about fatigue theory, and about programming with Matlab, which is one of the most important software for engineers, and now I am more prepared to mechanic tasks or jobs I may do.

Although I have learnt to much about Matlab, the short time I had to do this work, and the fact that I had to learn it from zero previous knowledge, make me feel a little bit disappointed because I could not carry out many tests or to work with the results, analyzing them and seeing how pieces behave, the first idea was to work with an hydraulic company, using their data, and that was probably the most interesting part, seeing real problems in real life, sadly we could not make many tests.

Nevertheless I hope this work will be useful for future people, I think I have made a base for future works where they will be more focused on the laboratory part than the programming or theory part.

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Stress range histories and Rain Flow Counting by John waegter

Fatigue notes , University of Zaragoza

## ***APPENDICES***

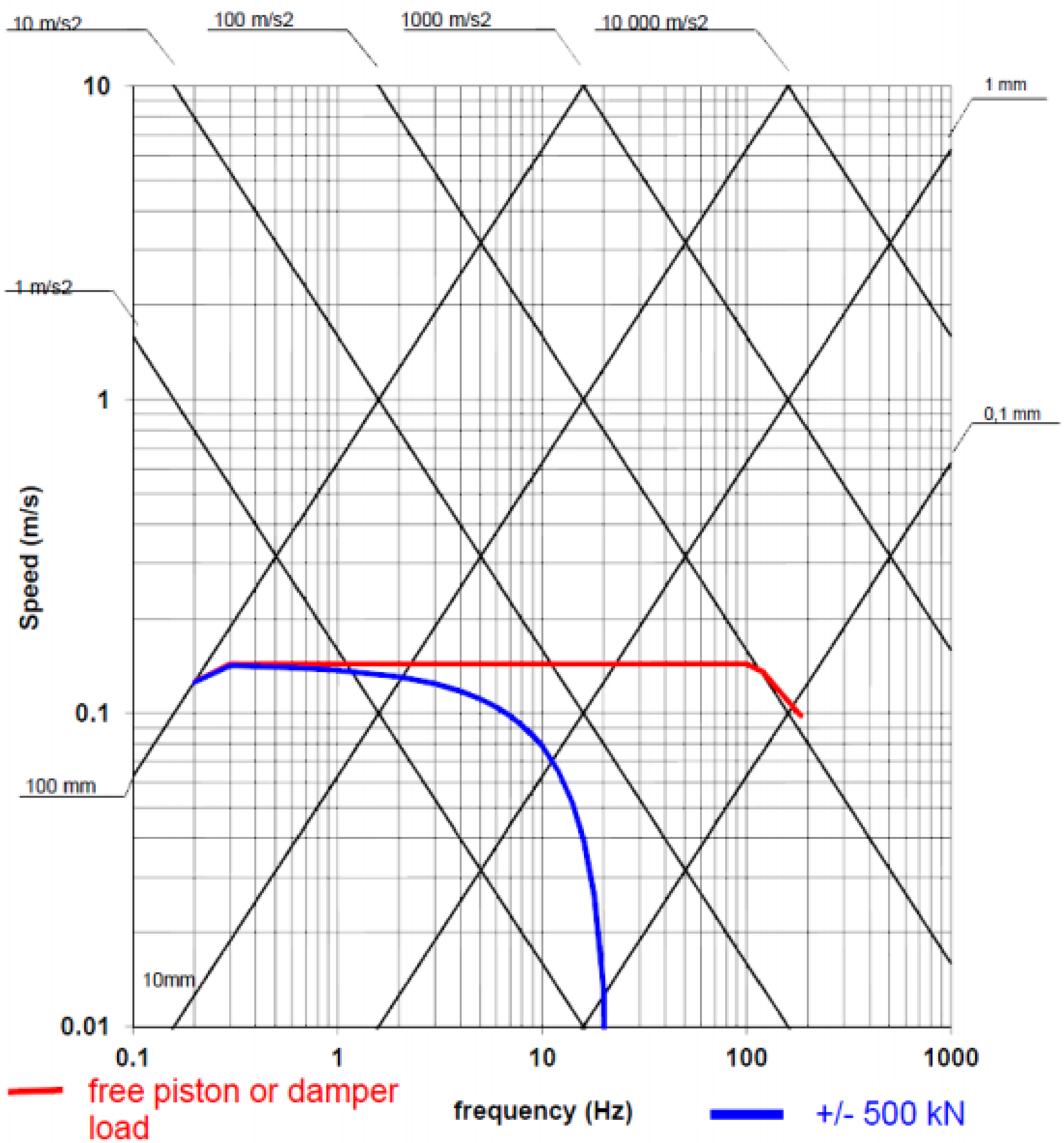
APPENDIX A.1

Temperature range: -100 - +600 °C
Dimensions: 350 mm x 300 mm x 550 mm (S x L x K).

Dynamic testing frequency characteristics:

| **Frequency (Hz)** | **Amplitude (+- mm piston stroke)** | **Speed m/s** | **Acceler $m/s^2$** |
|---|---|---|---|
| **0.2** | 100.00 | 0.13 | 0.2 |
| **0.3** | 75.26 | 0.14 | 0.3 |
| **0.4** | 56.18 | 0.14 | 0.4 |
| **0.5** | 44.74 | 0.14 | 0.4 |
| **0.6** | 37.11 | 0.14 | 0.5 |
| **0.7** | 31.66 | 0.14 | 0.6 |
| **0.8** | 27.57 | 0.14 | 0.7 |
| **0.9** | 24.39 | 0.14 | 0.8 |
| **1** | 21.85 | 0.14 | 0.9 |
| **2** | 10.40 | 0.09 | 1.6 |
| **3** | 6.59 | 0.08 | 2.3 |
| **4** | 4.68 | 0.07 | 3.0 |
| **5** | 3.54 | 0.05 | 3.5 |
| **6** | 2.77 | 0.04 | 3.9 |
| **7** | 2.23 | 0.03 | 4.3 |
| **8** | 1.82 | 0.02 | 4.6 |
| **9** | 1.50 | 0.00 | 4.8 |
| **10** | 1.25 | 0.08 | 4.9 |
| **12** | 0.87 | 0.07 | 4.9 |
| **18** | 0.23 | 0.03 | 3.0 |
| **20** | 0.10 | 0.01 | 1.6 |
| **22** | 0.00 | 0.00 | 0.0 |

APPENDIX A.2


10 m/s2
100 m/s2
1000 m/s2
10 000 m/s2
1 mm
1 m/s2
0,1 mm
100 mm
10mm
10
1
0.1
0.01
Speed (m/s)
0.1
1
10
100
1000
frequency (Hz)
free piston or damper load
+/- 500 kN

APPENDIX A.3

Machine Information.

| | |
|---|---|
| The greatest test Force (stat. / Dyn.) | 500 kN |
| Most of the test piece size | 6000 mm x 1200mm x 1800mm (P x L x K) |
| The maximum dynamic testing amplitude | +/- 200 mm |
| Transition Resolution | < 0.001 mm |
| Transition Accuracy | +/- 0.5% |
| Maximum piston speed | 2 m/s |
| the rigidity of the frame | 1200 kN/mm |