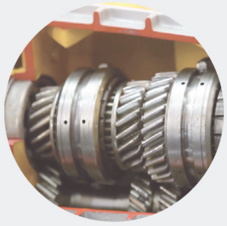
INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO

MESTRADO EM ENGENHARIA MECÂNICA






Create Cost Effective Post Processing Techniques for Multiple Measured and Simulated Components of CVT Transmissions

LUÍS ANTÓNIO SALVADOR MARTINS

novembro de 2018

POLITÉCNICO DO PORTO

CREATE POST PROCESSING TECHNIQUES FOR MULTIPLE MEASURED AND SIMULATED COMPONENTS OF A CVT TRANSMISSION

Luís António Salvador Martins

2018

ISEP – School of Engineering, Polytechnic of Porto

Mechanical Engineering Department

POLITÉCNICO
DO PORTO

Instituto Superior de Engenharia do Porto

CREATE POST PROCESSING TECHNIQUES FOR MULTIPLE MEASURED AND SIMULATED COMPONENTS OF A CVT TRANSMISSION

Luís António Salvador Martins

1130410

Dissertation presented to ISEP – School of Engineering to fulfil the requirements necessary to obtain a Master's degree in Mechanical Engineering, carried out under the guidance of Doctor Francisco José Gomes da Silva, Adjunct Professor and Doctor Raul Duarte Salgueiral Gomes Campilho, Adjunct Professor.

2018

ISEP – School of Engineering, Polytechnic of Porto

Mechanical Engineering Department

POLITÉCNICO DO PORTO

JURY

President

Manuel Jorge Dores de Castro, PhD

Adjunct Professor, Department of Mechanical Engineering, ISEP

Supervisor

Francisco José Gomes da Silva, PhD

Adjunct Professor, Department of Mechanical Engineering, ISEP

Second supervisor

Raul Duarte Salgueiral Gomes Campilho, PhD

Adjunct Professor, Department of Mechanical Engineering, ISEP

Examiner

Ricardo José Alves de Sousa, PhD

Auxiliar Professor, Department of Mechanical Engineering, University of Aveiro

ACKNOWLEDGEMENTS

Firstly, I would like to express my sincere gratitude to my coordinators Prof. Francisco Silva and Prof. Raul Campilho for the continuous support of my Master's study and related research, for their patience, motivation, and immense knowledge. Their guidance helped me in all the time of research and writing of this thesis. I could not have imagined having better advisors and mentors for my Master's study.

My sincere thanks also go to Gert Heirman, Naresh Kalidindi and Hervè Bratec, who provided me with an opportunity to join their team as an intern, and who gave access to the research facilities. Without their precious support, it would not be possible to conduct this dissertation. I thank my fellow teammates in for the stimulating discussions and for all the fun we have had in the last seven months. Also, I thank my friends in the following institution Instituto Superior de Engenharia do Porto.

Last but not the least, I would like to thank my family and my girlfriend: Ana, Cristiano and Inês, for supporting me spiritually throughout writing this dissertation and my life in general. This dissertation stands as a testament to your unconditional love and encouragement.

KEYWORDS

Continuously Variable Transmission, Hydraulic Block, Gear Measurements, road Load Data Acquisition, Programming, Algorithms

ABSTRACT

The automotive industry requires continuous innovation in order to fight the high competitiveness in this sector. More than ever, fuel economy, low emissions and comfort are the main goals when designing a vehicle. Continuously Variable Transmissions (CVT) are a type of transmissions that meet with those features and it can be the future of automatic transmissions.

The presented dissertation was developed during an internship in a company, specialist in the development and production of CVT transmissions, designated by Punch Powertrain NV, located in Sint-Truiden, Belgium. The work was incorporated in the Research and Development (R&D) department, in the team of simulation, where it was possible to enhance the academic experience.

This work is based on a need to post-process the results of several measured and simulated scenarios. Firstly, it was proposed to analyse the interference between the components of a hydraulic block. After the block is simulated individually, the inside walls can deform and it is important to analyse if there is interference with the movable components. Secondly, there are corrections done on gears. These corrections are evaluated through gear measurements, which need to be processed to determine if the modifications are within the nominal parameters. The last task was to analyse exported data from road load tests. In each transmission, five accelerometers are installed that record the loads subjected in the three coordinates. These files are read and, then, processed using an algorithm of a counting method, that can predict the cycles of each accelerometer for the different loads. All results are validated by the team leader and the specialists of each field. In the end, the internship allowed to increase the knowledge obtained from the Master's.

PALAVRAS CHAVE

Transmissão Continuamente Variável, Bloco Hidráulico, Medições em Rodas Dentadas, Aquisição de Dados de Carga em Estrada, Programação, Algoritmos

RESUMO

A indústria automóvel exige uma inovação contínua, de forma a combater a elevada competitividade neste setor. Mais do que nunca, economia de combustível, baixas emissões e conforto são as principais características na hora de desenhar um veículo. Transmissões Continuamente Variáveis (CVT) são um tipo de transmissão que cumpre esses objetivos e pode ser o futuro das transmissões automáticas.

A presente dissertação foi desenvolvida durante um estágio numa empresa especialista no desenvolvimento e produção de transmissões CVT, com o nome de Punch Powertrain NV e localizada em Sint-Truiden, Bélgica. O trabalho foi inserido no departamento de Inovação e Desenvolvimento (I&D), na equipa de simulação, onde foi possível enriquecer a experiência académica.

Este trabalho teve por base a necessidade de pós-processar os resultados de diversos cenários medidos e simulados. Em primeiro lugar, foi proposto analisar a interferência entre os componentes de um bloco hidráulico. Depois do bloco ser simulado individualmente, as paredes interiores podem deformar e é importante analisar se existe interferência com as componentes móveis. Em segundo lugar, existem correções feitas em rodas dentadas, para que possam trabalhar corretamente. Então, estas correções são analisadas através de medições, que precisam de ser processadas para determinar se as modificações estão dentro dos parâmetros nominais. A última tarefa foi analisar informação exportada dos testes de carga na estrada. Em cada transmissão, são instalados cinco acelerómetros que registam as cargas submetidas nas três coordenadas. Esses ficheiros são lidos e, depois, processados usando um algoritmo de contagem, que consegue prever os ciclos de cada acelerómetro para as diferentes cargas. Todos os resultados são validados pelo líder de equipa e pelos especialistas de cada área. No final, o estágio permitiu aumentar o conhecimento obtido durante o mestrado.

LIST OF SYMBOLS AND ABBREVIATIONS

List of abbreviations

2D	Two-Dimensional
AMT	Automated Manual Transmission
AT	Automatic Transmission
AWD	All-Wheel Drive
BEM	Boundary Element Method
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CFD	Computational Fluid Dynamics
CVT	Continuously Variable Transmission
CVXOPT	Python Software for Convex Optimization
DCT	Dual Clutch Transmission
EU	European Union
EV	Electric Vehicle
FDM	Finite Difference Method
FEA	Finite Element Analysis
FEM	Finite Element Method
FVM	Finite Volume Method
GD&T	Geometric Dimensioning and Tolerancing
GDP	Gross Domestic Product
GUI	Graphic User Interface
ICE	Internal Combustion Engine
ISO	International Standard Organisation
MBD	Multibody Simulation
mph	Miles per hour
MT	Manual Transmission

NVH	Noise, Vibration and Harshness
PD	Product Development
PHEV	Plug-in Hybrid Electric Vehicle
QP	Quadratic Programming
R&D	Research and Development
S-N	Stress-life
TDMA	Tri-Diagonal Matrix Algorithm

List of units

°	Degrees
bar	Pressure Unit
GPa	Gigapascal
mm	Millimetres
MPa	Megapascal
rad	Radians
µm	Micrometres

List of symbols

d	Reference circle diameter
d_b	Base diameter
X	Profile shift
z	Number of teeth
α_n	Normal pressure angle
α_t	Transverse pressure angle
α_{yt}	Transverse pressure angle at Y-cylinder
β	Helix angle
β_b	Base helix angle
β_i	Software Ponderation Index
Ψ	Tooth thickness half angle (reference circle)

Ψ_y	Tooth thickness half angle (lead measurement diameter)
ω_i	Property Importance Index

GLOSSARY OF TERMS

Term	Designation
Accelerometer	a device that measures an acceleration
Bolt preload	The load applied to a bolt as a result of it being installed, before any external loads are applied (e.g. tightening the nut on a bolt)
Gear misalignment	Misalignment implies the axial shifting of the position of the meshing surfaces due to either deflections or errors in the manufacture of the gears and their housings [1]
Passenger car	Motor vehicle designed and equipped mainly for transporting people, with a maximum of nine seats [2]
Pressure relief valves	Pressure relief valves are designed to open at a pre-set pressure and discharge fluid until pressure drops to acceptable levels (Punch Powertrain NV)
Tensile strength	The maximum engineering stress, in tension, that may be sustained without fracture. Often termed ultimate (tensile) strength [3]
Yield strength	The stress required to produce a very slight yet specified amount of plastic strain; a strain offset of 0.002 is commonly used [3]

FIGURES INDEX

TABLES INDEX

INDEX

INTRODUCTION

1.1 Contextualization

1.2 Main Goals

1.3 Methodology

1.4 Thesis Structure

1.5 Welcoming Company

1 INTRODUCTION

1.1 Contextualization

In the last one hundred years, vehicles have changed our lives and provided a better mobility which people exploit in plain commercial and personal activities. The powertrain system provides the driving force behind the mobility. The output from the power source – nowadays, dominated by the Internal Combustion Engine (ICE) – is controlled by a transmission and a driveline to deliver tractive effort to the wheels. Collectively, all these components are referred to as the powertrain system, which is controlled by the driver. Drivers, who are also viewed as discerning customers by the vehicle manufacturers, have a large range of criteria in choosing a car. Top speed, acceleration, fuel economy and towing capacity are some of the more quantitative features [4]. Also, non-technical features such as driveability, comfort and driving pleasure play a huge part in the sales success of vehicles. Thus, the current state of the art is categorized by the following topics: Environment, Traffic, Vehicle and Transmission [2].

The engine and transmission must be considered as one functional unit, also known as "powertrain matching" and "engine/transmission management". The use of a transmission has an impact on different areas such as traction availability, fuel consumption and reliability, service life, noise levels and user-friendliness of the vehicle. Transmission design engineering has been supplemented by several variants. Along with the manual two-stage countershaft transmission, usually for longitudinal engines, and single-stage countershaft transmission, chosen for transverse engines, now have many variants such as automatic transmissions (AT), continuously variable transmissions (CVT), dual clutch transmissions (DCT) and transmissions for all-wheel drive (AWD) [4]. The systematic design technique developed in the 1960s and the growing use of computer-aided design (CAD) tools are resulting in a reducing development cycle. This tendency is reinforced by competitive pressures and the systematic product planning is another important influence in this regard.

The majority of transmissions used on road vehicles are manual and conventional automatic transmissions. However, there are alternative proposals available which can transmit power with a stepless change of ratio, known as CVT. To be precise, a CVT allows an input and output ratio, uninterruptedly without any steps, in a range between two finite limits. To provide the power and speed for the vehicle, transmissions mechanism is divided into three main categories: hydraulic systems, variable radius pulleys and traction drives. As it happens on conventional transmissions, the hydraulic system provides lubrification, cooling and control. The supply is obtained from a pump which determines the maximum operating pressure on the control system. This operation is controlled by solenoids and valves, which are less in a CVT, compared to a normal AT.

1.2 Main Goals

The proposed main goal of this work was to create post-processing techniques for different measured and simulated scenarios using a programming language. These techniques were divided into three topics, as follows:

- Create a script which verifies that the operation of valves is guaranteed in all operating points of the hydraulic block;
- Create a script which automates CAE analysis of many possible deviations in spline geometry, to ultimately predict the resulting deviations of gear geometry;
- Refine the existing post-processing capabilities to distil a load collective which can be used for fatigue analysis.

1.3 Methodology

Despite this work is divided into three topics, there is one common task between those topics, which is researching about programming languages and choosing the most suitable one.

To guarantee the operation of the valves into the hydraulic block it was necessary to:

- Study all components and theoretical aspects related to the hydraulic block;
- Study the possible reasons for the faulty operation of the valves;
- Choose the best approach to predict the operation of all components, jointly with the company;
- Collect all data related to the simulation of the hydraulic block;
- Develop numerical scripts, according to the chosen approach;
- Validate all results from the developed program.

To analyse the gear geometry, it was necessary to:

- Research and study about theoretical aspects related to gear specifications and gear corrections;
- Collect all the gear measurements data and understand the main outputs of the results;
- Choose the method to process these data;
- Develop of the script, according to the previously chosen method;
- Present and validate of all results, together with gear experts.

To refine the existing programs, used for fatigue analysis, it was necessary to:

- Study all the road load tests and the location of the components, which were subject to the tests;
- Research about the output files, extracted from the road load software;
- Develop a script to read and export the data from the previous files;
- Choose the best method to process the previous data;
- Search for programs related to the chosen method;

- Process and validate all data, jointly with the experts.

1.4 Thesis Structure

This dissertation structure is divided into six major chapters. The first chapter is a contextualization about the project and the goals to achieve in the internship. The second section is related to the theoretical characteristics of the transmissions design and numerical software. The third chapter comprises the analysis of the interference in the hydraulic block. The fourth chapter is related to the analysis of the gear measurements. In the fifth chapter, it is presented the road load tests files and how to process it, without using the original software. The final chapter includes all conclusions about the company gaining’s, personal skills developed and it also presents proposals for future works.

1.5 Welcoming Company

Punch Powertrain is an independent full system supplier of powertrains, located in Sint-Truiden, Belgium. The company has more than 40 years of experience in the production of CVT transmissions. Punch also offers electric powertrains such as Plug Hybrids and Electric Vehicles, as well as DCT transmissions. The headquarters is located in Belgium and other sites are placed in Germany, Netherlands, Iran, India, China and Malaysia. The internship lasted for seven and a half months, starting in the middle of February until the end of September. During this period, the developed work was guided by Gert Heirman, as a Team Leader, and Naresh Kalidindi, as a Mechanical Engineer, both established in the CAE team.

BACKGROUND

2.1 Automotive Industry and Development

2.2 Transmissions

2.3 Fatigue Analysis

2.4 Mechanical Design

2.5 Advanced Software for Solving Numerical Problems

2 BACKGROUND

2.1 Automotive Industry and Development

2.1.1 Brief History of Automotive Industry

As with many inventions, there is no defining point in history that states, "Today the car was invented". Rather it is an evolution of ideas and actions. Since its rather modest beginnings, the automotive industry has grown to become the main industrial employer worldwide. Automotive industry can be divided into two major periods. The first one explores the several discoveries and inventions that will culminate in the first vehicle. The other era defines the evolution of the automotive industry and technologies used in vehicles [5]. Nowadays, more than twelve million people produce a staggering seventy million vehicles each year [6].

Before Henry Ford taking car manufacture to new heights, the first motorised vehicle had already been presented for nearly one hundred years ago. Most historians attribute the ultimate jour of the first motorized vehicle to Nicholas Joseph Cugnot, an engineer and mechanic in the French Military. The man responsible for the next big breakthrough was Niklaus August Otto, by inventing the successful four-stroke engine known as the Otto Cycle. In 1886, Benz received the first patent for a gas-fuelled car with his three-wheeled automobile. In the same year, Daimler designed the world's first four-wheel automobile. Both vehicles can be seen in Figure 1. Three years later, Daimler announced a new vehicle with a four-speed transmission which could reach speeds of ten mph. Since then, the automotive industry has been growing at a high pace. When Ford Motor Company introduced the Model T in 1908, the automotive industry changed again. Improving the assembly line process, Ford reduced the production cost and the assembly time. Each Model T was assembled in 93 minutes [5].

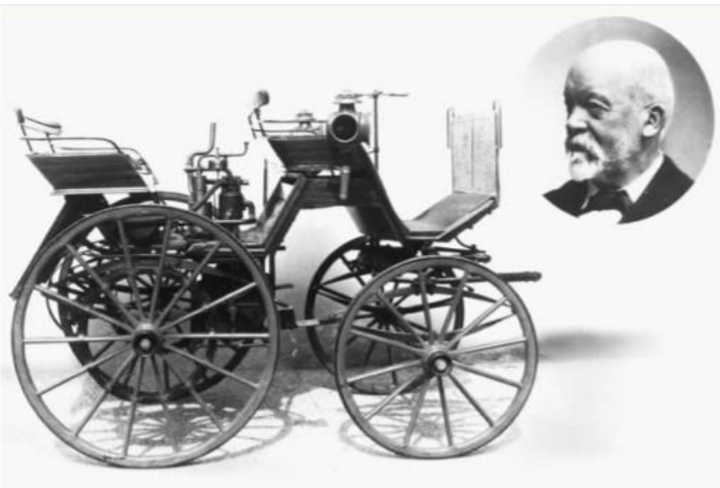


Figure 1 - The world's first four-wheeled automobile [5]

The history of the car was defined by other inventions, which improved comfort, security and efficiency, leading to the car as we know nowadays. Such achievements are represented in Figure 2 [7].

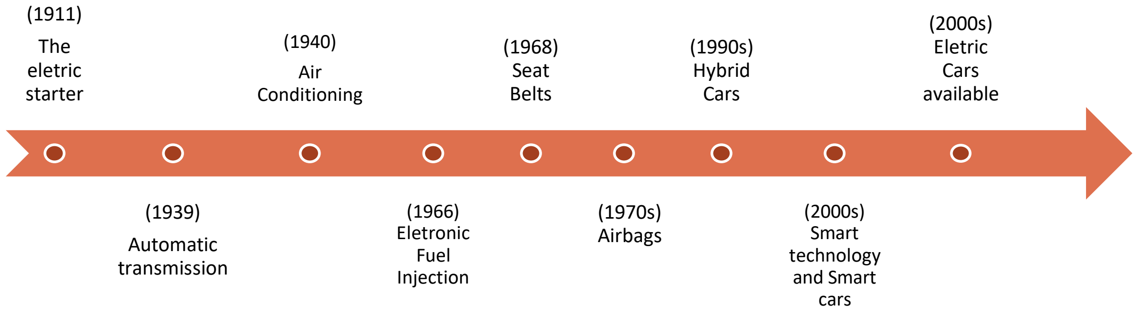


Figure 2 - The biggest achievements in the history of the automotive industry [7]

Not only improvements in comfort and safety made the difference in the automotive industry. Also, production systems were changed to reduce costs and time. Production systems and their evolution represent an example of the changing nature of the form and function of standardisation. In Table 1, it is explained several production systems.

Table 1 - Different production systems in the Automotive Industry [8]

Period	Production System	Description
Before 1911	Craft production	Based on plans and detailed drawings, with measurements, angles and other specifications. Produced based on hand manufacturing, depending on skills, experience and knowledge level of the workers.
1911	Taylorism and Standardisation	Introduced standards on how to do a task and defined work sequences, using standardised machines and tools. A control over production process led to an efficient flow.
1914	Ford's Mass Production	Based on Taylorism ideologies, combined with technological advancement. First production system represented by mass production. Main goals: technical, work and social standards.
1941-1992	TPS (Toyota Production System)	Focus on reducing any wasteful and non product-value adding activity. TPS is based on self-regulation, involvement and participation of the worker in the working processes and a system of social integration and control. TPS contributes to an evolutionary learning environment.

1989-1993	Reflective Production System of Volvo Uddevalla	The concept of production is concerned with the human being within production, instead of focusing on technology.
2002-today	Standardised Production System	Automakers production systems are focused on TPS and lean production systems. The key elements of these systems are group work, standardisation, quality, Just-in-time and continuous improvement.

Nowadays, automobile manufacturers still innovate at a quick rate, in particular, over the last fifty years. The growth of large companies has ended the competitiveness of small enterprises, reducing from more than fifty automakers to nearly ten constructors and led to a global reach from these companies [9]. The vehicle life cycle starts with the manufacturing of the extracted raw materials into parts and products. The original equipment manufacturers (OEM) are responsible for contributing to the final manufacturing/assembly stage. After this stage, the vehicle spends a long period of time in the use phase. In the past, the average life cycle has been reported around 12 years. Nowadays, the median life cycle increased to near 16 years. Around 5% of the vehicles still drive on the road after thirty years of operation. In Figure 3, there is a simplified diagram of the vehicle life cycle [10].

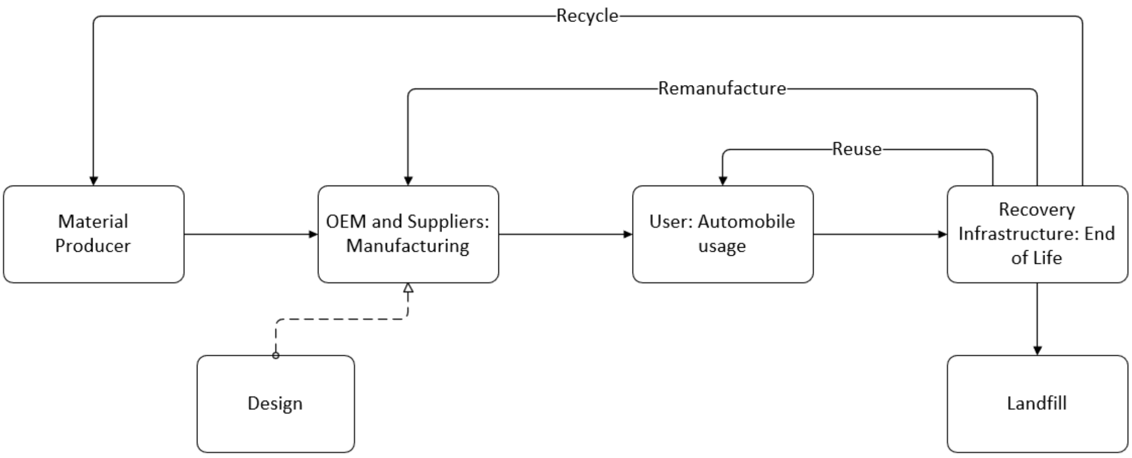


Figure 3 - Automobile Life Cycle [10]

2.1.2 Automotive industry impact on the worldwide economy

Automotive industry represents a large slice of global economic activity with connections to other industries and sectors. These linkages are in respect to the marketing, shipping, insurance and service sectors. Since World War II, a global interest in automobiles has been rising steadily, with exception of marked economic decline or the aftershock of oil crises [11]. This industry contributed to a strong growth in employment, production, economic output and exports [12]. However, the last global financial crisis in 2009 significantly affected the automotive manufacturing, leading to a market crash [13].

In the European Union (EU), this industry represents 11% of total employment in manufacturing [6] and 1% of total employment in the economy [14]. However, the automotive sector is direct and indirectly involved in employment, like transports (passengers transport), construction (roads, bridges and tunnels) and automobile use (sales, maintenance and renting or retail sale). In Figure 4, it is shown how many Europeans are working direct and indirectly in the automotive sector [6]. Although 80% of growth in the sector is expected to occur outside the EU, this area still employs twelve million people in EU [15].

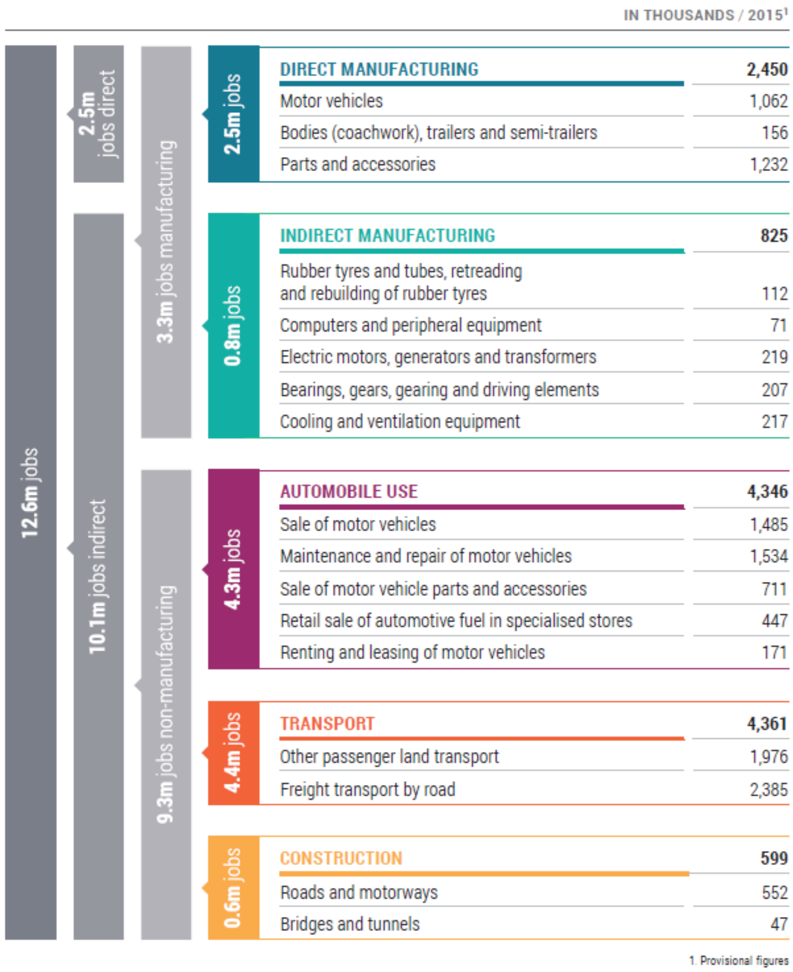


Figure 4 - Automotive sector: direct and indirect employment in the EU [6]

The automotive industry is decisive for Europe’s prosperity and accounts for 4% of the EU’s gross domestic product (GDP). Apart from the parallel industries involved in the automobile industry, the other three main topics of the chain, Upstream, Core

Automotive and Downstream, follow linked between each other. The adjacent industries are involved in all previous processes, as shown in Figure 5 [15].

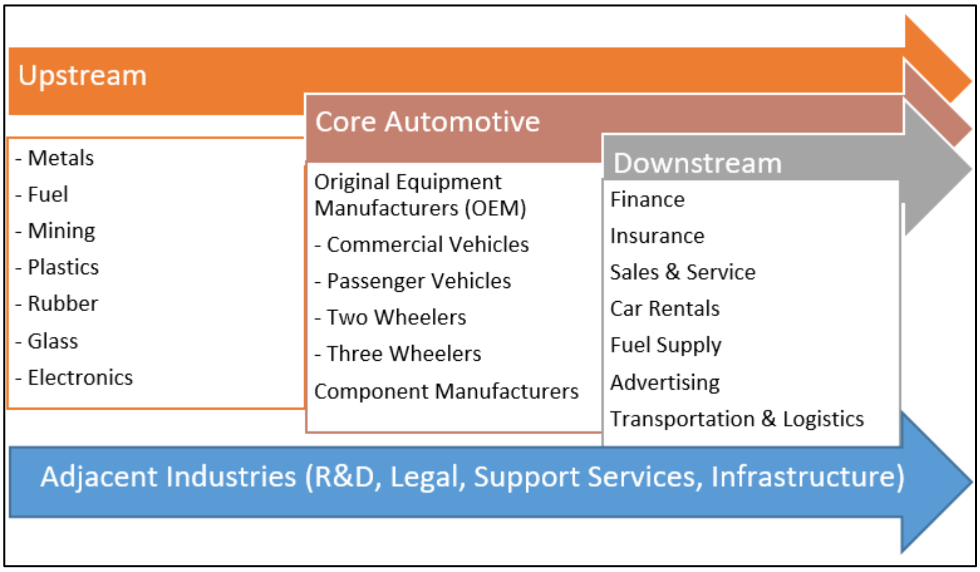


Figure 5 - Automotive Value Chain [15]

In terms of production, the principal producers remained almost unchanged, except for China. Their automotive industry has grown exponentially in the last twenty years, taking the lead. Next to China, three world great powers remain the biggest manufacture: Europe, North America and Japan/Korea, as shown in Figure 6 [6].

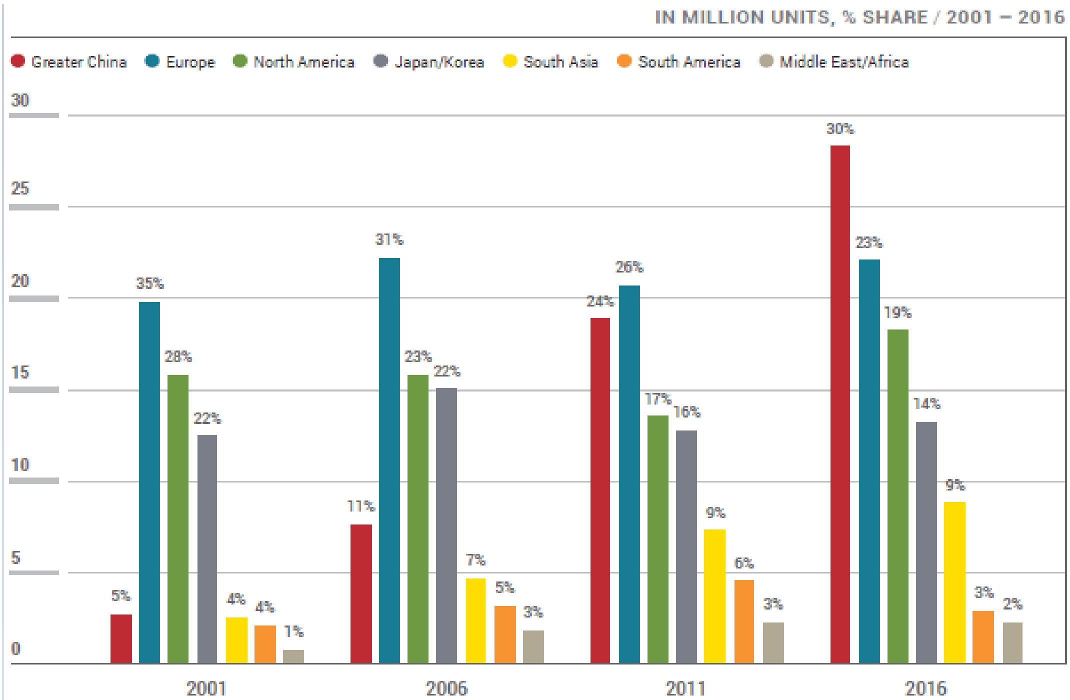


Figure 6 - World motor vehicle production [6]

The step after production is to sell the vehicles and sales are also a big foot in the worldwide economy. Once again, the Asian market was the one that grown more, leading to almost 25 million vehicles in 2017 [16]. The growth of car sales worldwide has been remarkable, reaching almost the 80 million cars. From twenty years ago until now, the sales doubled. Especially in the last four years, there have been recorded car sales maximums every year. It is expected that, in 2018, sales will exceed the 80 million cars, as shown in Figure 7.

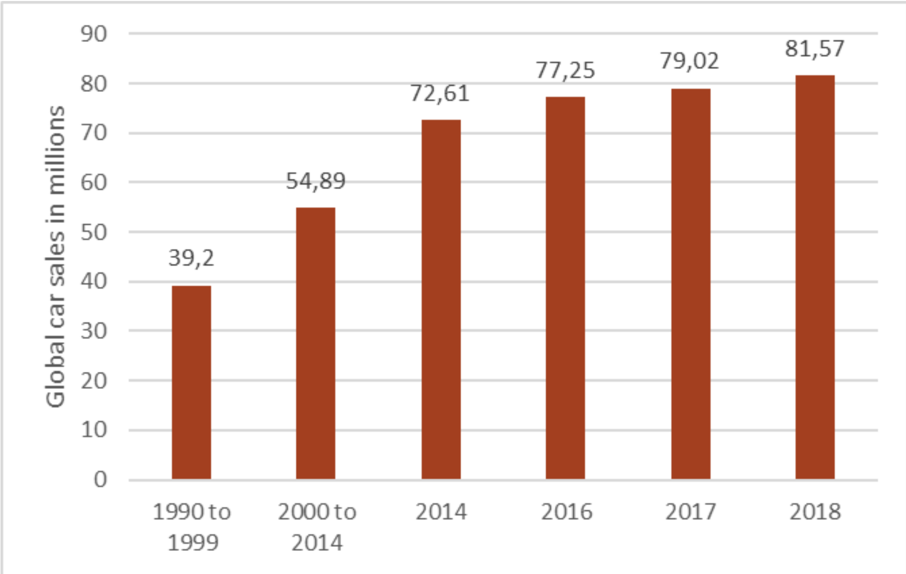


Figure 7 - Sales of passenger vehicles worldwide from 1990 to 2018 [17]

2.1.3 Manufacture of components for the automotive industry

As said before, the automotive sector represents a truly global industry. Nowadays, OEM are present in every corner of the world. Since the nineties, automakers are developing operations on a global scale, launching identical models with similar standards in different locations [18]. A growing body of literature focuses on innovative trends in manufacturing and the serious relevance of this sector for innovation across the broader economy. The application of this advanced manufacturing technologies makes, the location choices of large multinational firms and domestic ones, more complex than it has been in previous years [19].

The manufacturing engineer's involvement begins in product design, where feasibility and other manufacturing considerations are worked into the product design. This teamwork depends on the organization. In some cases, both teams work co-located, while in others only one manufacturing representative works in the design department. In Figure 8, it is shown the pattern the manufacturing process, from design to launch [20].

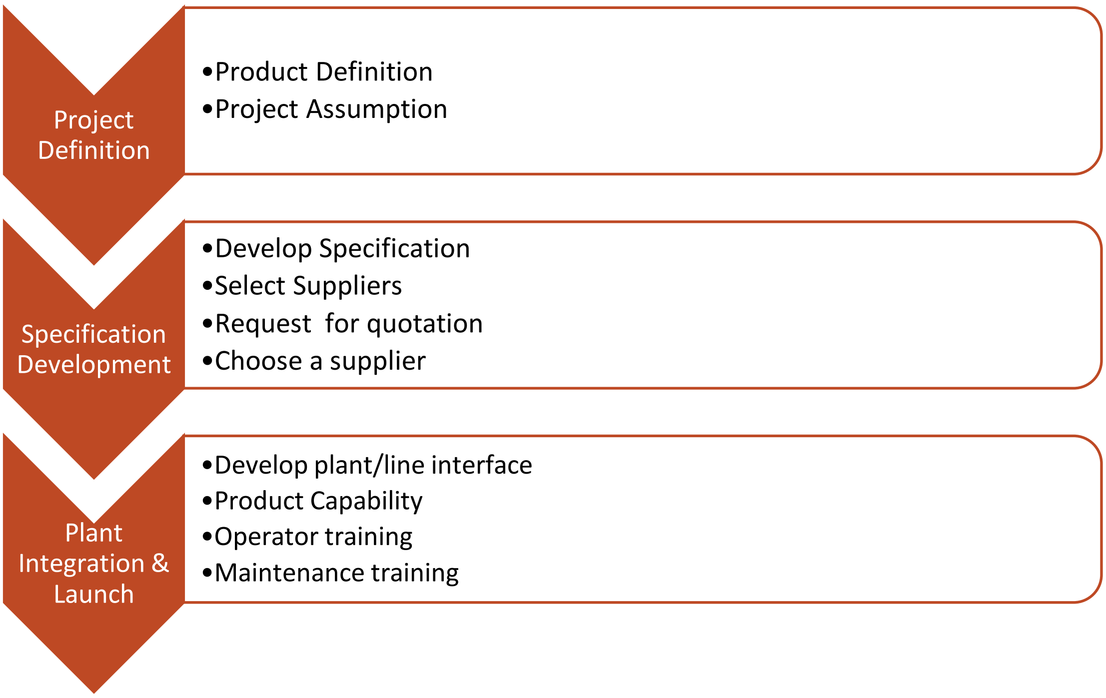


Figure 8 - Manufacturing Engineering Process [20]

The line design starts with the project definition phase, where product volumes, lifecycles and other business assumptions are considered. The Strategic Business Unit determines which plant will manufacture the product and, also, determines if the plan or supplier will complete the integration, the type of line desired, and the requirements for the specification. The manufacturing engineer develops the process specification. This document defines a general description of the product and equipment, the standards and compliance requirements, a documentation listing, project management expectations and specifications, including capacity, reliability and any known operator or material handling interfaces [20].

The automotive manufacturing activities can be described in two levels: a manufacturing *system* and *process* levels. The first procedure is typically divided into three different perspectives:

- **Structural aspect**: refers to the machinery, the material handling equipment, the labour resources and its allocations to the different activities;
- **Transformational aspect**: includes the functional part of the manufacturing system that is the conversion of the raw material into finished or semi-finished products;
- **Procedural aspect**: described the operating procedures and strategies.

Additionally, the strategic plan evolves the resources' allocation in the manufacturing enterprise. The second level refers to the operation strategy which is focused on production control, such as meeting the strategic plan objectives through planning, implementing and monitoring activities. These operational actions are described in the following categories [21]:

- **Aggregate Production Planning:** suggests plans based on the required volume, using a generic unit, to increase the level of confidence from the forecast information;
- **Production Process Planning:** controls the production techniques to be used, in addition to process routes and sequence;
- **Production Scheduling:** determine an implementation plan for the time schedule for every job in the process route;
- **Production Implementation:** the execution of the actual production plan according to the time schedule and allocated resources;
- **Production Control:** measure and reduce any deviations from the actual plan and time schedules.

It is also important to find the best material suitable for the function that is proposed. These materials need to fulfil several criteria before being approved. Part of the criteria follows the regulation and legislation with the environmental and safety concerns and the other criteria are requirements of the clients [10]. The materials and suppliers' parts move from upstream to downstream through the material supply system, the handling system and finally through the material distribution system. In the opposite direction, information flows to indicate that the customer side controls the quantity and quality of the production [21].

2.2 Transmissions

2.2.1 Introduction

Transmissions can be found in all vehicles, also in aircraft and watercraft. Mainly, the transmission transfers the power from the engine to the wheels. Changing gears allows matching of the engine speed and torque with the vehicle's load and speed conditions. In Manual Transmissions (MT), changing gears ratio is done by the driver. On the other hand, ATs are presented in several forms, however, the ability to change the ratio is operated without the interference of the driver [4]. In several countries, this system refers to the complete driveline between the engine and the wheels. However, the term "transmission" mentions to the gearbox unit and applies to the type of arrangement used on a specified vehicle, whether the selection of the gears has to be carried out manually or uses automatic means. The complete transmission system includes [22]:

- Gearbox;
- Clutch;
- Propeller shaft;
- Final drive and differential;
- Drive shafts to each driven wheel;
- Universal joints.

2.2.2 Transmissions Concepts

In order to understand better the different types of transmission designs and variants, some definitions need to be known as a standard for all considerations. The key factors in a gearbox are the direction of rotation, the transmission ratio, the torque and type of gearing.

2.2.2.1 *Direction of Rotation*

The direction of rotation in a powertrain is defined as positive when the direction of rotation is clockwise in a right-handed Cartesian system of coordinates. This is as viewed against the forward direction of movement related to the vehicle, as shown in Figure 9. In planetary gears, it is worthwhile to represent the speed of rotation of the individual transmission elements with their sign and relative to each other.

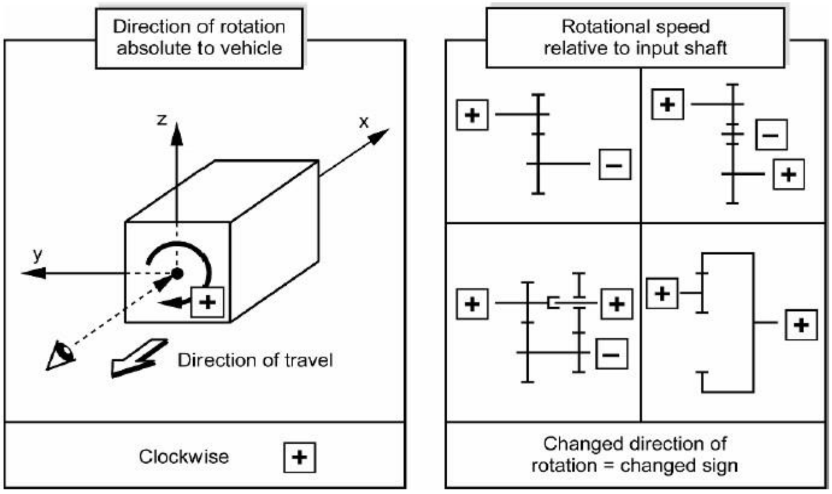


Figure 9 - Definition of the direction of rotation in a powertrain [2]

2.2.2.2 *Transmission Ratio*

The transmission ratio i_G is the connection between the angular velocity ω_1 of the input shaft to ω_2 of the gearbox output shaft, and it can be determined as follows:

$$i_G = \frac{\omega_1}{\omega_2} = \frac{n_1}{n_2} \qquad \{2.1\}$$

The ratio between the output speed n_2 and the input speed n_1 in a powertrain component is named the speed conversion. The torque conversion gives the relation between the output torque T2 and the input torque T1 of a powertrain component. The following characteristics result for the transmission ratio:

$i_G > 0$ transmission input and output shaft rotate in the same direction;

$i_G < 0$ change of direction in the transmission;

$|i_G| > 1$ speed reducing ratio;

$|i_G| < 1$ speed increasing ratio.

In case of CVT and with transmission combinations:

$i_G = \infty$ stationary output with rotating input;

$i_G = 0$ stationary input with rotating output.

The ratios inside a gearbox are designated by the gear ratio u. The gear ratio u of a gear pair is the ratio of the number of teeth z_2 of the larger wheel to the number of teeth z_1 of the smaller wheel (pinion):

$$u = \frac{z_2}{z_1} \; with \; z_2 \geq z_1 \tag{2.2}$$

German standard DIN 3990 [23] specifies that in the case of spur gears the number of teeth of a wheel with external gearing is positive and the number of teeth of a wheel with an internal toothing (ring gear) is to be taken as negative [2].

2.2.2.3 Torque

Other important features influencing a gearbox are the torque values acting on its shafts. The torque direction of the transmission input shaft is typically defined as positive. It changes along a transmission component, but the direction of rotation does not, which is represented in Figure 10.

The sign of the power *P* absorbed (positive) or delivered (negative) at a particular point can be determined from the speed of rotation and the torque at that point in the transmission as shown:

$$P = T\omega = 2\pi nT \; [W] \tag{2.3}$$

Müller [24] proposed four rules for speeds of rotation, torque and power values in a transmission:

- All parallel shafts in a transmission rotating in the same direction will have speeds with the same sign;
- In an “input shaft”, the signs for the speed of rotation and torque are the same; in an “output shafts”, they are opposite to each other;
- “Input power” is always positive; “output power” is always negative;

- Two equal connecting torque values of a free connecting shaft have opposite signs at the connecting ends.

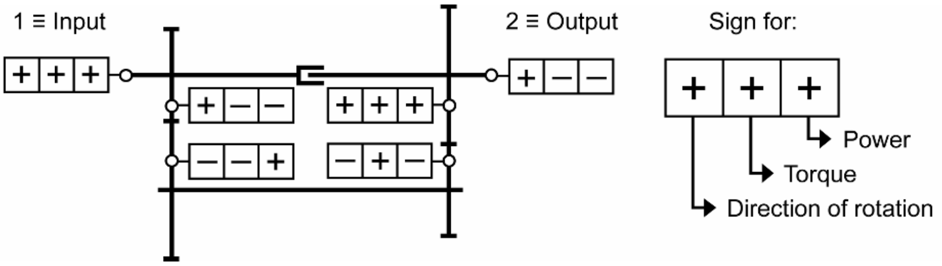


Figure 10 - Sign rules for rotational speed, torque and power [2]

A transmission comprises three parts, which must contain a “frame”. This important condition is necessary to provide a reaction for the difference in a force or torque between the input and output side resulting from the conversion of movement. In vehicle transmission, the gearbox housing is the frame. As shown in Figure 11, these relations are illustrated in the symbolic representation.

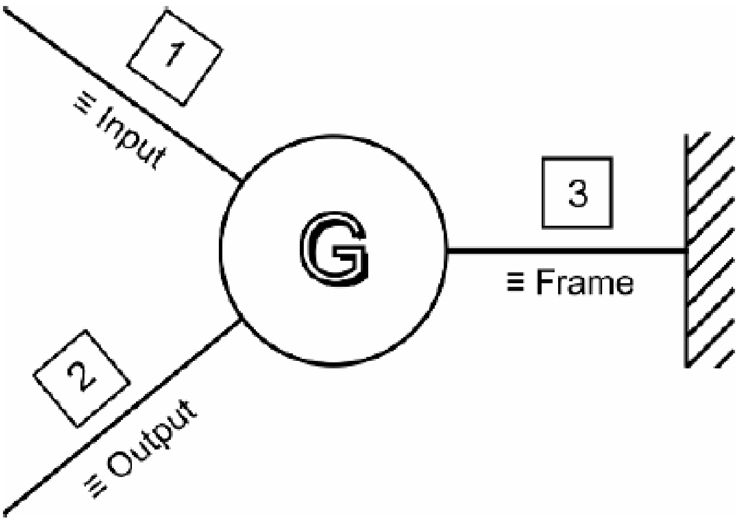


Figure 11 - Wolf transmission symbols [2]

2.2.2.4 Types of Gearing

There are several types of gearing used on a motor vehicle, but gearboxes work with one or more of the following:

- Spur gears – teeth parallel to the axis, used on a sliding-mesh gearbox. Mainly in reverse gear system;

- Helical gears – teeth inclined to the axis to form a helix. Gives increased strength and quieter operation;
- Double helical gears – two sets of opposing helical teeth;
- Epicyclic or planetary gears – a spur or helical gears rotating about centres that are not stationary.

These four types of gears are represented in Figure 12. Helical and double helical gears are used on constant-mesh and synchromesh gearboxes, while most automatic gearboxes use the last type of gearing.

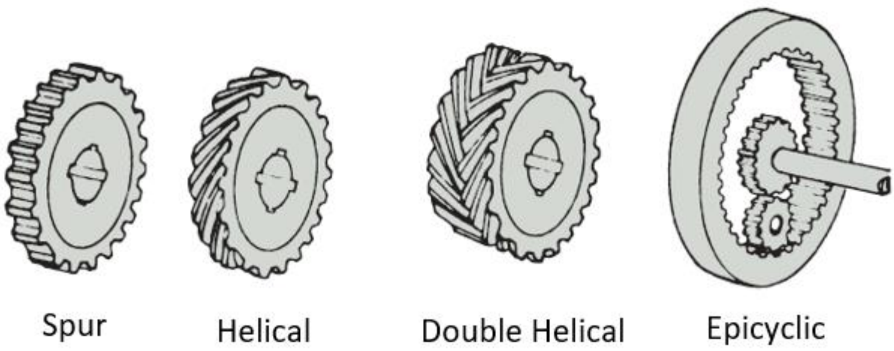
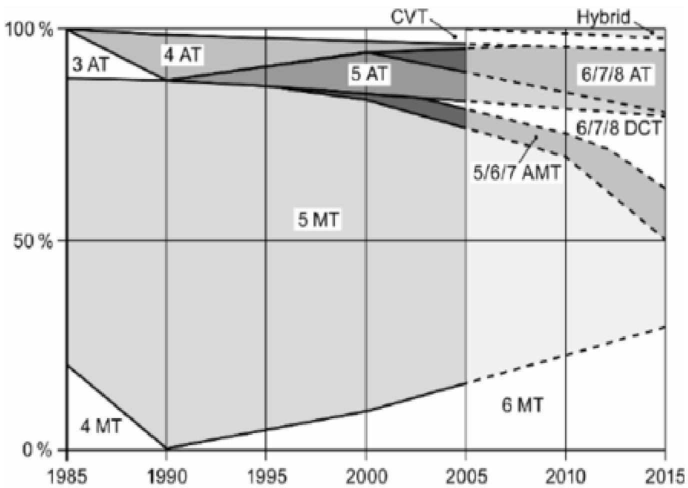


Figure 12 - Types of gear [22]

2.2.3 Transmissions Types

The vehicle market has suffered essential changes since about 1975. For passenger cars, the trend toward individualisation has led to considerable segmentation with numerous vehicle classes. This has also led to diversification in transmission design. In 1990, buyers had “black or white” alternative between MT or conventional AT. In the meantime, there is a variety of transmissions designs, as shown in Figure 13.



3 AT	3-speed AT
4 AT	4-speed AT
5 AT	5-speed AT
6/7/8 AT	6/7/8-speed AT
4 MT	4-speed MT
5 MT	5-speed MT
6 MT	6-speed MT
5/6/7 AMT	5/6/7-speed AMT
6/7/8 DCT	6/7/8-speed DCT

Figure 13 - Trend in the use of passenger car transmissions in Europe [2]

Some goals of designing new transmissions are reducing consumption, emissions, weight and increasing efficiency and comfort. To achieve these goals, new concepts were born, leading to a market diversification in transmissions designs: MT, Automated Manual Transmissions (AMT), AT, DCT, CVT and hybrid drives. Each design has its own strengths and weaknesses, which depend in turn on the conditions of use [2].

2.2.4 Manual Transmissions

Manual transmissions are the oldest type of gearbox and used for decades before automatic transmissions have been introduced. Despite their market is declining, MTs are still popular due to their simplicity, low cost and high efficiency. As the name suggests, shifting from gear to gear must be performed manually by the driver. Its efficiency depends on the drivers’ abilities, for example, in urban traffic [4].

2.2.4.1 Design and Operation

As shown in Figure 14, the transmission is bolted to the engine body through the bell housing which contains space to assemble the clutch system. This clutch system is bolted to the engine flywheel, so the engine power is transmitted through the clutch plate. In fact, when the clutch is engaged, the input shaft and clutch rotate at the same speed as the engine. On the other hand, when the clutch is disengaged, the transmission input is working separated from the engine, so shifting can be performed [4].

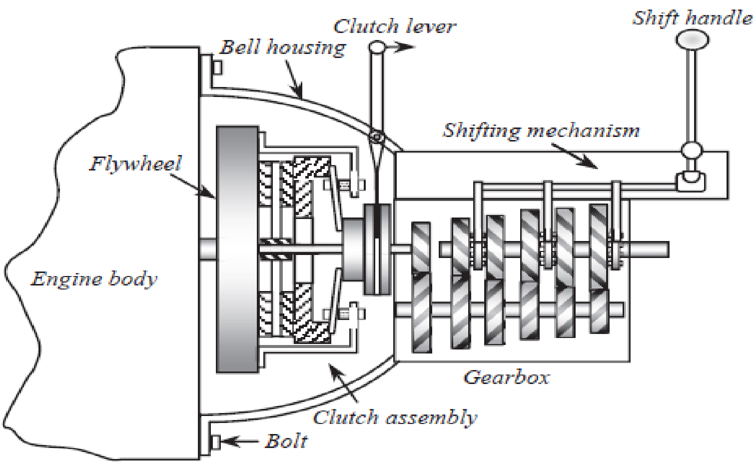


Figure 14 - Manual transmission assembly [4]

The clutch is activated as soon as the clutch pedal is pressed and the gear lever is pulled back, causing the release bearing to push the diaphragm spring. The seesaw effect of the spring pulls back the pressure plate and the clutch plate is released. The input shaft of the transmission is directly attached to the clutch plate through the splines and both rotate with the same speed [4].

There are two types of gear change: moving a gear to mesh the opposing gear or moving a linking member to deliver torque to already meshing gears. The first type is denominated "sliding-mesh" and it is an obsolete shifting method. This concept is illustrated in Figure 15a. The second type used in all modern manual transmissions is named "constant-mesh", shown in Figure 15b [4].

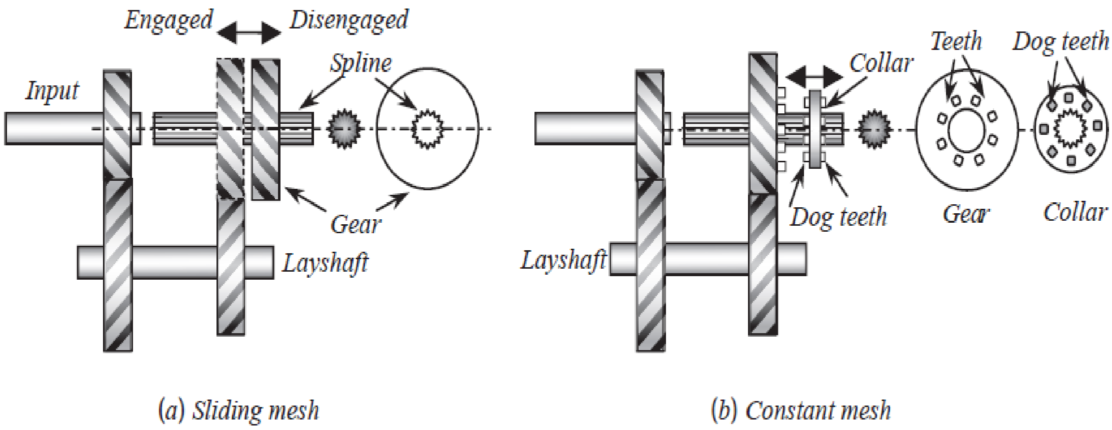


Figure 15 - Sliding mesh and constant-mesh gear meshing methods [4]

When the clutch is disengaged, the power is transferred to the output shaft. In constant mesh type, the two gears are in constant mesh (a pair for each gear ratio), but the gear on the output shaft has a hole in the centre, so it is not connected to the shaft and no torque is delivered between the two. The power is transferred through a sliding collar with a spline in its core and dog teeth over its sides (Figure 15b). The collar is always turning with the output shaft through the splines and when it is shifted to the side, its dog teeth fit into the machining teeth on the side of the gear and the three (shaft, collar and gear) get connected to each other and power is transferred. As the gear and output shaft in constant mesh design turn with different speed prior to their engagement, so these speeds need to be synchronized by the "synchronizer". When the two matching conical surfaces get close, the speed progressively synchronizes and the dog teeth subsequently engaged. This concept of using the two elements that come into gradual contact as the collar slides towards the gear is illustrated in Figure 16 [4].

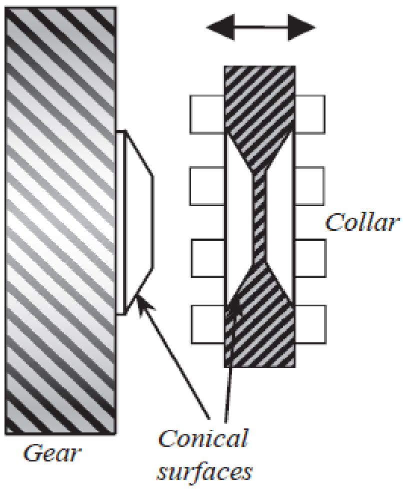


Figure 16 - Synchronizing concept [4]

The gear selection and shifting mechanism are illustrated in Figure 17 in three views, front, top and left. For a five-speed transmission, there are usually three forks that control the three collars. Each individual collar is used to engage two gears when it slides to left or right. The forks are fixed on three rods that can move back and forward. The relevant rod is chosen by the left-right movement of the shift handle. The choice between the two gears is done by moving the gear level front and back [4].

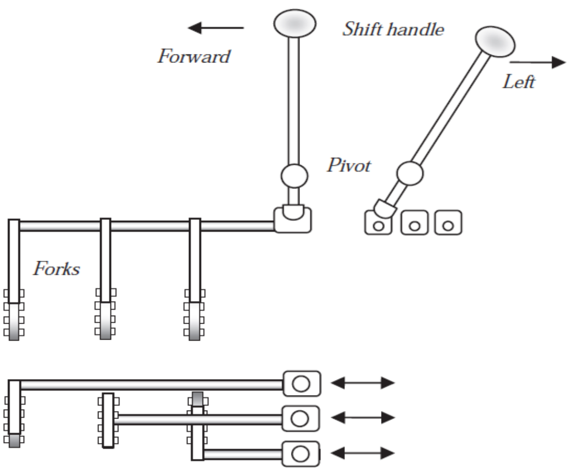


Figure 17 - Shifting mechanism [4]

2.2.5 Automatic Transmissions

Automatic transmissions dismiss the driver of the task of gear selection and this system allows the vehicle to be neither moved off or brought to rest in a smooth manner, without the driver worrying to do anything except controlling the accelerator or brake pedal. Drivers have limited gear selection: Drive for forwards, Reverse for backwards, Park and Neutral for stationary situations. Nowadays, gearboxes can have up to eight forward-moving gears, which improves overall performance and fuel efficiency. To become AT more popular than conventional MT, there was an inclusion of an electronic control system in modern vehicles. This solution gives the driver the option of an automatic gearbox that can be driven manually, which can be selected via the gear lever, a button, a switch or paddle shift levers on the steering column. In Figure 18, it is shown an automatic gearbox from inside [22].

With recent progress in automotive electronics, new types of automatic transmission have been proposed. Another concept is the AMT, which allows the controlled use of the well-developed manuals that also have great efficiency. Other derivations from MT are double clutch transmissions with the attractive feature of having continuous torque flow [4].

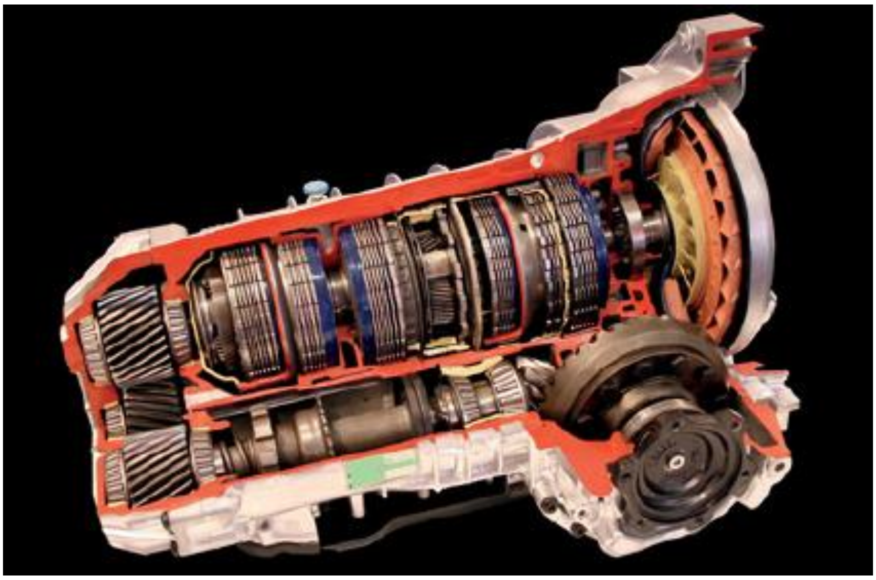


Figure 18 - Automatic gearbox internals [22]

2.2.5.1 Conventional Automatic Transmissions

In conventional automatic transmission, the clutch system is operated with a fluid coupling or torque converter to eliminate engaging/disengaging action during gear change. To perform gear ratio changes is used a completely different gearing system, named a planetary or epicyclic gear, instead of using conventional gears. These differences make the conventional automatics totally dissimilar from the manuals internally although the external shape looks similar to a MT, illustrated in Figure 19. This type of gear is able to produce multiple ratios and in order to achieve the required gear ratios, the gear teeth for all planetary sets must be designed in relation to one another [4].

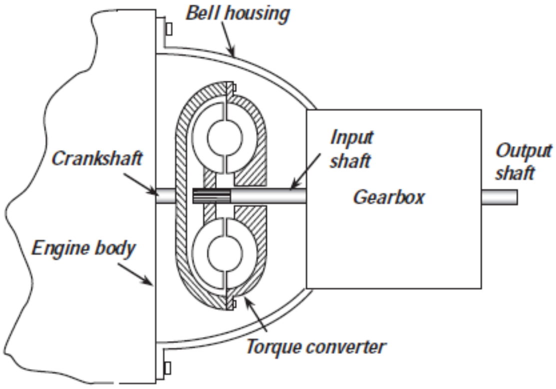


Figure 19 - Overall construction of a conventional automatic [4]

2.2.5.2 Automated Manual Transmissions

An AMT combines the advantages of both manual and automatic transmissions: high efficiency of manuals with the simple use of automation. An AMT can be developed from a manual gearbox with the support of an electronic control. The difficult part of the gear changing process, which is the clutch actuation, is performed automatically, so this solution makes gear shifting more comfortable. The mechanical connection between the selector lever and transmission is also eliminated, so the gearshifts are executed automatically, shift-by-wire. Other advantages of using AMT are the ability to use existing manual transmission manufacturing facilities, leading to lower production costs and still benefitting from their high efficiency and lower weight. However, the disadvantage of an AMT is the interruption of torque flow during shift actuation.

To convert a manual transmission to AMT, two tasks are required:

- Installing three actuator systems for the three actions a driver usually performs: 1 for clutching plus 2 for two movements in gear selection (Figure 20);
- Adding a control unit to make shifting decisions.

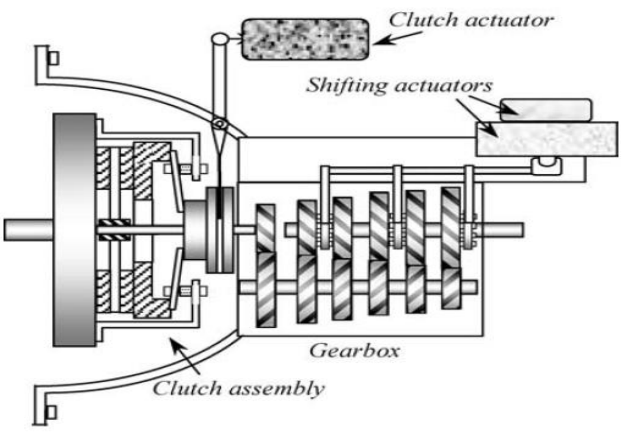


Figure 20 - Actuators for AMT [4]

2.2.5.3 Dual Clutch Transmissions

In manual transmissions, despite the high efficiency, the torque interruption is an inherent disadvantage. According to the operation principle of a MT, during gear shifting, the clutch is activated to separate the engine torque from the gearbox in order that meshing between the gears can be accomplished by a sliding motion. After selecting the next gear, the clutch is deactivated to restore the torque transmission to the wheels. Thus, the torque interruption is inevitable. DCTs are other transmissions based on the concept of the manual gearbox. A DCT is a layshaft-type gearbox with two input shafts and it is necessary one clutch for each shaft. These clutches are controlled by hydraulic and electronic systems. The biggest technical challenge is to establish very precise control of the coordination between one clutch disengaging and another clutch engaging. Usually, in DCT designs, the odd gears and the even gears are mounted in two different shafts. By using this arrangement, the gearshift can be performed without torque interruption between engine and wheels. The discontinuity of a gearshift is eliminated to a great degree, since the disengagement of a gear and engagement of the new gear happens simultaneously. The outcomes of this design are the smooth accelerations during gear shifting, compared with manual and conventional automatic transmissions. Contrary to what happens in conventional automatic transmissions, which uses torque converters, in DCTs, dry clutches or multi-plate wet, are used to deliver the engine torque to the gearbox [4].

2.2.5.3.1 Operation

As explained before, even an odd gear is placed in two input shafts and two power paths. Each input shaft has a clutch at the end to allow power interruption for shifting. According to Figure 21, that demonstrate a six-speed DCT, one distinctive of this gearbox is its coaxial input shafts with one solid shaft (shaft 1) positioned inside the other hollow shaft (shaft 2). Both shafts have its own clutch, which receives power from the engine. The lower and upper shafts are the output shafts and the power are transferred to these shafts by selecting the gear. Like a typical layshaft gearbox, the gears on the output shaft rotate freely until they are connected to the shaft by the gear selector. Consequently, only one gear is connected to the output at a time.

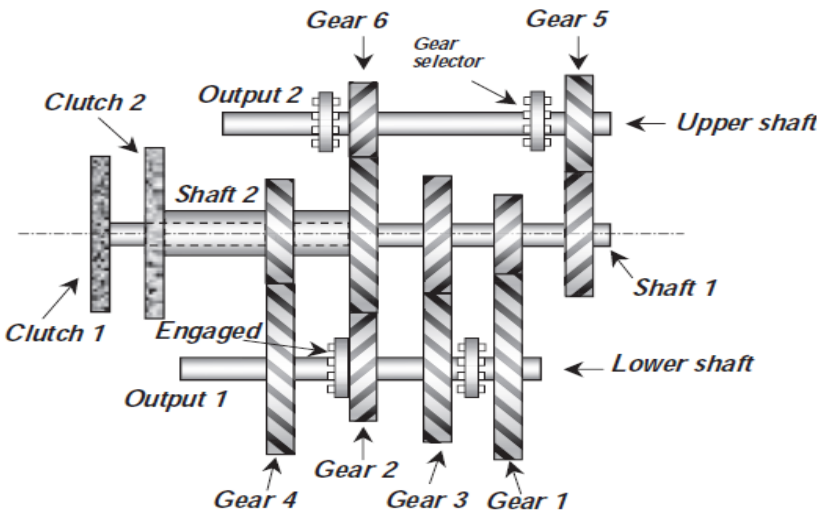


Figure 21 - Schematic of a 6-speed DCT [4]

Through the previous scheme, it is possible to explain better the functionality of the gearbox. As shown in Figure 21, if the vehicle is in gear 2, therefore clutch 2 is engaged and shaft 2 is transmitting power through gear 2 to the output shaft 1. The next step is to select gear 3, so the selector between gears 1 and 3 is moved towards gear 3. Subsequently, the output shaft 1 is rotating, so gear 3 and mating gear of input shaft 1 will start to rotate after selection. Consequently, clutch 1 will rotate, but it is not engaged. Therefore, pre-selecting a gear in a DCT will force the free clutch to rotate. The same procedure could be done if gear 1 wanted to be selected. To shift the gear pre-selected, the two clutches need to switch over, releasing the active one and engaging the free one. In this example, the power will be transferred through shaft 1 and gear 3 to lower output shaft. The gear selector connected to gear 2 is still connected, so the input shaft 2 will still rotate freely due to the rotation of gear 2. In a DCT, there are two paths for torque flow and, especially, during a gearshift the torque flow is complex. This torque flow depends on numerous parameters like: clutch clamp forces, layshaft angular velocity and the type of gear shift (upshift and downshift). Another important factor during a gearshift is clutch force regulation. Since both clutches simultaneously engage/disengage, if the pressure profiles are not appropriate, high torque variations must be avoided, otherwise, these variations will result in unwanted longitudinal acceleration to the vehicle and passengers [4].

2.2.5.4 Continuous Variable Transmissions

The traditional geared selector gearboxes with a finite number of gears do not fully exploit the power available from an ICE. With a CVT, the engine can be optimized at the ideal operating point for economy and performance [2]. The working principle of a CVT is based on a concept to transmit power from one rotating shaft to another with a continuously variable speed. This idea can be understood from a simple arrangement of two similar cones with a flat belt wrapped around them, illustrated in Figure 22. This concept can work in several applications but does not fulfil all the requirements needed in automotive applications. Thus, due to the high duty cycles and durability requirements, only a few types of CVTs have passed successfully in practice.

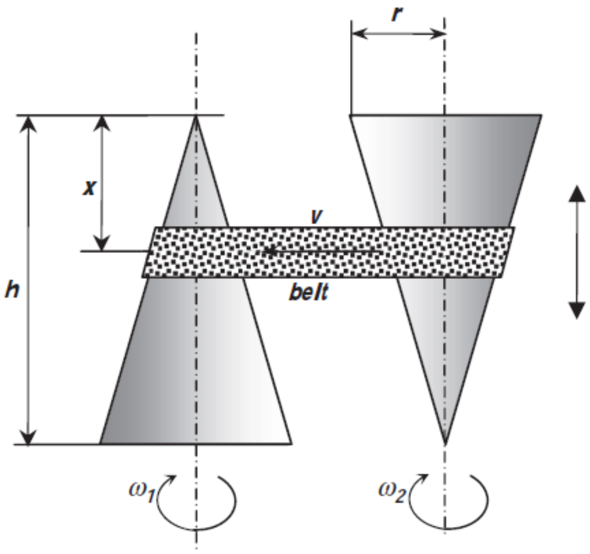


Figure 22 - A conceptual CVT [4]

As the belt moves along the parallel axes of the cones, x varies and, under a given rotational speed w_1 of input shaft, the output angular speed w_2 can be obtained by assuming zero slip, as shown [4]:

$$\omega_2 = \frac{x}{h-x}\omega_1[rad/s] \quad \{2.4\}$$

For a fixed input angular speed value, the output speed ranges continuously from almost zero up to high values. This means that a CVT provides different gear ratios, allowing a smooth shifting between ratios [4].

2.2.5.4.1 Types of CVTs

The different types of CVTs are classified based on some parameters. As shown in Figure 23, the flowchart is divided according to the nature of producing the output torque.

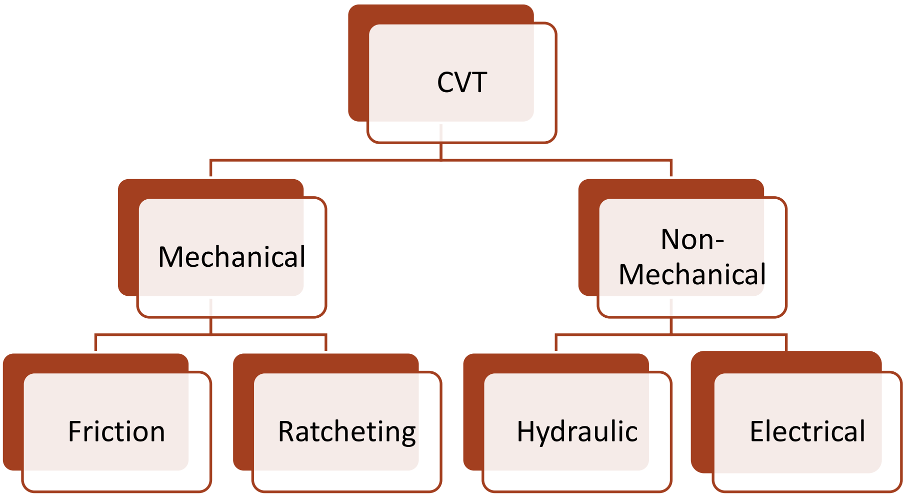


Figure 23 - Classification for automotive CVT [4]

2.2.5.4.2 Friction CVTs

Friction CVTs produce torque based on friction between mating surfaces, through belts or rollers. There are two types of friction CVTs used in automobiles: the belt and toroidal CVTs. The first system is similar to standard belt-pulley drive, with the difference that the pulleys are not fixed, so are able to move apart [4]. The principal component of the pulley transmission is the variator. The power is transmitted frictionally by the chain, which runs between two axially adjustable taper discs [2]. In Figure 24, it is shown the geometry of a belt type CVT. Both pulleys have fixed axes of rotation at a distance ***C*** from each other. The sides of each pulley are controlled to move apart or together laterally, but the displacements of each pulley are the opposite of the other.

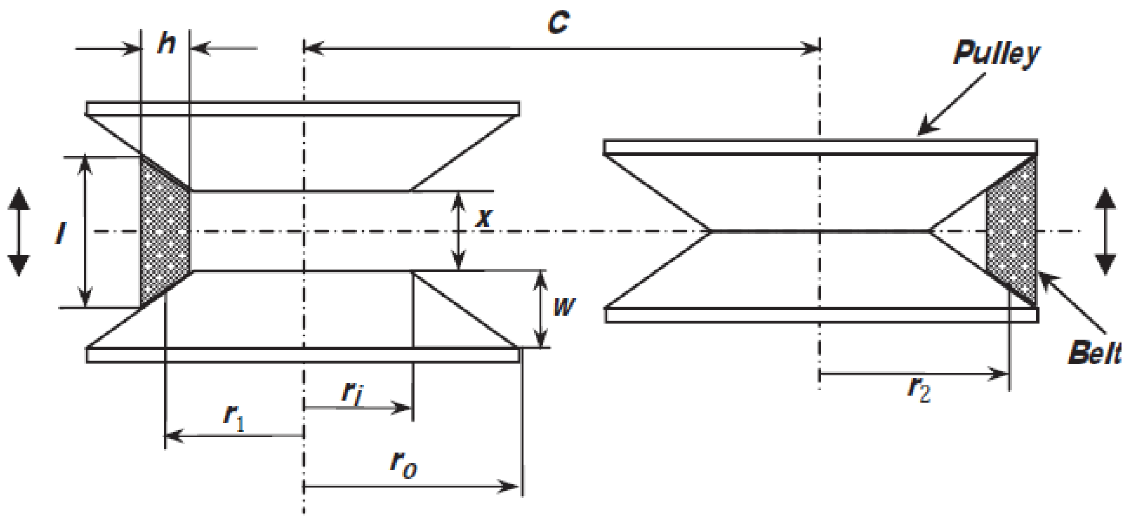


Figure 24 - Geometry of a typical belt CVT [4]

The second friction CVT is the toroidal type, which uses free wheels or rollers placed between cavities of two disks and relate the rotations of two input and output shafts. There are two variations of this type of transmission, named full toroidal and half toroidal, as shown in Figure 25. The interior surfaces of the disks are spherical and the wheels can oscillate laterally and change the radius of the contact points of input and outputs disks and in turn the speed ratio of the CVT.

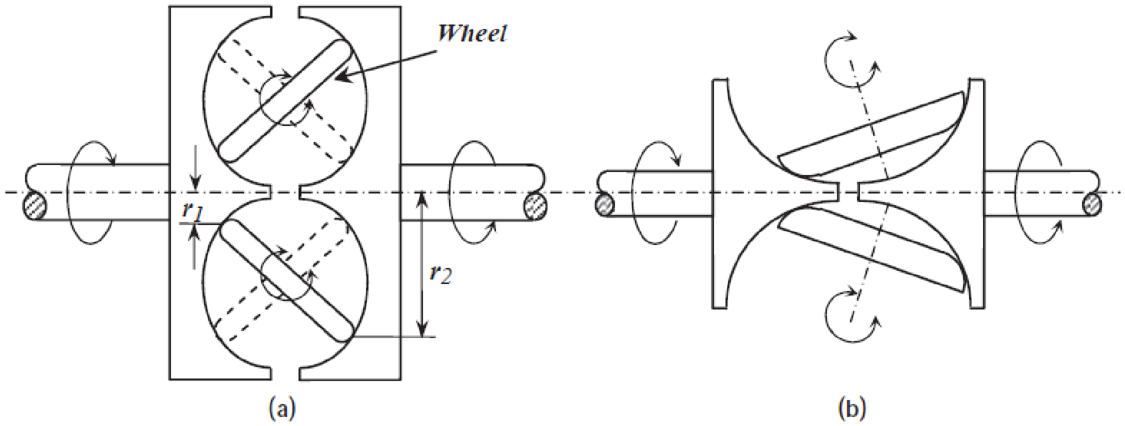


Figure 25 - Full toroidal (a) and half toroidal (b) CVT types [4]

One of the disadvantages in friction CVTs is the friction generated at the contacting points and surfaces. Friction is used to generate traction forces at the contact region, thus producing a torque. However, this friction has two complications: the build-up of heat and are sensitive to wear. The use of a lubricant can be a solution to these problems, but this will reduce the friction and torque capacity of the CVT. The friction force depends on the coefficient of friction and normal load. If the normal load is increased, the coefficient of friction can be compensated [4]. The torque-related pressure of the taper discs needs to be monitored because excessive pressure reduces the efficiency, which leads to increasing power consumption and stress on the transmission. It is also important to prevent the chain from slipping since this would inevitably cause the destruction of the transmission. Thus, the design and reliability of the contact pressure pump, and its control, is a serious concern in this type of CVTs [2].

Chains used in this category of transmission are divided into two types: tensional link chains and thrust link chains. The first one allows for smaller running radius and greater overall gear ratio with the centre distance. Therefore, these are more efficient since less power is required to adapt the chain to the ratio radius. These chains are also better suited to higher torques. The short pitch of thrust link chains requires more work for this purpose (Figure 26). However, this type has some benefits at the meshing impact and in noise generation [2].

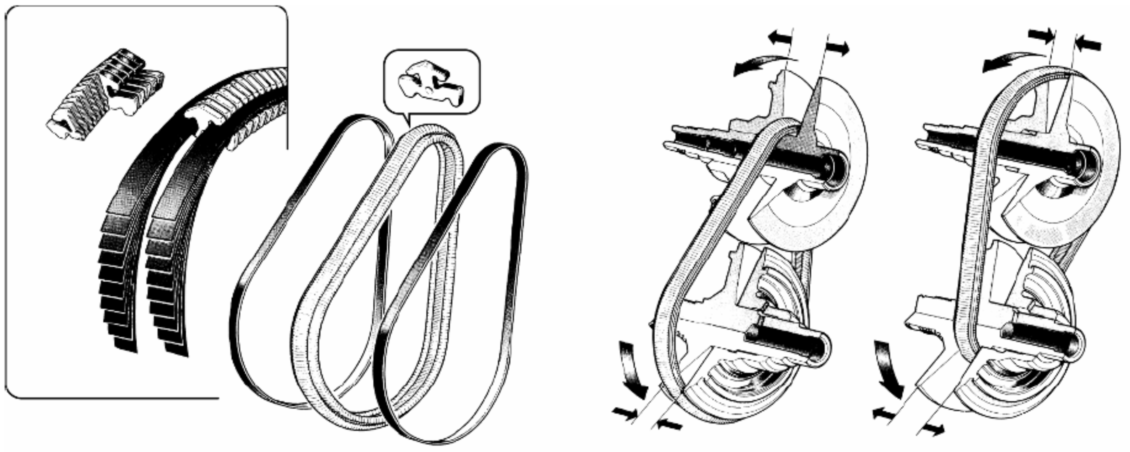


Figure 26 - Elements of a thrust link chain and principle of operation of a variator [2]

2.2.5.4.3 Ratcheting CVTs

A ratchet is a machine that produces rotation in one direction regardless of the direction of the input rotation. The non-uniform and oscillatory input originates an intermittent output. This type of gearboxes, ratcheting gearboxes, is based on the concept of producing the output rotation from a series of discontinuous rotations summed up at the output. Several numbers of mechanisms are necessary to build the gearbox [4].

2.2.5.4.4 Non-Mechanical CVTs

There are two main categories of this type of transmissions: hydraulic and electric components. The hydraulic system includes a pump and a hydraulic motor. The pump produces oil flow and runs the motor. The input mechanical power is transformed into fluid power by the pump and once again to mechanical power by the motor. This system can be converted to a CVT by selecting the pump and/or motor of variable displacement type. The electric system comprises a generator and a motor, which is similar to the hydraulic gearbox. The mechanical input power rotates the generator and produces an electric current that can drive an electric motor to generate mechanical power output. This CVT conversion is achieved by using electric power circuits that control the motor's voltage or frequency. In Figure 27a, the scheme shows a simplified representation of a hydraulic CVT, which the engine (E) rotates the variable displacement pump (P). The fluid is sucked from tank (T) to the pump, fed to the hydraulic motor (HM) and returns to the tank again. The second graph represents an electric system consisting of a generator (G) and an electric motor (M) connected by a controller [4].

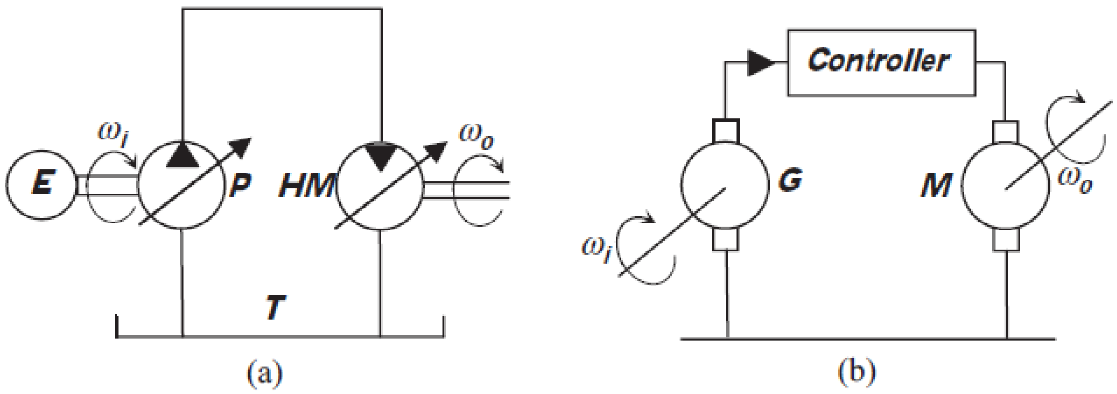


Figure 27 - Non-mechanical CVT types (a) hydraulic and (b) electrical [4]

2.3 Fatigue Analysis

Predicting fatigue damage for structural components exposed to different loading conditions is a complex problem. The simplest and most used damage model is the linear damage. However, the results from this approach do not consider the effect of load sequence on the accumulation of damage due to cyclic fatigue loading. Since the introduction of linear damage rule, many fatigue damage theories have been proposed to improve the accuracy of fatigue life prediction [25].

The objective of a fatigue test is to determine the fatigue life and/or the danger point, as the location of the failure. In some cases, it is also required that the test is designed so it does not only answer the specific problem, but it will also permit a generalization of the result obtained and contribute to the discovery of laws and rules related to this subject. The simplest sequence of amplitudes is obtained by applying reversals of stress of a constant amplitude to the test piece until failure occurs. Different samples are subjected to different stress amplitudes, but for each individual item, the amplitude will never be varied. This fatigue testing is named a constant-amplitude test. Depending upon the choice of stress levels, constant-amplitude tests may be classified into three categories [26]:

- **The routine test** – applied stresses are chosen in such a way that all samples are expected to fail after a moderate number of cycles (10^4 to 10^7);
- **The short-life test** – stress levels are situated above the yield stress and some of the specimens are expected to fail statically at the application of the load;
- **The long-life test** – stress levels are located below or just above the fatigue limit and a fraction of the sample does not fail after a preassigned number of cycles, usually between 10^6 and 10^7.

2.3.1 Stress-based Analysis

The stress-life (S-N) method was the first approach used to understand and quantify metal fatigue. For one hundred years, this method was the standard fatigue design method, where the applied stress is primarily within the elastic range of the material and the resultant cycles to failure are long. The stress-life method does not work well in low-cycle applications, where strains have a significant plastic component. The dividing line usually falls between low and high cycle fatigue is between 10 and 10^5 cycles, but this depends on the material being considered [27]. This method is distinguished from other fatigue analyses and design techniques by the following features [25]:

- Cyclic stresses are the governing parameter for fatigue failure;
- The high number of cycles to failure;
- Little plastic deformation due to cyclic loading.

2.3.2 Strain-based Analysis

Most components may have nominally cyclic elastic stress, but notches, welds or other stress concentrations present in the component can result in local cyclic plastic deformation. Thus, the local strain-life method assumes that the life spent on crack nucleation and small crack growth of a notched component can be approximated by a smooth laboratory sample under the same cyclic deformation at the crack initiation site, illustrated in Figure 28. By using this concept, it is possible to determine the fatigue life at a point in a cyclically loaded component if the relationship between the localized strain in the specimen and fatigue is known [25].

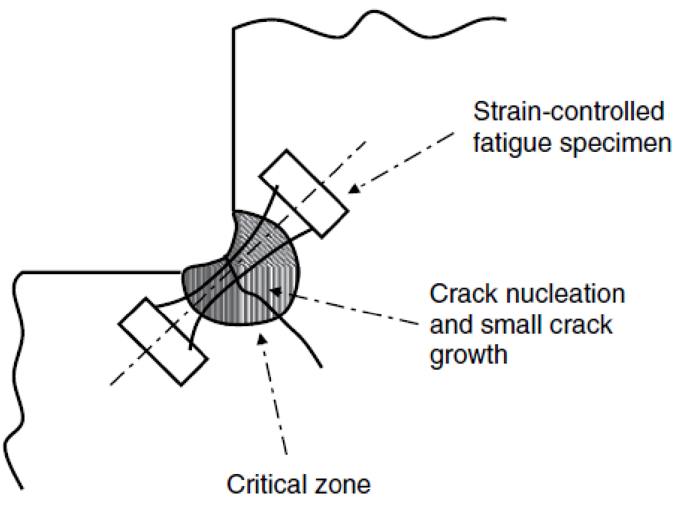


Figure 28 - Concept of the local strain life approach [25]

Crack growth is not explicitly accounted for in the strain-life method. Rather, failure of the component is assumed to occur when the equally stressed volume of material fails.

Thus, strain-life methods are often considered initiation life estimates. For some applications, the existence of a crack is an overly conservative criterion for component failure. In these situations, fracture mechanics methods may be employed to determine crack propagation life from an assumed initial crack size to a final crack length. The total life are then reported as the sum of the initiation and propagation segments [27].

The local strain-life approach has gained acceptance as a useful method for evaluating the fatigue life of a notched component. Both the America Society for Testing and Materials (ASTM) and the Society of Automotive Engineers (SAE) have recommended procedures and practices for conducting strain-controlled tests and using these data to predict fatigue life. This method may be made by using the strain-life approach with the following information [27]:

- Material properties obtained from smooth sample strain-controlled laboratory fatigue data (cyclic stress-strain response and strain-life data);
- Stress-strain history at the critical location (e.g., at a notch);
- Techniques for identifying damaging events (cycle counting);
- Methods to incorporate mean stress effects;
- Damage summation technique (e.g., Miner's rule).

2.3.3 Cycle Counting Techniques

The life of a component subjected to a variable load history is predicted when reducing the complex history into a number of events which can be compared to the available constant amplitude test data. This process of reducing a complex load history into a number of constant amplitude events involves what is termed *cycle counting*. These techniques will be applied to strain histories, stress, torque, moment and load [27].

One-parameters cycle counting methods such as level crossing, peak-valley, and range counting have been commonly used for extracting the number of cycles in a complex loading history. The following sections present descriptions of the one-parameter cycle counting methods [25].

2.3.3.1 Level Crossing Cycle Counting

In this counting method, the strain axis of the strain-time plot is divided into a number of increments. A count is then recorded each time a positively sloped portion of the strain history crosses an increment located above the reference strain. Similarly, each time a negatively sloped portion of the strain history crosses an increment located below the reference strain, a count is made. This process is shown in Figure 29. Once the counts are determined, they must be combined to form completed cycles. A variety of methods are available for the combining of counts to obtain completed cycles [27]. The cycle extraction rule follows that the most damaging fatigue cycles can be derived by first constructing the largest possible cycle, followed by the second largest possible cycle, and so on. This procedure is repeated until all available counts are used up [25].

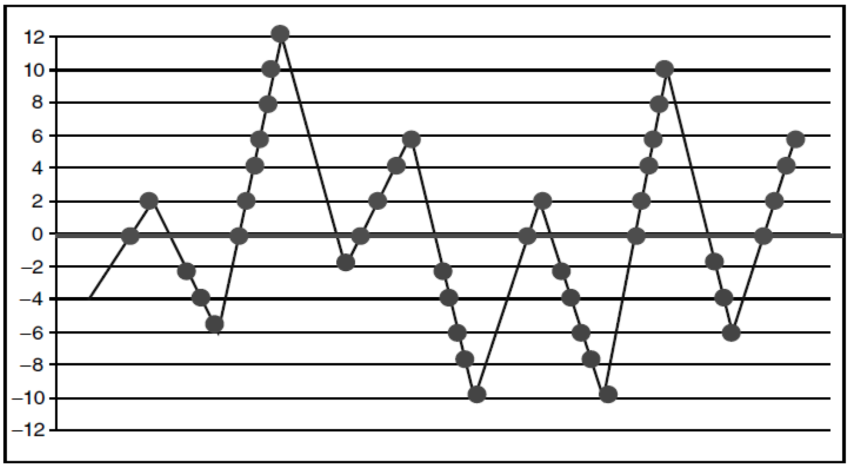
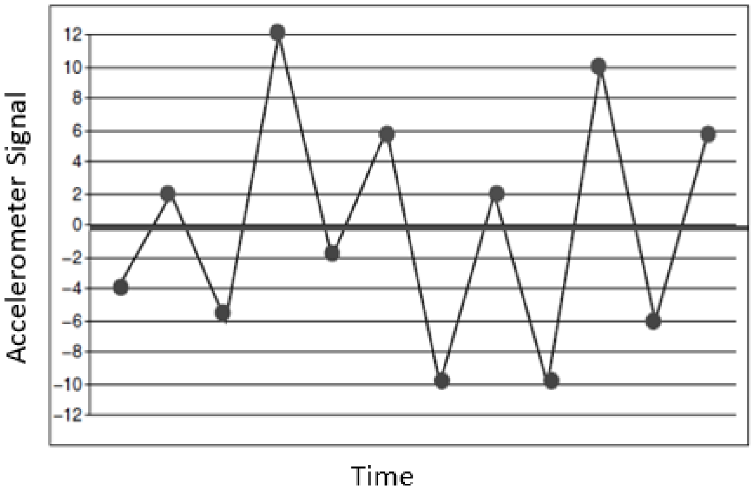


Figure 29 - Level crossing counting of a service load-time history [25]

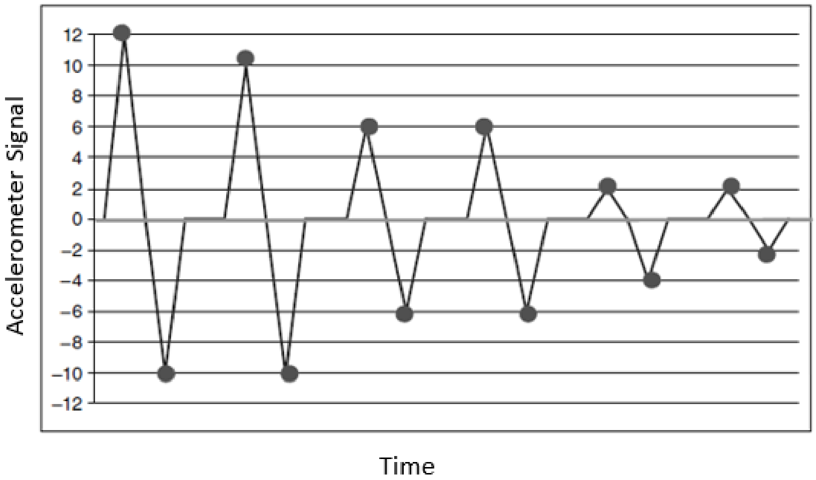
2.3.3.2 *Peak-Valley Cycle Counting*

The peak counting method is based on the identification of local maximum and minimum strain values in a load-time history and, subsequently, it constructs the possible cycles from the most to the least damaging events, according to the extracted counts. The peak is the transition point where a positive-sloped segment turns into a negative-sloped segment, and the valley is the point where a negative-sloped segment changes to a positive sloped one [25]. The most damaging history is obtained by first combining the largest peak with the largest valley. The second largest cycle is then formed by combining the largest peak and valley of the remaining counts. This procedure is continued until all counts have been used. Figure 31 shows the resulting completed cycles obtained from using this procedure for the peak count obtained for the strain history in Figure 30 [27].



Peak/Valleys	Counts
12	1
10	1
6	2
2	2
-2	1
-4	1
-6	2
-10	2

Figure 30 - Peak counting of a service load-time and results from the peak counting Method [25]



Range	Cycles
22	1
20	1
12	2
6	1
4	1

Figure 31 - Process to derive cycles and tabulated cycles extracted from peak-valley counting [25]

2.3.3.3 *Range Counting*

This counting technique defines one count as a range, the height between a successive peak and valley. According to the *SAE Fatigue Design Handbook*, a sign convention is assigned to a range [28]. Positive and negative ranges are defined on positively sloped reversals and negatively sloped reversal, respectively. Each range represents a half cycle. The counts of positive and negative ranges are illustrated in Figure 32 [25].

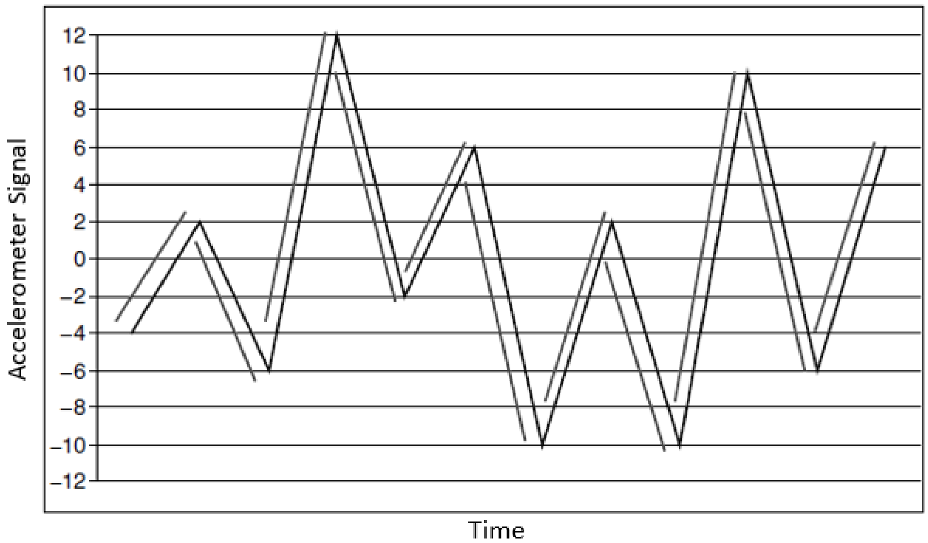


Figure 32 - Range counting of a service load-time history [25]

2.3.4 Rainflow Counting

The rainflow cycle counting method can faithfully represent variable-amplitude cycle loading. Generally, this technique leads to better predictions of fatigue life. It can identify events in a complex loading sequence that are compatible with constant-amplitude fatigue data [29].

The first step in implementing this procedure is to draw the strain-history so that the time axis is vertically oriented, with increasing time downward. One could now imagine that the strain history forms a number of "pagoda roofs". Cycles are then defined by the manner in which rain is allowed to "drip" or "fall" down the roof. There are specific rules due to the dripping rain so as to identify closed hysteresis loops. The rules specifying the manner in which rain falls are as follows [27]:

1. The strain-time history is drawn so as to begin and end at the strain value of greatest magnitude, to eliminate the counting of half cycles;
2. A flow of rain is begun at each strain reversal in the history and is allowed to continue to flow unless:
    a. The rain began at a local maximum point (peak) and falls opposite a local maximum point greater than that from which it came;
    b. The rain began at a local minimum point (valley) and falls opposite a local minimum point greater in magnitude than that from which it came;
    c. It encounters a previous rainflow.

The foregoing procedure can be clarified with the example of Figure 33, which shows a strain history and the resulting flow of rain. The following discussion describes in detail the manner in which each rainflow path was determined. The given strain-history begins and ends at the strain value of greatest magnitude (point *A*). Rainflow is now initiated at each reversal in the strain history, as follows [27]:

A. Rain flows from point *A* over points B and D and continues to the end of the history since none of the conditions for stopping rainflow is satisfied;
B. Rain flows from point B over point C and stops opposite point D, since both B and D are local maximums and the magnitude of D is greater than B (rule 2a above);
C. Rain flows from point C and must stop upon meeting the rain flow from point A (rule 2c);
D. Rain flows from point D over points E and G and continues to the end of the history since none of the conditions for stopping rainflow is satisfied;
E. Rain flow from point E over point E over point F and stops opposite point G, since both E and G are local minimums and the magnate of G is greater than E (rule 2b);
F. Rain flows from point F and must stop upon meeting the flow from point D (rule 2c);

G. Rain flow from point G over point H and stops opposite point A, since both G and A are local minimums and the magnitude of A is greater than G (rule 2b);
H. Rain flows from point H and must stop upon meeting the rainflow from point D (rule 2c).

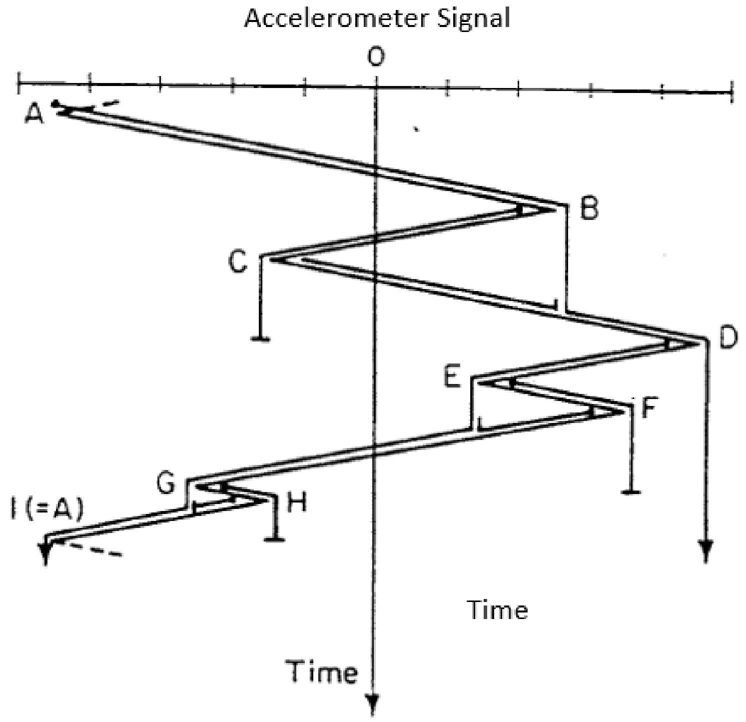


Figure 33 - Rainflow counting [27]

2.4 Mechanical Design

The term "design" is normally associated with an object's aesthetic appearance with reference to its shape, external aspect and its function. It is often referred to as designer clothes, design icons and beautiful cars. Generally, design starts with a need or requirement, but also an idea. In the end, the product is manufactured from a set of drawings or computer representations and other information [30].

Regardless of whether it is designing gearboxes, heat exchangers, satellites, or doorknobs, there are several techniques that can be used during the design process to ensure successful results [31]. This process can be divided into levels of formality or complexity. In four definitions, the development of a product is defined by: idea, sketches and calculations, evaluation and final solution. Thus, this model encompasses the generation of the "bright idea", drawings and calculations, giving form or shape, judgment of the design and re-evaluation if necessary, resulting in the final product. This process of evaluation and reworking an idea is very common in the project, which takes the design activity back a step to improve it. In Figure 34, a more formal description of the design process is shown, which might be more associated with engineers operating in a research and development department [30]. The six terms used in Figure 34 are described as follows:

- **Recognition of need**: Design starts when an individual or a company recognizes a need or identifies a potential market for a product, device or process. The statement of need is referred to as the brief or market brief [30]. The need is often triggered by a particular circumstance [32];
- **Definition of the problem**: Involves all specifications of the product or process to be designed. For example, include inputs and outputs, characteristics, dimensions and limitations on quantities [30]. Specifications define the cost, the number to be manufactured, the expected life, the range, the operating temperature and reliability [32];
- **Synthesis**: Process of combining the ideas developed into a form or concept, which offers a potential solution to the design requirement [30]. The brainstorming approach has been widely known and employed in practice, trusting on team experience, observations and common sense [33]. Sometimes it is called the *invention of the concept* [32];
- **Analysis and Optimization**: Involves the application of engineering science. Those techniques are used to examine the design and give quantitative information. Analysis and synthesis invariably go together [30]. It is recommended to use drawing instruments at this point, especially, CAD [33]. The process of refining a set of criteria to achieve the best compromise [30]. Intimately and iteratively related to analysis and synthesis processes [32];
- **Evaluation**: Final proof of a successful design [32]. The process of identifying whether the design satisfies the original requirements. It may involve an assessment of the analysis, prototype testing and market research [30];
- **Market**: Introducing the design is the final and vital step. The presentation is a selling job. When presenting a new solution, engineers want to demonstrate that their solution is the best one [32].

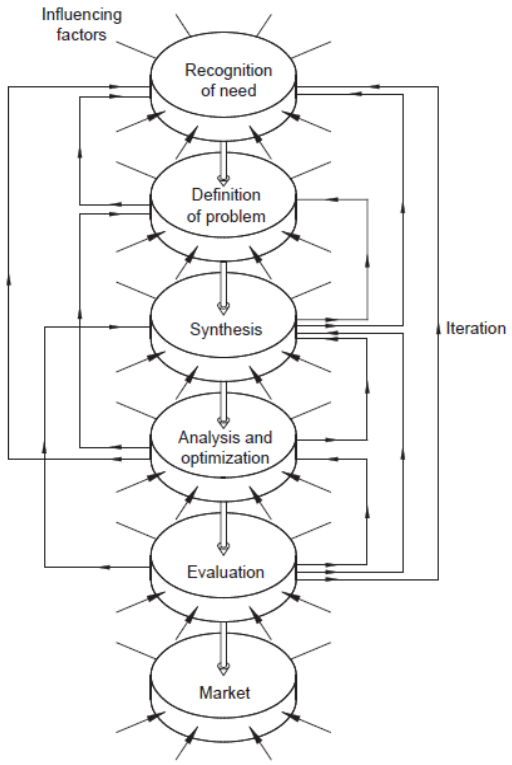


Figure 34 - The design process illustrating some if the iterative steps associated with the process [30]

Figure 34 does not represent a method of design but a description of what occurs during the process of design. However, the method of design used is often unique to the engineer or design team. Therefore, a design methodology is not an exact science and there are indeed no guaranteed methods of design [30].

2.4.1 Tolerancing

A tolerance is a difference between the maximum and minimum limits [34]. In the past, in most countries, there has been a reliance on undefined good workmanship. It is impossible to manufacture parts without deviations from the nominal shape. One reason for this impossibility is the surface irregularities and the intrinsic surface roughness. These deviations can be in term of size, form, orientation and location. During manufacturing, attempts are made to keep these deviations as small as possible, otherwise when it is too large, the usability of the piece will be impaired [35]. In general, variability in dimensions must be allowed to ensure that manufacture is possible. The term tolerance is also applied to the output of machines or processes. The designer specifies a dimension on a component and the allowable variability on this value that will give acceptable performance. Control of dimensions is necessary in order to ensure assembly and interchangeability of components [30].

Usually, tolerances are specified in bands, which are defined in British or ISO (International Organisation for Standardisation) standards [34]. The last organisation follows several rules [35]:

- Each feature requires limits for its deviations determined by its function;
- The drawing must specify all dimensional and geometrical tolerances necessary to completely define the shape and size of the part – the drawing must be definitive;
- Above certain values of tolerances, there is no gain in the economy by increasing them further. These tolerances are not exceeded in normal workshop practice without particular effort;
- General tolerances take account of the workshop accuracy. The tolerances are specified on the drawing, usually in or near the title block, referring to a standard specifying the general tolerances;
- If the function requires narrow tolerances, the required tolerances must be indicated individually. If the function allows larger tolerances, it should not be indicated individually;
- The workshop should only accept drawings where tolerance class is equal to its normal workshop accuracy;
- The workshop should ensure by sampling inspection that its normal accuracy is not impaired in the course of time;
- If a tolerance is exceeded, the decision whether or not the part is to be rejected depends on its function.

Geometric tolerancing encourages a dimensioning philosophy called "functional dimensioning", which defines a part based on how it functions in the final product, although it does not mean that the designer should only design the component without considering other factors. At this point, some companies use a process called "simultaneous engineering". This method considers inputs from marketing, engineering, manufacturing, inspection, assembly and service. Usually, this process gives better products at a lower price [34]. There are three main benefits of using Geometric Dimensioning and Tolerancing (GD&T):

- **Improving Communication** – Provide uniformity in drawing specifications and interpretation, which reduces controversy, guesswork and assumptions, letting to use the same language in the design, production and inspection;
- **Better Product Design** – Improve product designs by providing designers with the tools to "say what they mean" and by following the functional dimensioning philosophy;
- **Increasing Production Tolerances** – Using functional dimensioning, tolerances are assigned to the part based upon its functional requirements. This often results in a larger tolerance for manufacturing. It eliminates the problems that result when designers copy existing tolerances or assign tight tolerances because they do not know how to determine a reasonable tolerance.

Considering the last point, it is important to define the difference between manufacturing variations and tolerance. The manufacturing variation in components, which are supposed to have the same dimension, are represented in Figure 35. According to the image, the tolerance specified by the designer for the dimension is ±0.06 mm from the nominal value. This value is used in two different ways, depending on who is reading it. The manufacturing engineer uses this value to determine which manufacturing machine to use in making the component. On the other hand, the machinist or the quality-control inspectors use it for determining when the tool needs to be changed. Nowadays, the best practice tool has been to manufacture according to "6-sigma". This method is a quality-oriented tool that uses the five-step DMAIC process: Define, Measure, Analyse, Improve and Control [31].

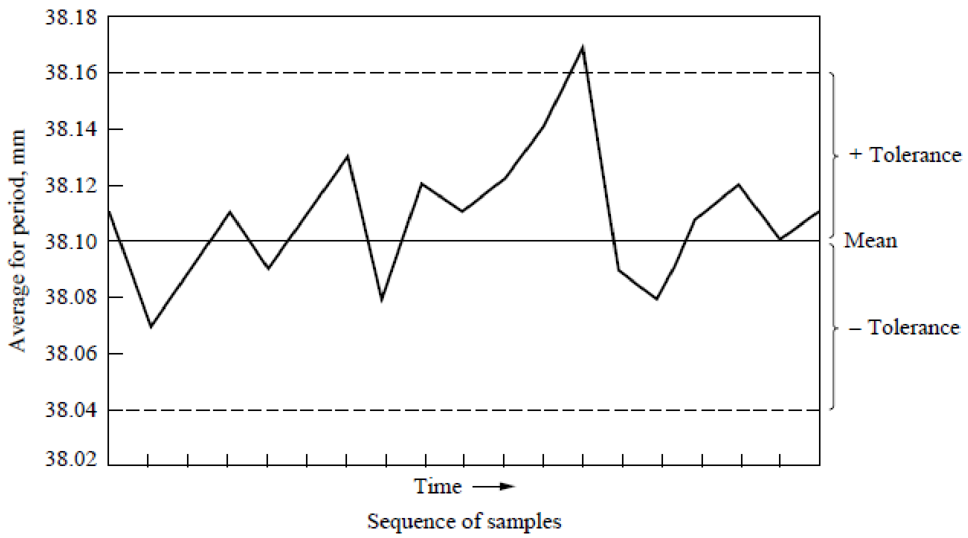


Figure 35 - Manufactured component distribution relative to the design specification [31]

The general tolerances for machined parts are now standardized in ISO 2768-2 [36], which have been in use in the industry over the last years. There are multiple derivations and application for this standard, such as straightness, roundness, cylindricity, parallelism, perpendicularity, angularity, coaxiality and symmetry. An alternative to the general tolerances according to ISO 2768 [36] is the use of a general tolerance on the surface (with or without a datum system) according to a company standard. For holes, a general positional tolerance may be specified in addiction [35].

2.4.2 Numerical Simulation in Mechanical Design

A design must be functional, reliable, competitive, manufacturable and marketable. Before computer programming is attempted, the designer should have in mind a quantitative procedural structure. An algorithm is a step-by-step procedure for accomplishing a task [37]. The designer uses a guideline to help in making decisions. That tasks are detailed in Table 2.

Table 2 - Algorithmic Approach Guideline [37]

Step	Description
Specification Set	It is the ensemble of drawings, text, bill of materials and other definitions that assure function, safety, reliability, competitiveness, manufacturability and marketability. No matter who builds it, assembles it and uses it, materials employed, end treatment, tolerances, length, size and many others.
Decision Set	Set of decisions which establish the specification set. It expresses in such a way that the engineer can focus on function, safety, reliability and competitiveness, material and condition, function, safety design factor and many others.
Design Variables	"Thinking parameters". Numerical inputs that are allowed to change during the design process.
Adequacy Assessment	It is the cerebral, empirical and related steps undertaken to determine if a specification set is satisfactory or not.
Figure of Merit	It is a number whose magnitude is a monotonic index to the merit or desirability of a specification set.
Optimization Algorithm	An optimization strategy is chosen in the light of the number of design variables (dimensionality), the number and kinds of constraints (equality or inequality) and whether the decision variables are an integer or continuous.
Assemble Program	Two skills for the design to master. First skill is the ability to take a specification set and perform an adequacy assessment. This skill is analytic and deductive. The second skill is to create a specification set by surrounding the results of the first skill with a decision set, a figure of merit and an optimization strategy. This skill is a synthesis procedure which is quantitative and computer-programmable.

2.5 Advanced Software for Solving Numerical Problems

In the last fifty years, the technological revolution is based on the development of computers, both software and hardware [38]. This fast development of the computer has given new opportunities, leading to engineering work with mathematically complex problems solved in the computer, visualization and simulation [39]. Before explaining in detail the several numerical methods, it is important to understand what is happening in the background and what are the other options for solving problems. The three main methods to solve engineering problems can be seen in Figure 36.

Analytical Method	Numerical Method	Experimental Method
•Classical Approach; •100% accurate results; •Closed form solution; •Applicable only for simple problems; •Complete in itself.	•Mathematical representation; •Approximate, assumptions made; •Certain results must be validated by experiments and/or analytical method.	•Actual measurement; •Time consuming and expensive set up; •Applicable only in physical prototype; •Results cannot be delivered blindy and a minimum of 3 to 5 prototypes must be tested.

Figure 36 - Methods to solve engineering problems [38] [39]

In parallel with computer evolution, engineers, scientists and mathematicians have been developed more accurate and refined numerical methods, in order to solve systems with complex equations [38]. The objective of the design analysis is to attempt to predict the stress or deformation in the component so that it may safely carry the loads that will be imposed on it [40]. The finite difference (FDM) and finite element (FEM) methods have been used as very efficient commercial software for development and optimisation of materials processing and transformation [38]. In Table 3, it is explained some details of these two methods.

Table 3 - FDM and FEM definitions [38]

FDM	FEM
The simplest method from mathematical formalism and implementation in a programming language. Typically used in materials science, not inclined towards mathematics. Its lack of flexibility for use in complicated geometries has impeded its implementation in industry.	A powerful method to solve the equations in integral form, divided into two possibilities for application: 1. The integral form of the physical problem to solve: a function that results from a variational principle, which the minimum corresponds to the desired solution.

It is described as a way to solve the differential equation and it uses Taylor's series to convert a differential equation to an algebraic equation.	2. An integration formulation must be obtained from an initial system of partial differential equations by weak formulation – weighted residual method. More general character and capable of dealing with complex geometries.

Apart from these methods, two more techniques are used in specific situations. Just like the FEM, Boundary Element Method (BEM) also involves nodes and elements, but it only contemplates the outer boundary of the domain. This method reduces the dimensionality of the problem by a degree of one and, thus, solves the problem faster. It is a very powerful and efficient tool to solve acoustic or Noise, Vibration and Harshness (NVH) problems. The other technique focuses on representing and evaluating partial differential equations as algebraic equations. The Finite Volume Method (FVM) is similar to FDM, in which the values are calculated at discrete volumes on generic geometry. The FVM is easily formulated to allow unstructured meshes. This method is used in most computational fluid dynamics (CFD) packages [41]. For the same problem, all of these methods can be used to solve it. However, the results are different, especially in the accuracy, ease programming and the time needed to obtain the solution.

On the other hand, computer simulations are a step-by-step mathematical approximation applied to a real-world or theoretical environment [42]. The most usual types of simulations are described in Table 4.

Table 4 - Most common types of simulations [43]

Simulation type	Definition
Equation-based	Applied in sciences, which can guide the mathematical models based on differential equations. This model refers to simulations based on global equations, associated with physical theories. Equation-based simulations can either be particle-based, which there are *n* many discrete bodies and a set of differential equations governing their interaction, or it can be field-based, which there is a set of equations governing the time evolution of a continuous medium or field.
Agent-based	The most common in the social and behavioural sciences, it also can be found in solutions for artificial life, epidemiology and ecology. It is similar to particle-based.

	However, there are no global differential equations on agent-based simulations, governing the motions of the individuals. Rather, the behaviour of the individuals is dictated by their own local rules.
Multiscale Simulations	Combine together modelling elements from different scales of description, such as a model that simulates the dynamics of bulk matter. The more traditional technique is serial multiscale modelling. The idea is to select a specific area, simulate it at the lower level of description, summarize the results and pass them up into the part of the algorithms calculating at the higher level.
Monte Carlo (MC) Simulations	Computer algorithms that use randomness to calculate the properties of a mathematical model and where the randomness of the algorithm is not a feature of the target model. Usually allows accounting for risk in quantitative analysis and decision making

2.5.1 Finite Element Analysis

The FEM is sometimes referred to as finite element analysis (FEA). It is important that users have the knowledge to use FEA packages properly, following the next points [44]:

- Which elements are to be used for solving the problem at hand;
- How to discretise to get good results;
- Hot to introduce boundary conditions properly;
- How to element properties are developed and what are their limitations;
- How to displays are developed in pre and post-processor development to understand their limitations.

Thus, a simulation process proceeds through a logical series of operations and can be categorized as: modelling (pre-processing), solution and visualization. Some details about the individual phases are described below.

2.5.1.1 Modelling / Pre-processing

2.5.1.1.1 CAD Data

Usually, the component's CAD geometry is designed in a different software and then imported into a pre-processor (e.g. HyperMesh) to start the FEM simulation process. In many cases, the imported geometry cannot be meshed directly and needs a clean-up first due to:

- "Broken" surfaces;

- Surfaces which are not stitched together;
- Redundant (multiple) surfaces;
- Surfaces which are too small to mesh in a reasonable way.

One example to demonstrate these issues is represented in Figure 37. In the surface at the left, it notes a lateral offset of the green edges (red circle). This small offset will be considered during meshing and will result in very poor-quality elements. In the middle image, it is possible to locate a distorted element. After doing the corrections, the elements have a perfect shape (image at the right) [41]. A perfectly computed finite element solution has absolutely no value if it corresponds to the wrong problem [45].

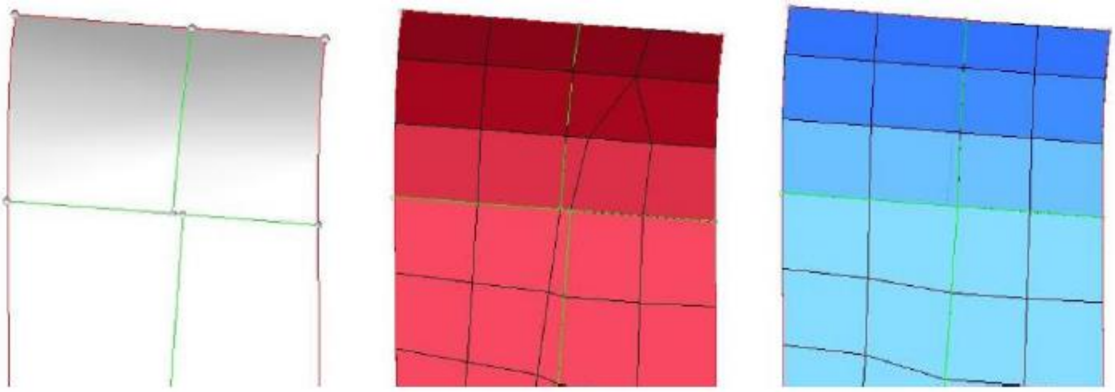


Figure 37 - Imported geometry mesh [41]

2.5.1.1.2 Meshing

Once the geometry is in a proper shape, it is time to create a mesh, either it is a beam mesh (1D), a shell mesh (2D) or a solid mesh (3D), as shown in Figure 38. The quality of the mesh reflects on the quality of the results generated, so meshing step is a crucial step on the FEA. The computation time depends on the number of elements (nodes). In some cases, 2D and 1D mesh are used instead of a 3D mesh. Despite this step is a highly automated process, mesh quality, its connectivity and element need to be checked and, if necessary, these elements are improved by updating the underlying geometry or by editing single elements [41].

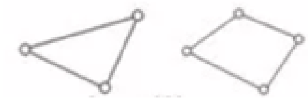
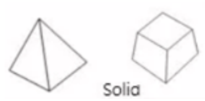
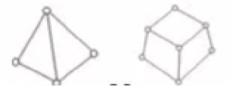
Type	Actual Model	Finite Element Expressions (Geometric Properties Defined by Nodes)
1D	 Rod (Truss) Beam	 Length (L)
2D	 Shell, Plane Stress, Plain Strain, Axisymmetric	 Area (A)
3D	 Solid	 Volume (V)

Figure 38 – Type of models and geometric properties defined by nodes [46]

In general, increasing the number of nodes improves the accuracy of the results, as follows in Figure 39. On the other hand, it also increases the solution time and cost. What is actually done is to increase the number of nodes in the areas of high stress, instead of reducing the global element size and remeshing the entire model. Completed the meshing step, material (e.g. Young's Modulus) and properties information (e.g. thickness values) are assigned to the elements [41].

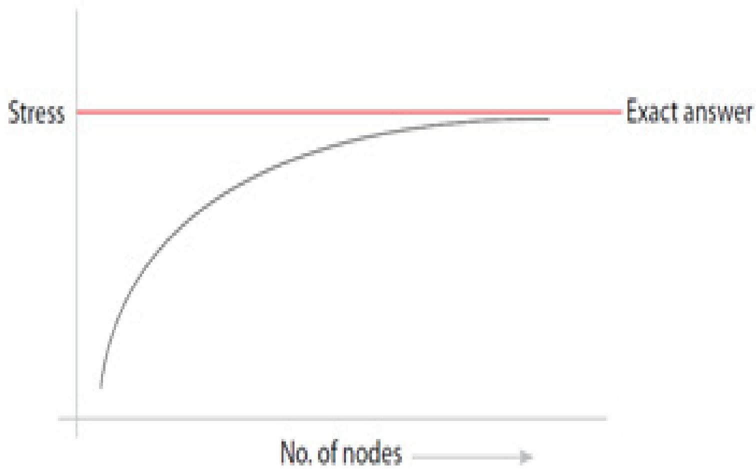


Figure 39 - Results accuracy vs Number of nodes [41]

2.5.1.1.3 Loads, Constraints and Solver Information

The parts are subjected to loading conditions, so various loads and constraints are added to represent it. Different load cases can be defined to represent different loading conditions on the same model. Solver information is also added to determine what kind of analysis is being run or which results to export. The person or team responsible for the analysis needs to think of all kind of load situations that can happen on the structure and decide whether it is used on simulation or not. A Multibody Simulation (MBD) can be helpful to determine the load from the static or dynamic event. Depending on the software that it is being used (e.g. HyperMesh), sometimes it is necessary to export the FEM model (consisting of nodes, elements, material properties, loads and constraints) [41].

2.5.1.2 Solution

There is nothing for people to do, during the solution phase. The FEM software assembles the algebraic equations in matrix form and computes the unknown values of the primary field variables [45]. The processing time depends on the computer hardware, particularly on processors. More processors mean less time to show results. Despite this process is automatic, it can be aborted, due to mistakes did during the model building phase. The most common errors are following described [41]:

- Element quality;
- Invalid material properties;
- Material property not assigned to the elements;
- Insufficiently constrained model, which can show a rigid body motion due to external loads.

2.5.1.3 Visualization / Post-Processing

Computational accuracy does not guarantee the precision of the Finite Element Analysis. When all iterations and modifications are done to the model and the results are acceptable, it is necessary to validate it, so outcomes are validated by a correlation with test results or approval of the results by an experienced CAE department [41].

Once the solution has ended successfully, post-processing of the simulation results is done next. Usually, plots contain stresses, strains and deformations, and are then examined to verify how the part responded to the different loading conditions. Based on the results, the model is subject to modifications and a new analysis will be run to examine how the adjustments affected the part. Before viewing the results, it is important to imagine how the object would deform for the given conditions. Then, displacements and animation for displacements should be the first results to show, and any other output comes after it. Excessive displacement or illogical movement of the components indicate something is wrong. Softwares have the ability to display scaled results, when outputs have small magnitudes, as shown in Figure 40 [41]. While solution data can be manipulated in many ways in postprocessing, the most important objective is to apply sound engineering judgment in determining whether the solution results are physically reasonable [45].

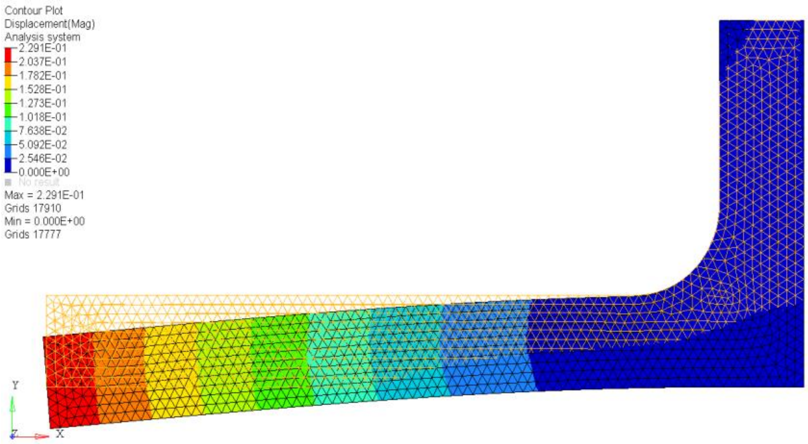


Figure 40 - Displacements scaled by factor 100 [41]

Another very useful option is the visualization technique, which animates results. This possibility is also, and especially, useful while interpreting results from a static analysis. The animated motion of the model provides insight into the overall structural response of the system due to the applied constraints [41].

2.5.2 Loads and Displacements

A correct solution of a structure should satisfy the next requirements: Equilibrium, Compatibility and Force-displacements relationship. The first necessity is based on the equilibrium of each node between external forces applied to a structure and the internal forces induced in its members. Compatibility is achieved when the members deform so that they all fit together. If the internal forces and deformations satisfy the stress-strain relationships of the members, the force-displacement relationship is also accomplished. Nowadays, for FEA, the two more used basic methods are:

- **Force method**: First of all, some of the internal forces and/or reactions are taken as primary unknowns, called redundants. Next, the stress-strain relationship is applied to express the deformations of the members in terms of external and redundant forces. Finally, by applying the compatibility conditions that the deformed members must fit together, a set of linear equations yield the values of the redundant forces. The stress resultants are calculated and the displacements of the nodes in the direction of external forces are found. This method is also named as the *flexibility method* and *compatibility approach*.
- **Displacement method**: In this method, the unknown variables are the displacements of the nodes necessary to describe the deformed state of the structure. The deformations of the members are then calculated in terms of these displacements and, by use of the stress-strain relationship, the internal forces are related to them. Finally, by using the equilibrium equations at each node, a set of linear equations is written and the unknown nodal displacements'

solution is found. This method is known as the *stiffness method* and *equilibrium approach*.

The applicability of these methods depends on the number of unknowns in a particular structure. Calculating the degree of static indeterminacy and kinematic indeterminacy, it is possible to compare the force and displacement methods. In Figure 41, there are three examples of structures to determine their redundants. In Figure 41a, the number of redundants is two in the force method and thirteen for the displacement approach. In the 3 x 3 planar frame shown in Figure 41b, the static indeterminacy and kinematic indeterminacy are twenty-seven and thirty-six, respectively. In Figure 41c, it is shown a six-bar planar truss, which the number of unknowns for the force and displacement methods is four and two, respectively. Instead of the number of unknowns, there is another criterion to choose the most suitable method: conditioning of the flexibility and stiffness matrices [47].

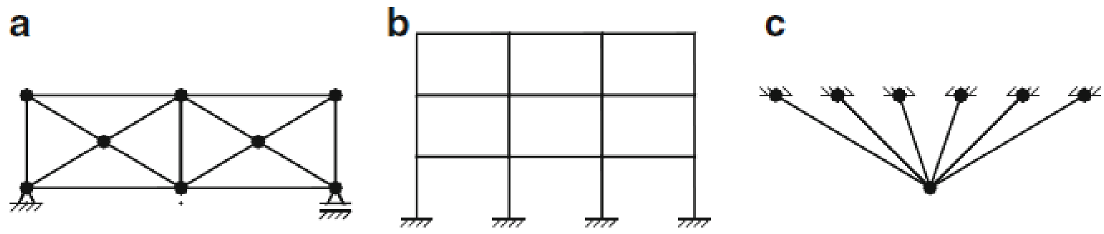


Figure 41 - Some simple structures. (a) A planar truss. (b) A planar frame. (c) A simple planar truss [47]

The main goal of any stress analysis or solid mechanics problem is to find the distribution of displacements and stresses under the stated loading and boundary conditions. To find an analytical solution to the problem, one of the following basic equations of solid mechanics needs to be satisfied, as shown in Table 5.

Table 5 - Total number of equations [48]

	Number of equations		
	In 3-dimensional problems	In 2-dimensional problems	In 1-dimensional problems
Equilibrium equations	3	2	1
Stress-strain relations	6	3	1
Strain-displacement relations	6	3	1
Total number of equations	15	8	3

Summarized, there are as many equations as there are unknowns to find the solution to any stress analysis problem. In practice, there are also additional equations, such as external equilibrium equations, related to the equilibrium of the body under external loads, compatibility equations, pertain to the continuity of strains and displacements, and boundary conditions, correlated to the prescribed conditions on displacements and/or forces at the boundary of the body. Although any analytical (exact) solution has to satisfy all equations specified previously, the numerical (approximate) solutions usually do not satisfy all the equations, like those obtained by using the finite element method. A good understanding of all basic equations of solid mechanics is essential in deriving the finite element relations and in estimating the order of error involved in the finite element solution by knowing the extent to which the approximate solution violates the basic equations, including the compatibility and boundary conditions [48]. Most problems related to solid and structural mechanics can be formulated according to one of the two methods: differential equation method (e.g., Galerkin approach) or variational method (e.g., Rayleigh-Ritz approach) [48].

2.5.2.1 Displacement-based Method

The displacement-based FEM can be regarded as an extension of the displacement method of analysis of beam and truss structures. In this analysis, there are several basic steps that are used in the displacement method [49]:

1. Idealize the entire structure as an assemblage of beam and truss structure that are interconnected at structural joints;
2. Identify the unknown joint displacements that completely define the displacement response of the structural idealization;
3. Formulate force balance equations corresponding to the unknown joint displacements and solve these equations;
4. With the beam and truss element end displacements known, calculate the internal element, stress distributions;
5. Interpret, based on the assumptions used, the displacements and stresses predicted by the solution of the structural idealization.

The most important steps of the complete analysis are the correct idealization of the actual problem, explained in step one and the right interpretation of the results, as in step five. It might be required to define an appropriate idealization, depending on the complexity of the actual system to be analysed, considerable knowledge of the characteristics of the system and its mechanical behaviour. Considering the analysis of truss and beam assemblages, originally these solutions were not considered as finite element analysis due to the difference with the general finite element analysis of two- or three-dimensional problem. The stiffness properties of a beam element are physically the element end forces that correspond to unit element end displacements. These forces can be estimated by solving the differential equations of equilibrium of the element when it is subjected to the appropriate boundary conditions. After the solution of the equilibrium differential equations, all three requirements of a correct solution throughout each element are satisfied, the exact element internal displacement and stiffness matrices are calculated. Such solutions would give the exact element stiffness coefficients if the exact element internal displacements (calculated in the solution of the differential equations of equilibrium) are used as trial functions. Nevertheless, approximate stiffness coefficients are obtained if other trial functions are employed, which can be more suitable [49].

For two- or three-dimensional finite element analysis, it is used the variational approach with trial functions, which approximate the actual displacements due to the unknown exact displacement functions, especially in the case of truss and beam elements. The differential equations of equilibrium are not satisfied as a result. However, this error is minimized as the finite element idealization of the structure. The general formulation of the displacement-based finite element method is based on the use of the principle of virtual displacements [49].

2.5.2.2 Force-based Method

The force method of structural analysis, in which the member forces are used as unknowns, is appealing to engineers, since the properties of a structure depend usually on the number of forces, instead of the number of displacements. This technique was used extensively until 1960. After this period, the arrival of the digital computer and the amenability of the displacement method for computation attracted most researchers. As a result, the force method and some of the advantages it offers in optimisation and non-linear analysis, have been abandoned. There are six different approaches to the force method of structural analysis, classified as follows [47]:

- Topological force method;
- Combinatorial force method;
- Algebraic force method;
- Mixed algebraic-combinatorial force method,
- Integrated force method,
- Metaheuristic based method.

For this analysis, three different properties are encountered: topological, geometrical and material. Dividing the study into these properties results in a considerable simplification in understanding the model behaviour leading to methods for efficient analysis. This chapter is focused on topological properties, needed to study the force (and displacement) method. For the same structure, the equations evolved in this technique may differ from those used in the displacement method. This number depends on the size, flexibility and stiffness matrices. The orders of these matrices are the same as the degree of kinematic indeterminacy of a structure, respectively [47].

2.5.3 Computational Fluid Dynamics

Computer Fluid Dynamics (CFD) is the analysis of systems involving fluid flow, heat transfer and associated phenomena by means of computer-based simulation. This method is very powerful and spans a wide range of industrial and non-industrial application areas, such as:

- Aerodynamics of aircraft and vehicles;
- Hydrodynamics of ships;
- Power plant: combustion in internal engines;
- Turbomachinery;
- Cooling of equipment;
- Biomedical engineering;
- Meteorology.

Back in the 1960s, CFD techniques were very used by the aerospace industry in the design, R&D and manufacture of jet engines. Nowadays, the methods are useful in several applications, described previously. Increasingly, CFD is becoming a vital module in the design of product and processes. Developments in CFD have been made to guarantee the same capability as other CAE tools, like stress analysis. The main reason why CFD has lagged behind is the tremendous complexity of the underlying behaviour. The availability of affordable high-performance computing hardware and the introduction of user-friendly interfaces have led to a recent upsurge of interest in this techniques [50].

2.5.3.1 CFD design

CFD codes are designed around the numerical algorithm that can solve fluid flow problems. All commercial CFD packages include sophisticated user interfaces to input problem parameters and to examine the results, in order to provide easy access to this software. Therefore, all codes involve three main elements: pre-processor, a solver and a post-processor [50].

2.5.3.1.1 Pre-processor

First of all, the input of a flow problem is specified as a CFD program by an operator-friendly interface and the subsequent transformation of this input into a form suitable for use by the solver. The user activities at this stage involve:

- Definition of the geometry of the region of interest: the computational domain;
- Grid generation – the sub-division of the domain into a number of smaller: a grid (or mesh) of cells (or control volumes or elements);
- Selection of the physical and chemical phenomena that need to be modelled;
- Definition of fluid properties;

- Specification of appropriate boundary conditions at cells which coincide with or touch the domain boundary.

The solution to a flow problem (e.g. velocity, pressure, temperature) is defined at nodes inside each cell. Like all analysis, the accuracy of the results is dependent on the number of cells in the grid. Also, both the accuracy of a solution and its cost in terms of necessary computer hardware and calculation time are governed on the fineness of the grid. Similarly, optimal meshes are non-uniform, finer in areas where large variations occur from point to point and rougher in regions with relatively little change. Efforts are underway to develop CFD codes with a self-adaptive meshing capability. Ultimately CFD programs will automatically refine the grid in areas of rapid variations. At the moment, it is still up to the skills of the CFD user to design a grid that is more suitable to guarantee the best compromise between the desired accuracy and solution cost. More than 50% of the time spent in the industry on a CFD analysis is dedicated to the definition of the domain geometry and grid generation. Up-to-date pre-processors give to the user access to libraries of material properties for common fluids and a facility to invoke special physical and chemical process models alongside to the main fluid flow equations [50].

2.5.3.1.2 Solver

For these techniques, there are three different numerical methods to analyse the problems: finite difference, finite element and spectral methods. The most well-established CFD codes are the FVM, which is a special FDM formulation. The numerical algorithm follows the next steps:

- Integration of the governing equations of fluid flow over all the control volumes of the domain;
- Discretisation – conversion of the resulting integral equations into a system of algebraic equations;
- A solution of the algebraic equations by an iterative method.

The control volume integration is the first step and exclusively to the FVM, distinguished from all other CFD techniques. The resulting statements express the conservation of relevant properties for each finite size cell. The affiliation between the numerical algorithm and the underlying physical conservation principle proceeds as one of the main attractions of the FVM and turns its concept simpler to understand by engineers than the finite element or spectral method. The conservation of a general flow variable ϕ (e.g. velocity component or enthalpy) within a finite control volume can be expressed as a balance between the various processes tending to increase or decrease it [50]. In other words, it can be written as shown in Figure 42.

Rate of change of ϕ in the control volume with respect to time	=	Net rate of increase of ϕ due to convection into the control volume	+	Net rate of increase of ϕ due to diffusion into the control volume	+	Net rate of creation of ϕ inside the control volume

Figure 42 - Conservation of a general flow variable [50]

CFD scripts comprise discretisation techniques suitable for the handling of the transport phenomena, convection and diffusion as well as for the source terms and the rate of change with the respect to time. The physical phenomena are complex and non-linear thus an iterative solution approach is required. The most popular solution procedures are by the tri-diagonal matrix algorithm (TDMA) line-by-line solver of the algebraic equations and the SIMPLE algorithm to ensure correct linkage between pressure and velocity. Commercial programs also have the possibility to use more recent techniques, such as Gauss-Seidel point iterative with multigrid accelerators and conjugate gradient methods [50].

2.5.3.1.3 Post-processor

Like in pre-processing, developers have been working hard to improve the post-processing field. Due to the increased popularity of engineering workstations, many of which have outstanding graphics capabilities, the leading CFD packages are now equipped with versatile data visualisation tools, such as:

- Domain geometry and grid display;
- Vector plots;
- Line and shaded contour plots;
- 2D and 3D surface plots;
- Particle tracking;
- View manipulation (translation, rotation, scaling);
- Colour post-script output.

More recently, these tools also include animation for dynamic result display, and in addition to graphics, all codes produce trusty alphanumeric output and have data export facilities for further manipulation external to the code. Such as other CAE tools, these graphics output capabilities of CFD have revolutionised the communication of ideas to the non-specialist [50].

THESIS DEVELOPMENT

3.1 Welcoming Company

3.2 Programming Softwares

3.3 Hydraulic Block

3.4 Gear Teeth Analysis

3.5 Road Load Acquisition

3 THESIS DEVELOPMENT

3.1 Welcoming Company

Punch Powertrain is a growing company, dedicated to research, development and producing powertrains. Its work is not only focused on CVT's transmissions but also DCT transmissions and powertrains for Plugin Hybrids (PHEV) and Electric vehicles (EV). The products destination is mainly the Chinese market, supplying most of the Chinese OEMs. These agreements made it possible to increase production from three hundred thousand to one million units per year, both in Belgium and China. The first thirty years of the company were dedicated to the European market, equipping brands like BMW, Fiat, Mini and MG-Rover. Only in the 21st century, the first steps are taken on the Chinese market. Together with this market, CVTs start appearing in South Korea brands, such as Hyundai and Kia Motors. Nowadays, Punch Powertrain delivers to most of the Chinese OEMs, but the company will start equipping some European vehicles in 2022.

3.1.1 Team organization

The Research and Development (R&D) are divided into different Product Development (PD) groups, which is also divided into teams. This work was integrated into PD1 of the Mechanical Engineering 2 team. This team is composed of eleven members, performing the following tasks: simulation and gear train analysis. The team is led by Hervé Bratec (substituting Gert Heirman, in the middle of the internship). This work was developed along the CAE team. It was daily guided by Naresh Kalidindi. The CAE team is composed of four other elements. The chart shown in Figure 43 represents the organisation of the PD1 group.

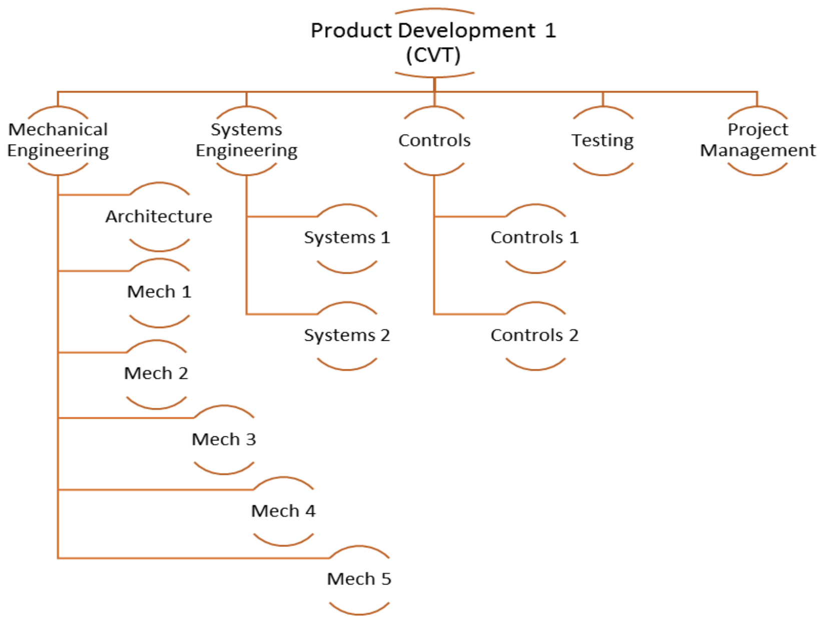


Figure 43 - Product Development 1 Organisation Chart

3.2 Programming Softwares

Since this work will be developed based on programming software, it is important to define the most suitable software to compute all data. Different programming languages are available. Associated with these programming languages, there are some pros and cons. In this chapter, it is only described the different software available and its languages, which are compiled in Table 6. All criteria to choose the best software are presented in the following section.

Table 6 - Programming Software Description

Software	Programming Language
Spyder	Python
MatLab	C++; C; Java
SciLab	C++; C; Java, Fortran
Jupyter	Python
FreeMat	C++; C; Java, Fortran; Assembly

3.2.1 Software Selection

In this segment, all solutions are considered and quantified, in order to find the best answer. The following tables connect the properties and the methods to order them and choose the most suitable processes and software. The process is divided into four steps.

The first step is to define properties and attribute a value, as shown in Table 7. The scale has the minimum number of one, the worst case, and the maximum value of ten, the best scenario. Properties are described as follows:

- **User-Friendly:** It is pretended to use a programming language that suits better to the problem exposed. The highest value means the best language to use;
- **Processing Time:** It is pretended to have a fast program, so the highest value is the fastest running program;
- **Access:** It is important that everyone can have access to the software. The highest value means that the program is free;
- **Outside Modules:** Some software needs outside modules to run. The highest value means fewer modules used.

Table 7 - Software properties values for Software choice

Properties	Spyder	MatLab	SciLab	Jupyter	FreeMat
User-Friendly	8	8	5	8	6
Processing Time	7	8	6	5	5
Access	10	5	10	10	10
Outside Module	7	9	6	6	6

The following step is to determine the Property Importance Index (ω_i), according to the order defined next: *User-Friendly* software is the most important property to develop a program, so everyone can learn in an easy and fast way, followed by the P*rocessing Time* that it takes to run the scripts. Although the company has a licence for some paid software, it is better when programs are made available as open-source, so *Access* is the third important property. The last aspect to consider is the *Outside Modules*, that need to be used to run the script or even to show results in a simpler way. The three columns in the middle are organized by its importance. For example, comparing *User-Friendly* and *Access*, the first one is more important, so it gets a 70% comparing to the other property. In the fourth column, the small value is divided by the value of the most important property. With the same example, the importance value of *Access* is divided by the Importance value of *User-Friendly*, which will result in an Importance factor of 0.429. Then, all the Importance factors are summed, making a total of 2.429. The final step is to find the Ponderation Weight Indexes, which consists of divide the Importance factor by its total. These Importance rates are described in Table 8.

Table 8 - Property Ponderation Indexes (ω_i) for Software choice

	2/1	3/1	4/1		Importance	ω_i
Language	60	70	75		1.000	0.412
Processing Time	40				0.667	0.275
Access		30			0.429	0.176
Outside Modules			25		0.333	0.137
				Total	2.429	1.000

The third step is to define Software Ponderation Weight Index (β_i), using the values of Table 7. Considering the values in each column in the table, all values are divided by the highest one. The results of these calculations are shown in Table 9.

Table 9 - Software Ponderation Indexes (β_i) for Software choice

	Language	Processing Time	Access	Outside Modules
Spyder	1.000	0.875	1.000	0.778
MatLab	1.000	1.000	0.500	1.000
SciLab	0.625	0.750	1.000	0.667
Jupyter	1.000	0.625	1.000	0.667
FreeMat	0.750	0.625	1.000	0.667

Finally, the performance index can be determined, using the following equation:

$$y_i = \sum \omega_i \times \beta_i \qquad \{3.1\}$$

Where ω_i is the Property Importance Index, from Table 8, and β_i is the Software Ponderation Weight Index, from Table 9. Like the previous indexes, the highest Performance Index is the most suitable solution, as shown in Table 10. *Spyder* presents the highest rate and it will always be the first option to develop any program in this work. *MatLab* is very close to the previous one and it will be used in the last case.

Table 10 - Software Performance Indexes for Software choice

Software	Performance Index
Spyder	0.935
MatLab	0.912
SciLab	0.731
Jupyter	0.851
FreeMat	0.748

3.3 Hydraulic Block

3.3.1 Problem proposed

As previously mentioned, transmissions have a hydraulic system, which lubricates, cools and controls it. The main part of this system is the hydraulic block, which is located in the bottom of the transmission, as shown in Figure 44. This piece is composed of two blocks (solenoid body and manifold), one intermediate plate, bolts and several valves and solenoids. The fluid is controlled by the solenoids and it is directed through the labyrinth of channels to the interfaces. These channels handle different pressures. This work focusses in only one *valve* and *bore* and it is proposed to develop a script to predict any interference between both parts. The wall with the biggest deformations is between the green and red colours. The goal is to develop a program that can guarantee the operation of this system in all points.

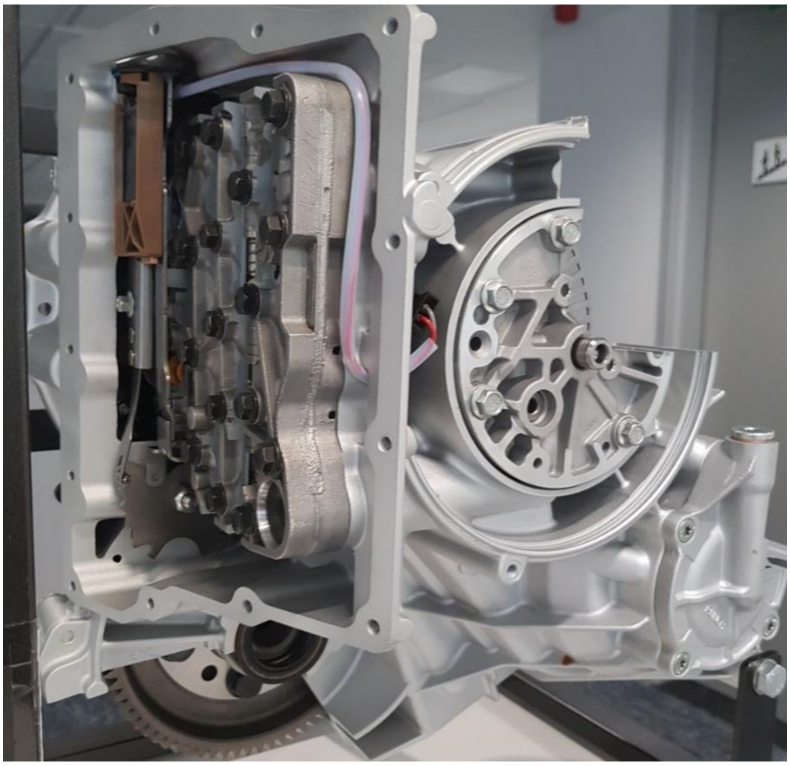


Figure 44 - Hydraulic block location (Courtesy of Punch Powertrain NV)

As the name implies, pressure relief valves are actuated to reduce pressures in the channels, moving back and forward. Due to the high difference of pressures in channels, the wall that separates it can deform in direction of the lowest pressure. The deformed wall will be in contact with the valve, which can cause the cylinder stuck or slow it down. The hydraulic block is simulated to determine stress and displacements. When is required, strains can also be predicted. However, this last simulation is required, only when the Yield Strength is exceeded, leading to the plastic zone of the material. In this situation, the specifications of the part need to be changed, since only the elastic zone is relevant to use. Thus, the relevant data for this work are the stresses and deformations, with focus on the last one. It is only simulated the blocks, intermediate plate and bolts, without valves and solenoids. The simulations were run in ABAQUS, but some steps are created on HyperMesh.

3.3.2 Solutions Identification

At this point, the goal is to present several solutions to the problem proposed. The important aspect is the type of analysis. This point focuses on the different variables involved and which ones are included. The analysis can involve only geometrical deviations or can also consider pressures on channels and the casting of the parts.

Interference in the *Line* can be predicted in different approaches. One way is to study the geometrical displacements of the bore. This method consists of checking the distance between the nodes, to examine if the tolerances are respected. It is the easiest technique, due to the simplest calculations and programming. The second approach involves the previous method. However, it includes the pressures and the casting specifications for the blocks. The third option is to introduce numerical algorithms, which are supported by some assumptions. This last option will be divided into two analyses, as explained in the next section. In Table 11, it is shown the considerations and the variables needed to implement each of these methods. Further, all reflections will be quantified and the best approaches will be selected.

Table 11 - Considerations and Variables

Solution	Considerations	Variables
1	• Interference between the cylinder and bore • Cylindricity • Pressures	• Displacements • Tolerances • Distance formula
2	• Interference between the cylinder and bore • Cylindricity • Pressures and Leakages	• Displacements • Tolerances • Channels Pressure • Design information
3	• Type of algorithm • Accuracy • Rigid Body Motion	• Displacements • Tolerances • Algorithm

3.3.3 Choice of Solutions

As the analysis in section 3.2.1, it is time to choose the most suitable software, using the same procedure. The first step is to identify the methods and attribute a value, as shown in Table 12. The four properties have different meanings, explained next:

- **Assumptions:** It is intended the minimum assumptions, so the highest value means fewer assumptions;
- **Variables:** It is also intended the minimal variables, to have the same result. The highest value means fewer variables used;
- **Accuracy:** The result of the post-process has to be the most similar to a real scenario. The highest value means the most similarity;
- **Complexity:** It expresses the complexity of the mathematical theories behind the algorithm. The highest value represents the simplest method.

Table 12 - Method property values for Analysis choice

Method	Geometrical Analysis	Complete Analysis	Quadratic Programming	Linear Programming
Assumptions	7	6	7	5
Variables	8	5	8	7
Accuracy	6	7	7	5
Complexity	7	4	6	7

The second step comprises the ponderation value of each property, according to the previous explanation of the properties. In this case, the most important properties are the *Complexity* and *Accuracy*, followed by the *Variables*. In the final position, it is the *Assumptions*. This order was established to use the minimal resources and obtain the best results. Table 13 relates the importance and determines the Property Importance Index (ω_i).

Table 13 - Property Ponderation Weight Indexes (ω_i) for Analysis choice

	1/2	1/3	1/4	Importance	ω_i
Complexity	50	60	70	1.000	0.323
Accuracy	50			1.000	0.323
Variables		40		0.667	0.215
Assumptions			30	0.429	0.138
			Total	3.095	1.000

Next step determines the ponderation weights of the method, according to property. Using the values from Table 12, the Method Ponderation Weight Index (β_i) is found. The results of these calculations are shown in Table 14. Like the previous indexes, the higher the value, more importance the method exhibits.

Table 14 - Method Ponderation Indexes (β_i) for analysis choice

	Complexity	Accuracy	Variables	Assumptions
Geometrical Analysis	1.000	0.857	1.000	1.000
Complete Analysis	0.571	1.000	0.625	0.857
Quadratic Programming	0.857	1.000	1.000	1.000
Linear Programming	1.000	0.714	0.875	0.714

Using equation {3.1}, the highest Performance Index is the most suitable solution, as shown in Table 15. *Geometrical Analysis* and *Quadratic Programming* have the highest rate and both will be used in this work.

Table 15 - Method Performance Indexes for Analysis choice

Method	Performance Index
Geometrical Analysis	0.954
Complete Analysis	0.761
Quadratic Programming	0.954
Linear Programming	0.841

3.3.4 Input Data

After simulation of the hydraulic block, it is time to analyse the results. Simulations can predict deformations of the wall. First of all, the required data is extracted, which are the local coordinates and relative displacements of the bore surface. These coordinates are in the rectangular systems. All coordinates are related to a local referential. These values are the input data for all developed work in this section. An example of this surface and its mesh is shown in Figure 45. All coordinates are expressed in millimetres [mm].

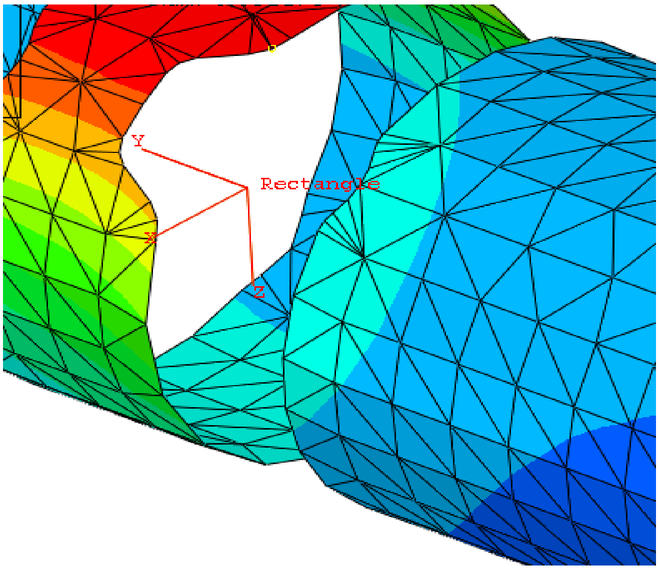


Figure 45 - Surface mesh of the *bore*, modelled with C3D4H (Courtesy of Punch Powertrain NV)

3.3.5 Case Study 1

Initially, it is defined as the tolerance between the bore and valve are the same. Tolerances state how much the valve can move inside the bore. Drawing specifies the maximum and minimum tolerances. For each measured distance, that is lower than the minimum value is considered a contact or it will not fit. The zone with a distance larger than the maximum tolerance is considered also critical, since it can cause leakages and press the valve, increasing the contact on the opposite side of the valve. These values are suitable for both approaches, described in the next segments. With respect to material, both components are made of an aluminium alloy. However, it is considered that the *valve* is undeformable.

3.3.5.1 Geometric Analysis

All work presented in this section was developed in *Spyder*, using the *Python* language. The first approach is based on a geometric analysis. In other words, the program will only consider the position of the operation points and the tolerance between the *valve* and *bore*.

The first goal is to read the files containing the coordinates and the relative displacements, without copying it to an excel sheet. This data is presented in two different files. One contains the local coordinates of the nodes and the other file has the relative displacements. Both files are exported directly from *ABAQUS*. Then, the program starts with the representation of the *bore* in *Spyder*. This step is important since it will confirm if the imported data are correct. This validation is represented by a plot of the nodes, as shown in Figure 46. It is easy to identify a cylinder, which reproduces the meshed surface exported from the simulation. This surface represents the *bore*.

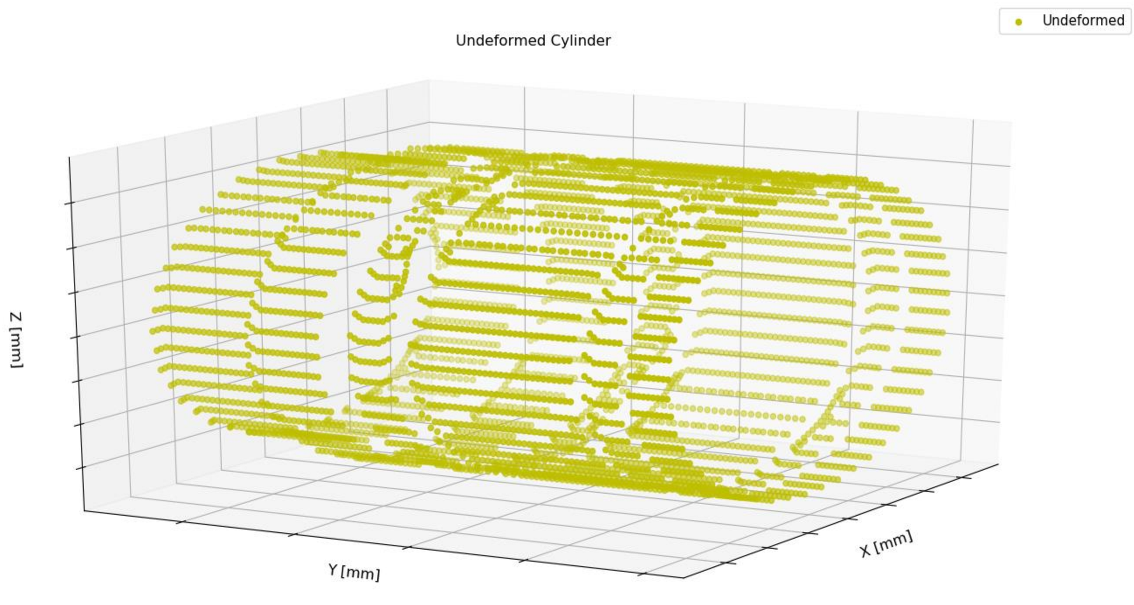


Figure 46 - Undeformed Coordinates, Case Study 1

Another important feature is to represent the deformed bore. Hence, relative displacements were imported and added to the local coordinates, respectively. This stage creates new coordinates that will give the shape of the deformed *bore*. Displacements are small, so it needs to be scaled. In order to see clearly, displacements were amplified one hundred times, as shown in Figure 47 and Figure 49. The smallest length of the section of the *bore* has the highest displacements for both load cases, which agrees with Figure 48 and Figure 50. This last two figures are exported from the simulation.

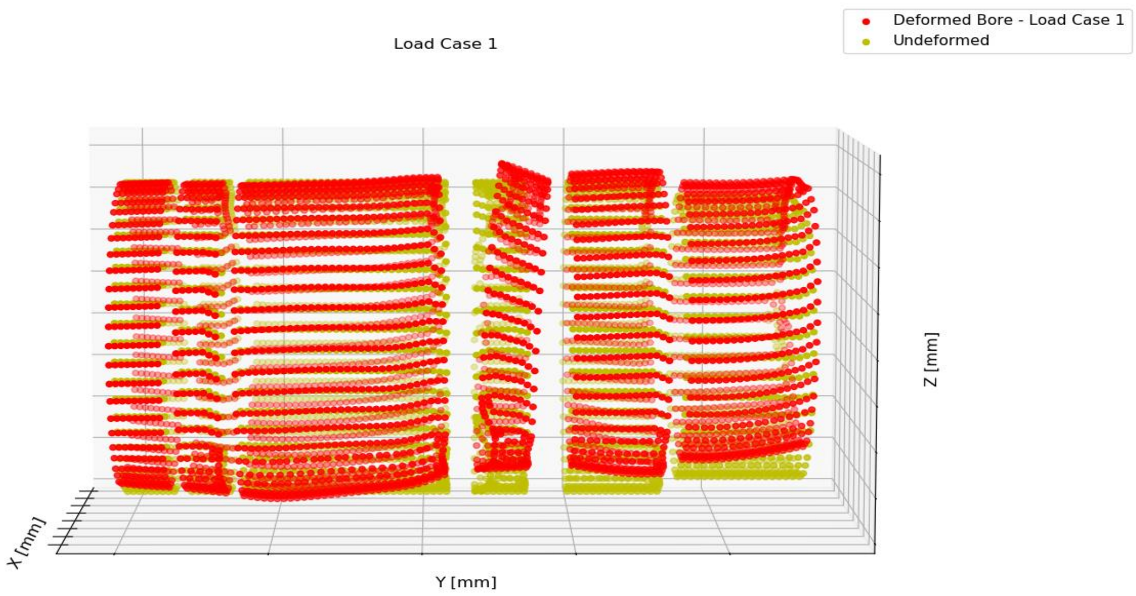


Figure 47 - Deformed Bore, Case Study 1, Load Case 1 (scale factor: 100)

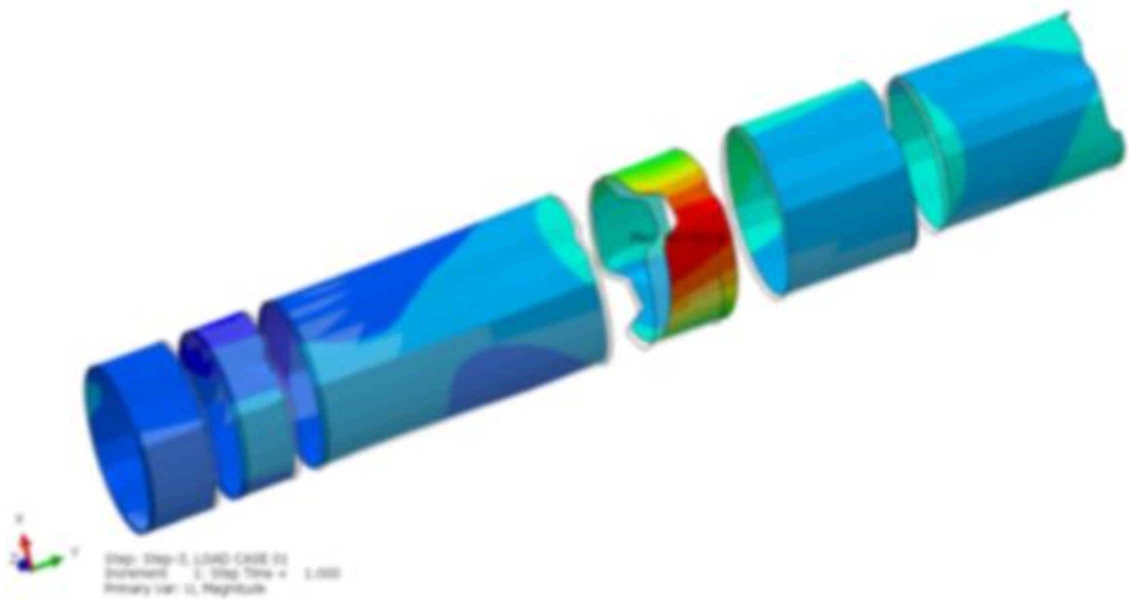


Figure 48 - Simulation result, Case Study 1, Load Case 1 (scale factor: 50)

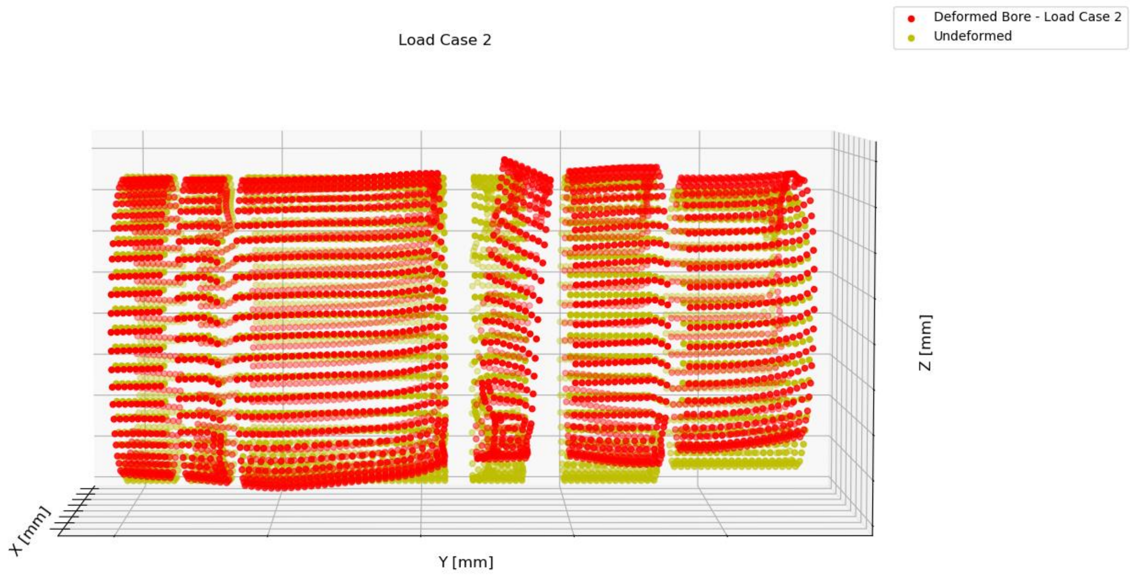


Figure 49 - Deformed Bore, Case Study 1, Load Case 2 (scale factor: 100)

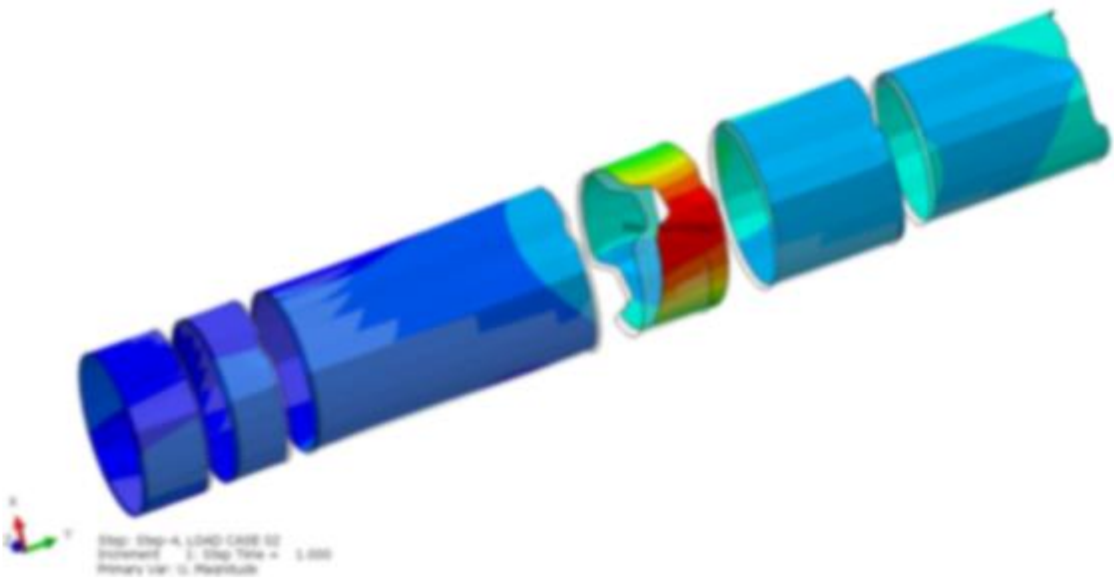


Figure 50 - Simulation result, Case Study 1, Load Case 2 (scale factor: 50)

Since this analysis focusses only in a geometrical interference, the program will be developed according to the distance between the coordinates of the *bore* and *valve*. It is only presented the local coordinates of the *bore*, consequently, it is necessary to create the local coordinate of the *valve* – virtual nodes. Diameters of both parts can also be found in drawings from Annex 6.1. Figure 51 illustrates the imported local coordinates and the virtual coordinates, which was created by the program. Every point is defined in a 2D plane, using equation {3.2}, which represents the distance between the origin and the point in the surface.

$$\Delta r = x \cos\theta + y \sin\theta \qquad \{3.2\}$$

where x and y are the coordinates of each node. The variable θ is the angle between the two previous coordinates.

As it is known the tolerance between both parts, it is possible to create the virtual node. The minimum tolerance is subtracted in equation {3.2}. The third direction (Z) does not need to be changed. After this procedure, it is possible to have a node beneath the other, as shown in Figure 51 with points *a)* and *b)*.

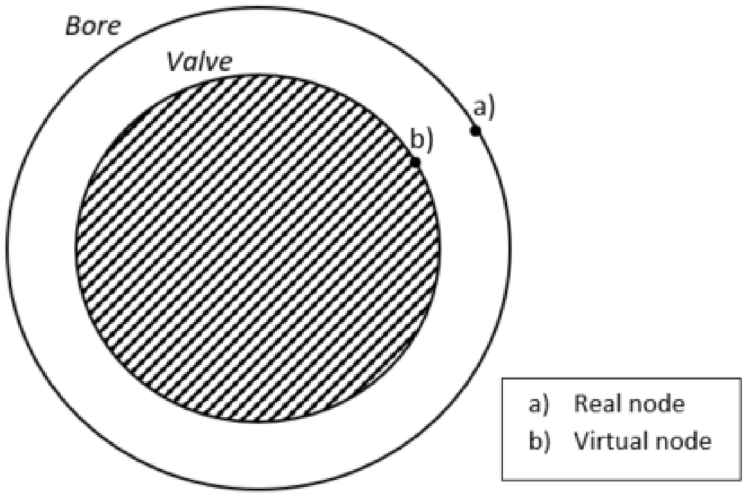


Figure 51 - Bore and Valve coordinates representation

After defining all coordinates, the main goal of this chapter is ready to be analysed. It was chosen the distance formula (Δd), in equation {3.3}, to determine the distance between all nodes.

$$\Delta d = \sqrt{(x_b - x_a)^2 + (y_b - y_a)^2 + (z_b - z_a)^2} \qquad \{3.3\}$$

where x_a, y_a and z_a define the 3D point of the *Valve* surface and x_b, y_b and z_b represent the 3D point of the *Bore* surface. In Figure 52, it is illustrated these variables, which are used in the equation {3.3}.

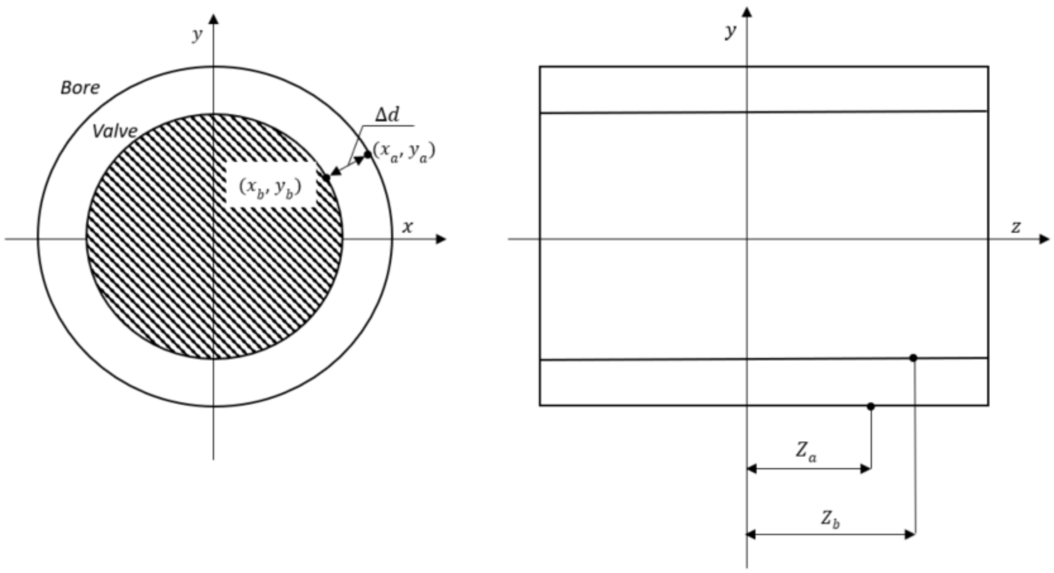


Figure 52 - 3D Coordinates representation

Diagrams are crucial to understanding in a better way where the contacts are worst. Thus, it is created two plots with colourmap to simplify the analysis. It is also easy to interpret the colourmap. Every distance lower than the tolerance, colours are yellow, orange and red, where the last colour has the smallest value. Both results are shown in Figure 53 and Figure 54.

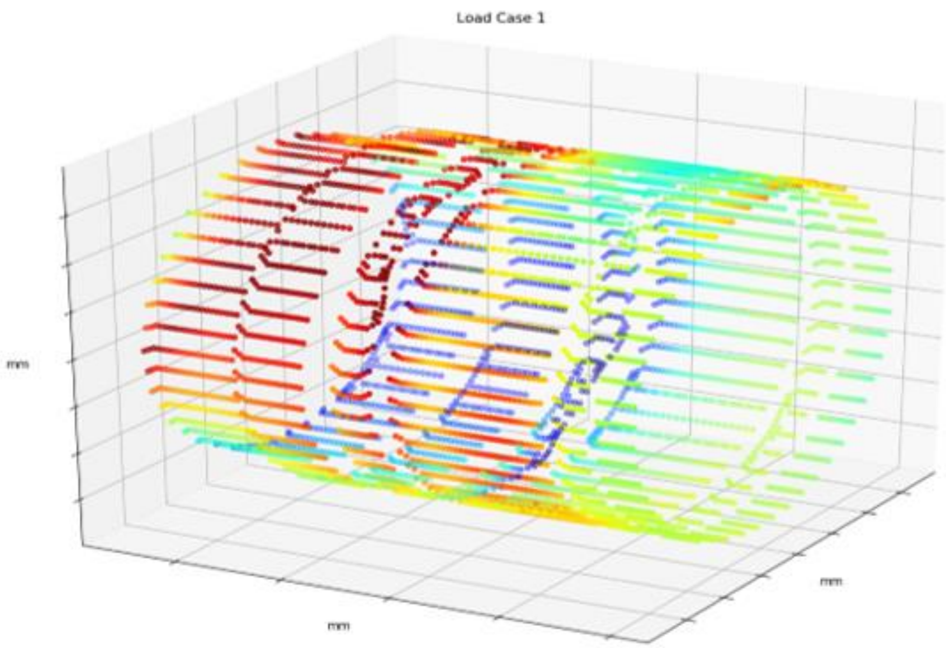


Figure 53 - Geometrical Analysis results, Case Study 1, Load Case 1

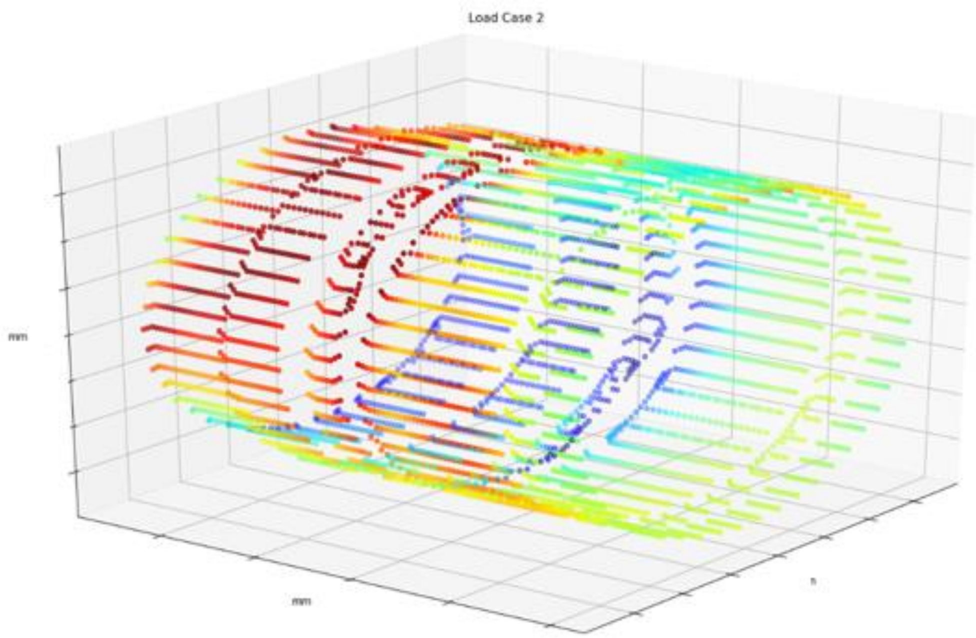


Figure 54 - Geometrical Analysis results, Case Study 1, Load Case 2

After understanding the figures, the location of the critical zones is identified. These zones occur on the bottom of the hydraulic block. So that the analysis can be validated, these results were compared with a real tested block. Although the project is different, the components and the pressures are the same.

3.3.5.2 Quadratic Programming

Like the previous section, this work was developed with *Python* language, in *Spyder*. The second suggested approach was to use an algorithm to determine the compatibility of the *valve* in the deformed *bore*. As seen previously, Quadratic Programming (QP) was the most suitable algorithm to solve that problem. It was necessary to install a free module for convex optimization (CVXOPT).

QP is a mathematical optimization process to solve problems, minimizing a quadratic function, subject to a linear inequality and/or equality constraint. A quadratic program with *n* variables and *m* constraints is formulated as follows:

- A real-value, n-dimensional vector $\boldsymbol{q}$;
- A *n x n*-dimensional real symmetric matrix *P*;
- A *m x m*-dimensional real matrix *G*;
- A m-dimensional real vector $\boldsymbol{h}$.

The objective of quadratic programming is to find an n-dimensional vector $\boldsymbol{x}$, that will:

$$\text{minimize } \frac{1}{2}\boldsymbol{x}^T P\boldsymbol{x} + \boldsymbol{q}^T\boldsymbol{x} \tag{3.4}$$

$$\text{subject } G\boldsymbol{x} \leq \boldsymbol{h}, \tag{3.5}$$

where $\boldsymbol{x}^T$ denotes the vector transpose of $\boldsymbol{x}$. $G\boldsymbol{x} \leq \boldsymbol{h}$ means that every entry of the vector $G\boldsymbol{x}$ is less than or equal to the corresponding entry of the vector $\boldsymbol{h}$.

The analysis is divided into two parts. The undeformed verification is to ensure that there are no contacts between nodes and the program is running properly. In the second analysis, it is introduced the relative displacements and determined how much the wall deform so the *valve* will not fit in the *bore*, for all operating points.

The first step of this chapter is to define the matrices to minimize. Matrix $\boldsymbol{x}$ is defined further ahead. Thus, matrices P and $\boldsymbol{q}$ are expressed as follows:

$$P = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & L/2 & 0 \\ 0 & 0 & 0 & L/2 \end{bmatrix} \tag{3.6}$$

$$q = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{3.7}$$

One point in the cylinder is considered and it will be the assumption for the first matrix. Figure 55 illustrates the point a), which is fully defined along with $\boldsymbol{x}$. Thus, P is defined by equation {3.6}. The second matrix is considered zero, since the point is characterized in the previous matrix.

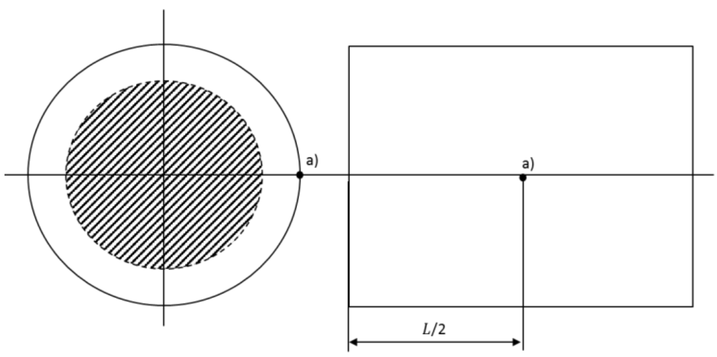


Figure 55 - a) Point assumption

The second step is to define matrices to subject. Once again, the *bore* is represented with the local rectangular coordinates and the *valve* is defined by its *virtual nodes*. Before defining the undeformed *bore* matrices, points on the cylinder are expressed as follows, after rigid body motion:

$$x_b = X + \theta_y \cdot Z \qquad \{3.8\}$$

$$y_b = Y - \theta_x \cdot Z \qquad \{3.9\}$$

The length of each point from the origin is defined by the equation {3.10} and Figure 56 illustrates it. The variable θ is obtained from the undeformed coordinates. The coordinate Z is unchangeable.

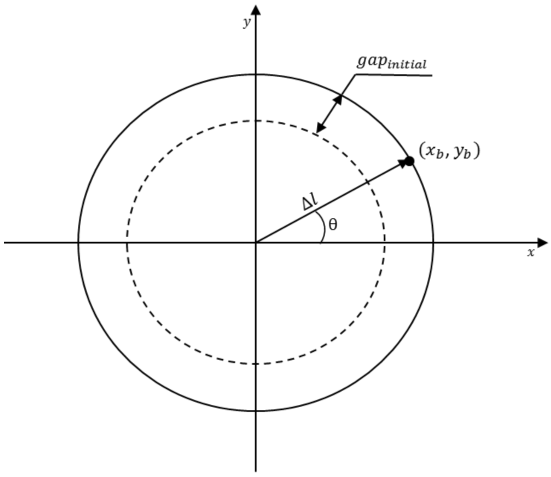


Figure 56 - Length of point illustration

$$\Delta l = x_b \cdot cos\,\theta + y_b \cdot sin\,\theta \qquad \{3.10\}$$

After defining the exterior points, the *virtual nodes* are created. One of the inequalities constraints is presented as follows. It is used equation {3.10} and the tolerance, 0.009 mm, represented by $gap_{initial}$.

$$gap_{initial} - \Delta L \geq 0 \qquad \{3.11\}$$

From equations {3.8}, {3.9}, {3.10} and tolerance, previous equation is written by:

$$[cos\,\theta \quad sin\,\theta] \cdot \begin{bmatrix} 1 & 0 & 0 & Z \\ 0 & 1 & -Z & 0 \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ \theta_x \\ \theta_y \end{bmatrix} \leq [0.009] \qquad \{3.12\}$$

This equation is written for every point, so at the end, it will have a matrix with *m* lines. The exception goes to matrix $\boldsymbol{x}$, which is a general form, equal for every node, that will be determined. It is easy to identify the different matrices to minimize and to subject, which are:

$$G = [cos\,\theta \quad sin\,\theta] \cdot \begin{bmatrix} 1 & 0 & 0 & Z \\ 0 & 1 & -Z & 0 \end{bmatrix} \qquad \{3.13\}$$

$$x = [X \quad Y \quad \theta_x \quad \theta_y]^T \qquad \{3.14\}$$

$$x = [0.009] \qquad \{3.15\}$$

The second analysis is referred to verify the deformed *bore*. The relative displacements are added in each node. Like the points, the displacements also have a length related to it. To determine that length is used equation {3.16}, as follows next. In Figure 57 it is shown a representation of the relative displacements length. Variable α is the angle between coordinates x_d and y_d.

$$\Delta r_{deformation} = \Delta r_d = x_d \cdot cos\,\alpha + y_d \cdot sin\,\alpha \qquad \{3.16\}$$

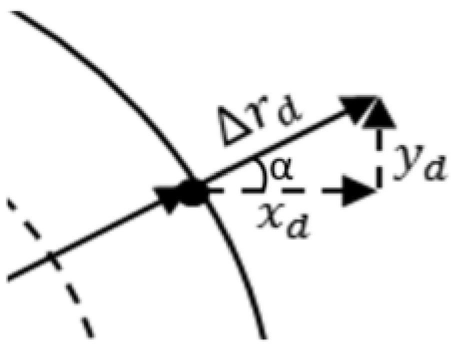


Figure 57 - Relative displacements representation

Equation {3.16} will be included at the right side of equation {3.12}, resulting in the inequality, as follows:

$$[cos\,\theta \quad sin\,\theta] \cdot \begin{bmatrix} 1 & 0 & 0 & Z \\ 0 & 1 & -Z & 0 \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ \theta_x \\ \theta_y \end{bmatrix} \leq [0.009] + [\Delta r_d] \qquad \{3.17\}$$

The results of this program will predict the scale factor of the relative displacements. In other words, it will run until it does not find a solution, which means the *valve* will not fit on the *bore*. The program runs first for Load Case 1 and automatically runs for Load Case 2. Like the previous analysis, there are also illustrations with colourmaps to easily identify the critical displacements, in Figure 58 and Figure 59.

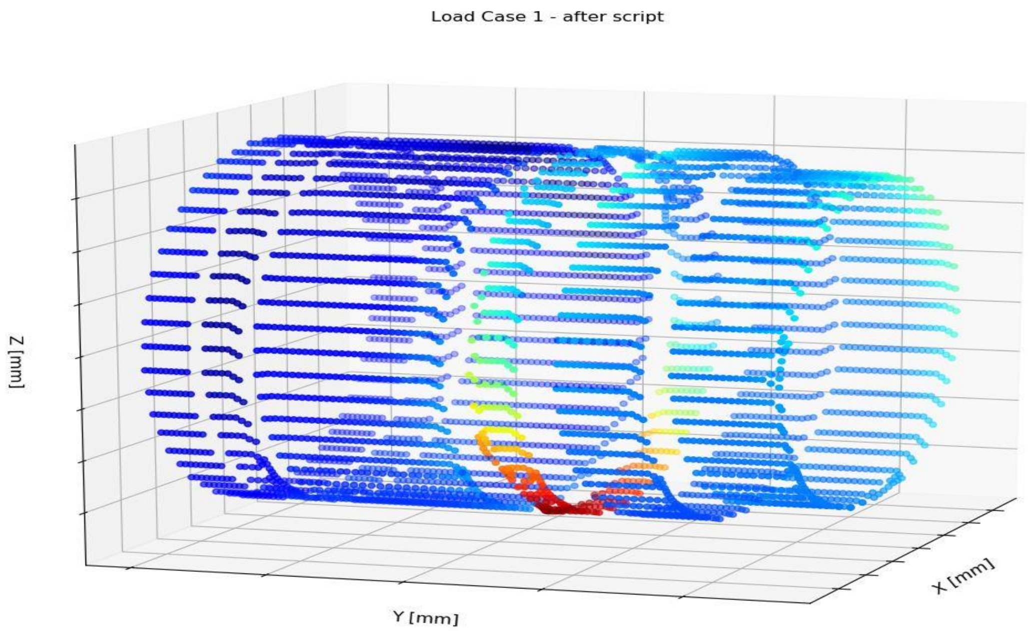


Figure 58 - QP results illustration for maximum tolerance, Case Study 1, Load Case 1

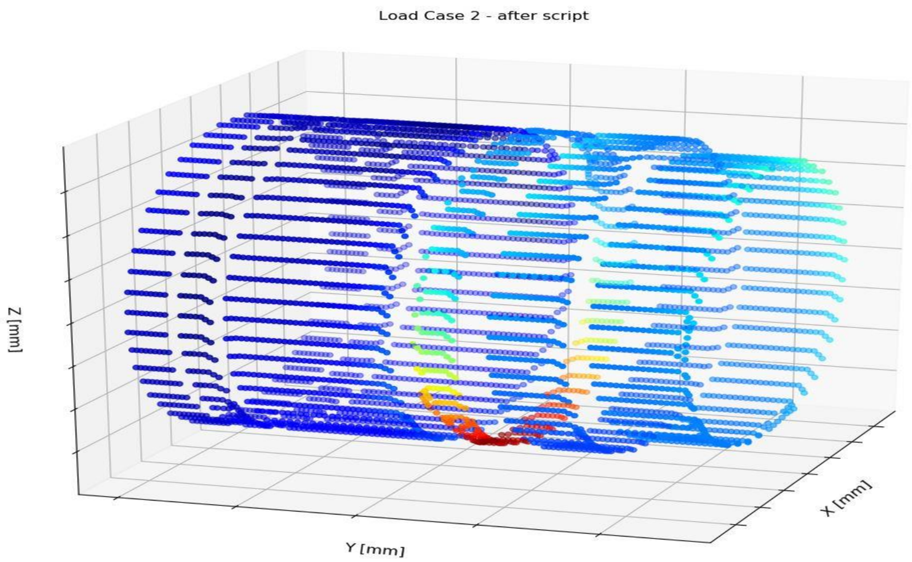


Figure 59 - QP results illustration for maximum tolerance, Case Study 1, Load Case 2

3.3.6 Case Study 2

All previous programs are applied to this case study. Thus, this chapter will be the presentation of the post-processing results and a comparison with a tested hydraulic block. The materials of the *bore* and the *valve* are made of an aluminium alloy.

3.3.6.1 Geometric Analysis

Using the same order of the previous sector, Figure 60 represents the undeformed bore, created from the rectangular coordinates. The tolerances used in this chapter were the same as the Case Study 1. However, this was confirmed with the drawings of the Solenoid Body and the Valve, shown in Annex 6.2.

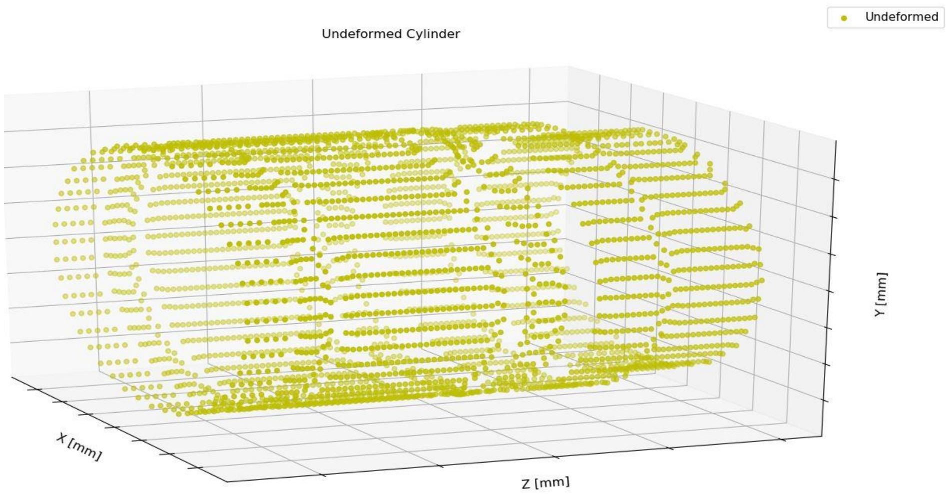


Figure 60 - Undeformed Bore, Case Study 2

So it would be possible to understand clearly the deformations on each section, Figure 61 and Figure 63 represent the deformed nodes compared to the undeformed nodes. The results of the simulations are shown in Figure 62 and Figure 64 to use as a comparison. The intention to validate these results is also presented.

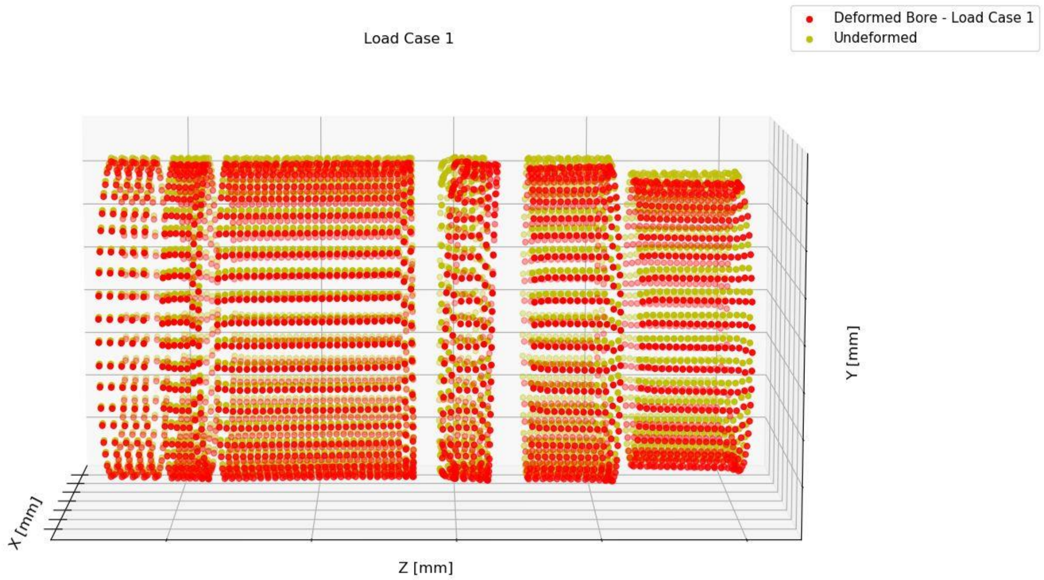


Figure 61 - Deformed Bore, Case Study 2, Load Case 1 (scale factor: 30)

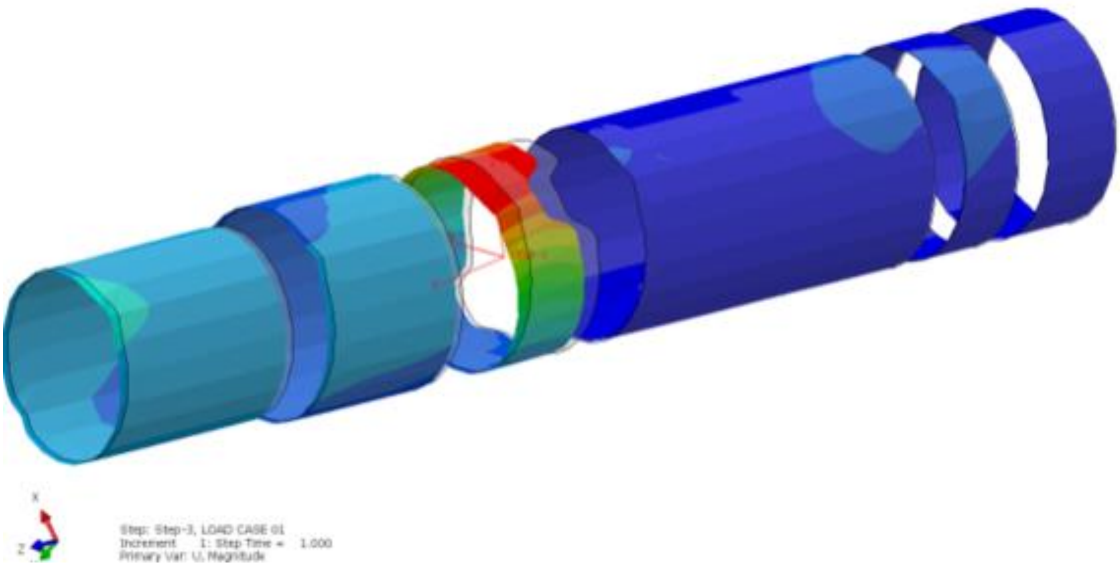


Figure 62 - Simulation result, Case Study 2, Load Case 1 (scale factor: 30)

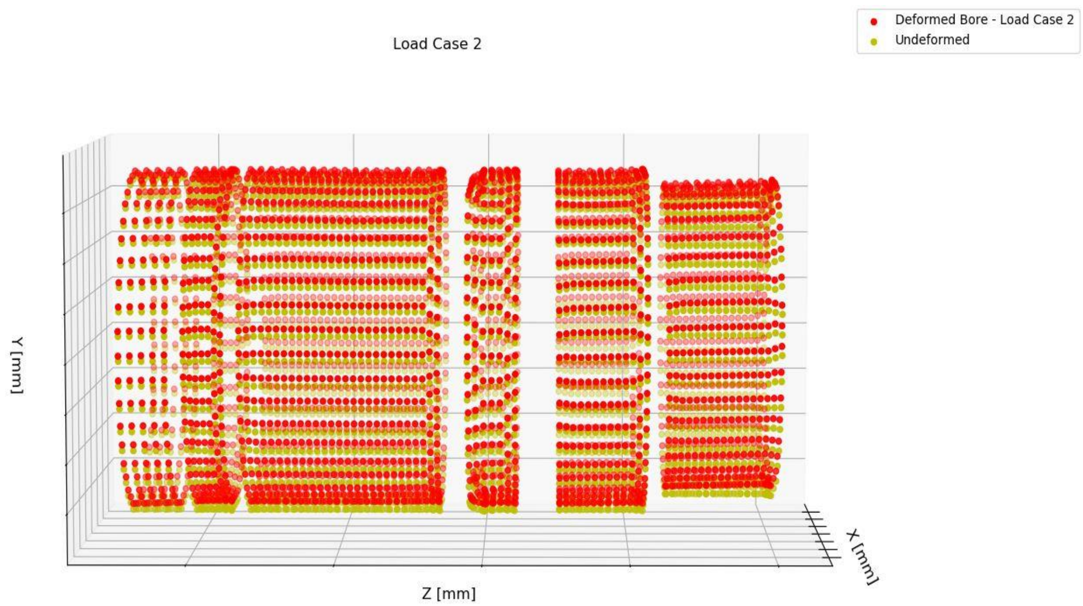


Figure 63 - Deformed Bore, Case Study 2, Load Case 2 (scale factor: 30)

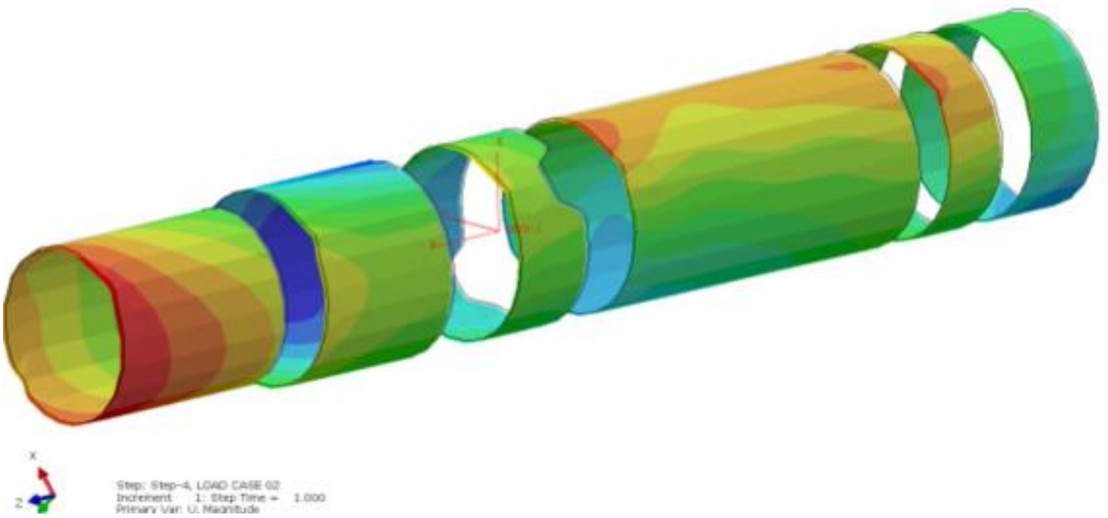


Figure 64 - Simulation result, Case Study 2, Load Case 2 (scale factor: 30)

Also, in this case, the results are shown in two plots to simplify the analysis. The results for Load Case 1 are represented in Figure 65 and, in Figure 66, it is possible to study the results of the Load Case 2.

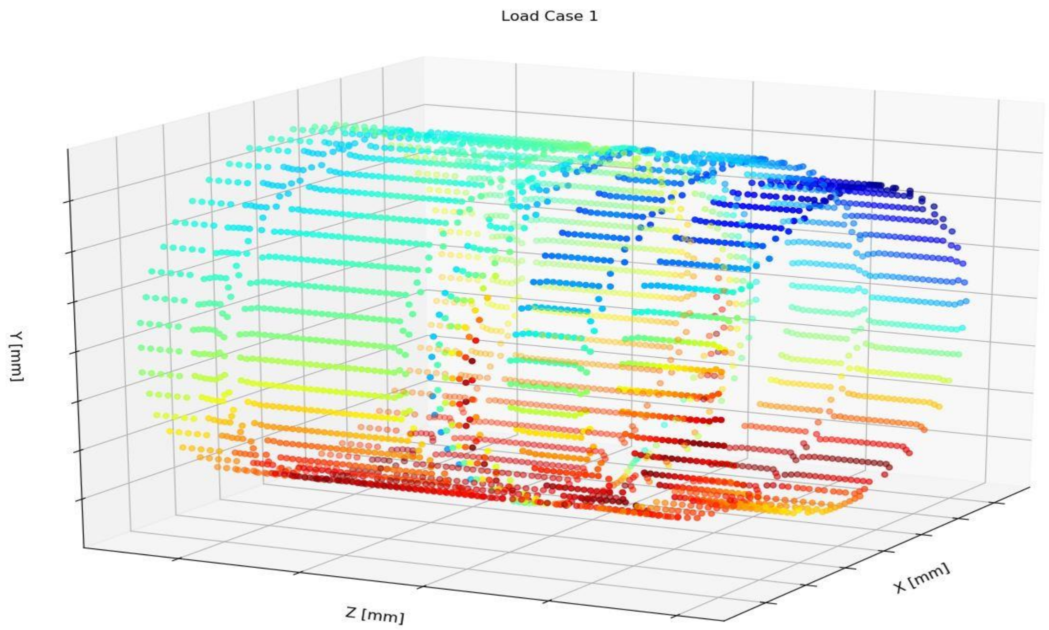


Figure 65 - Geometrical Analysis results, Case Study 1, Load Case 2

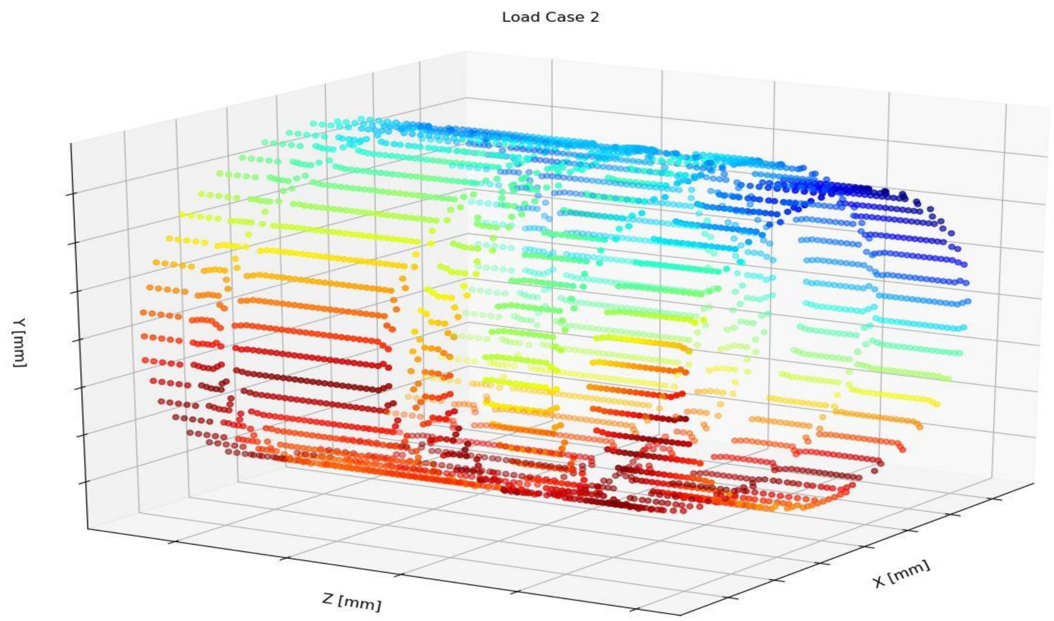


Figure 66 - Geometrical Analysis results, Case Study 2, Load Case 2

The intention to validate these results is also presented. Analysing an old real block, it is possible to find scratches on the bottom of the block. In this case, there was some improvements to eliminate this issue. The responsible team to implement these improvements was the Hydraulic Team.

3.3.6.2 Quadratic Programming

Applying the program used in the previous Case Study, the following results represent the maximum scale factor, which does not allow the *valve* fits on the *bore*. The results are represented by Figure 67 and Figure 68.

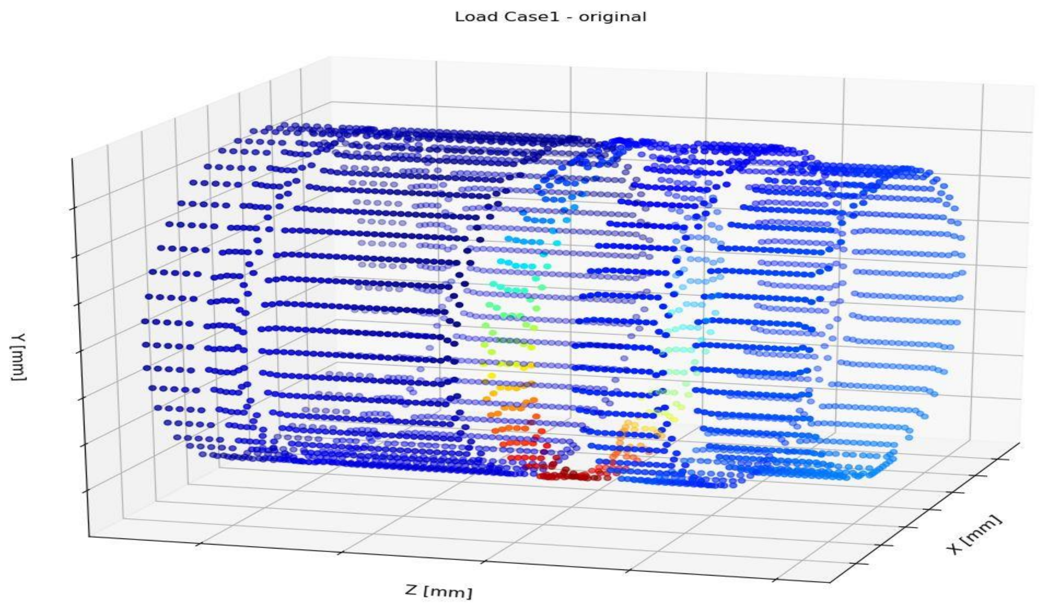


Figure 67 - QP results illustration for maximum tolerance, Case Study 2, Load Case 1

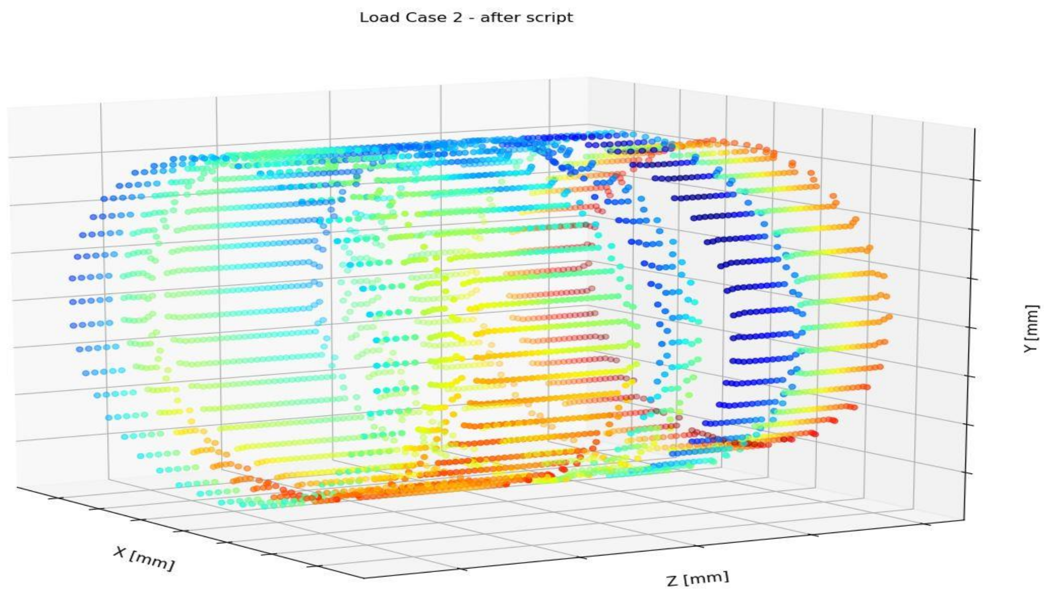


Figure 68 - QP results illustration for maximum tolerance, Case Study 2, Load Case 2

The scale factor in Load Case 1 is under 1, which means that the maximum displacement allowed was exceed before the script runs. In other words, in Load Case 1, the *valve* will get stuck in the *bore*.

3.3.7 Graphic User Interface

All previous diagrams can be easily selected from a Graphic User Interface (GUI). This functionality is important to manage which files are read. GUI is divided into three pop-up windows:

- **Diagrams Selection**: Different options to view the results of the application. The user can choose from the undeformed *bore* to the plots with a colourmap, as shown in Figure 69;
- **Instructions**: Information to the user knows how the application works, as shown in Figure 70;
- **File Selection:** Window containing three buttons. Two of them are to select files and the other is to run the application, as shown in Figure 71.

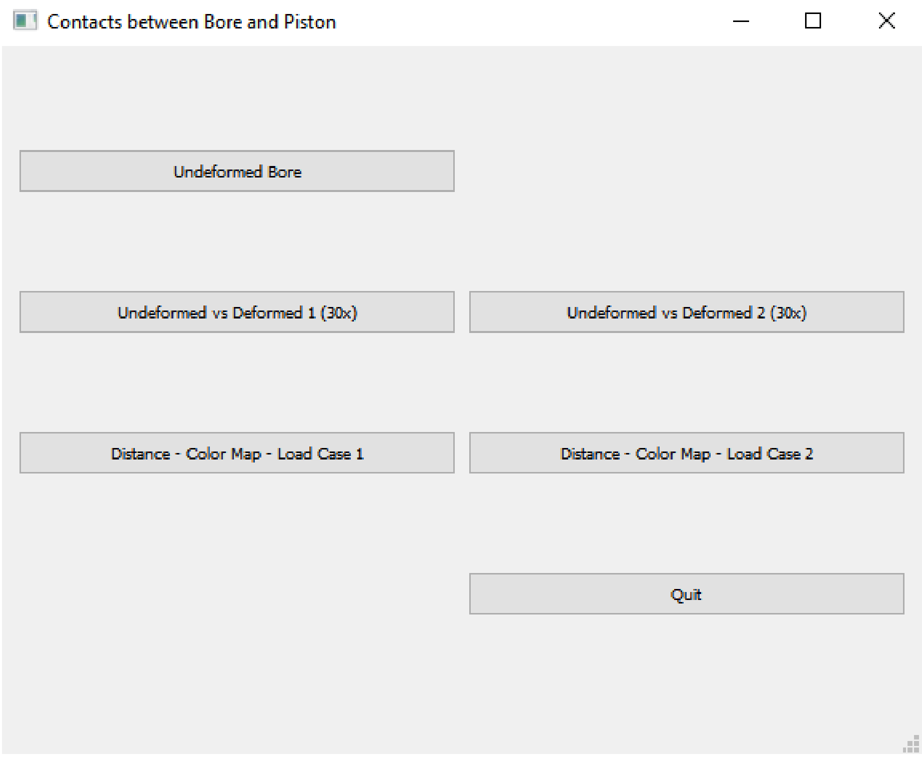


Figure 69 - Diagram Selection pop-up window

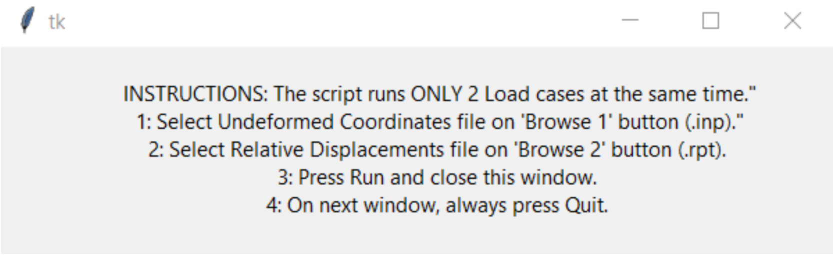


Figure 70 - Instructions pop-up window

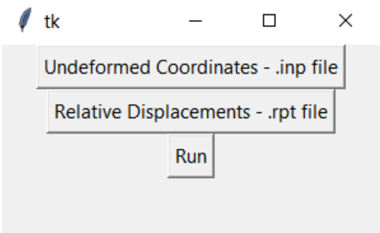
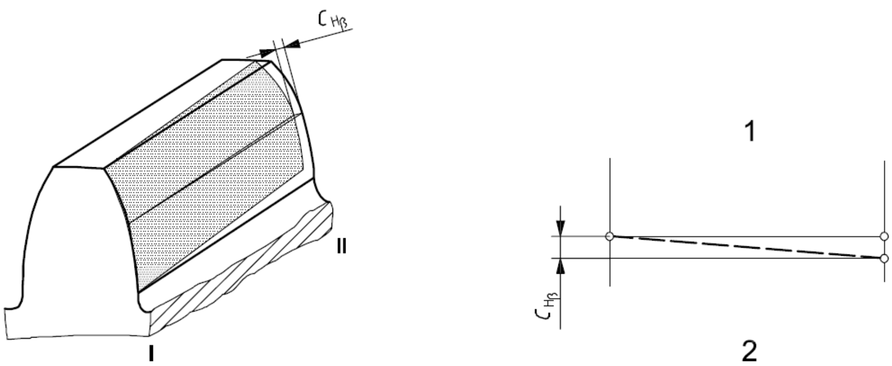


Figure 71 - File Selection pop-up window

3.4 Gear Teeth Analysis

Occasionally, it is necessary to adjust the gears geometry. Tooth flank modifications are implemented to the tooth flank face. The modifications can be implemented in the characteristic profiles of the tooth flank or in relation to the flank face. The studied modification is implemented on the face and is known as *Flank Line Slope Modification* $(fH\beta)$. These modifications and also gear specifications follow the standard ISO 21771:2007 [51]. This modification is a continuously increasing reliefs of the flank extended across the entire face width. Figure 72 illustrates this type of correction in a better way. This correction is done in right and left flank.



Key

$C_{H\beta}$ amount of flank line slope modification

1 space

2 tooth

Figure 72 - Flank line slope modification [51]

3.4.1 Input data

This chapter is based on the measurements done in the tooth of the gears to determine $fH\beta$ and, posteriorly, analyse it. The main goal of this work is to create a script to read inputs, the $fH\beta$ measurements, and illustrate it on plots to compare with the nominal values. This work is divided into two different input gear measurements. The following gear information is related to both case of study and it is part of the main inputs:

- Number of Teeth (z);
- Reference Circle Diameter (d);
- Base Diameter (d_b);
- Lead Measurement Diameter (-);
- Profile Shit (*x*);
- Normal Pressure Angle (α_n);
- Helix Angle (β);
- Transverse Pressure Angle (α_t);
- Transverse Pressure Angle at the Y-cylinder (α_{yt});
- Base Helix Angle (β_b);
- Tooth Thickness Half Angle, reference circle (Ψ)
- Tooth Thickness Half Angle, lead measurement diameter (Ψ_y).

In both cases, the values were given in a gear measurement file. Also, these gear specifications are transcribed to an excel sheet. The entire script will be written in the *Python* language, as decided before.

3.4.2 Script

After import the data and representing $fH\beta$, it displays a cosine/sine amplitude, as shown in Figure 73. This amplitude needs to be removed to demonstrate the corrected values. First of all, it is searched the rotation, which brings the gear microgeometry as close as the gear designed microgeometry, according to the specifications. This correction is based on the Galerkin Method. In this case, the shape functions are the modifications to the $fH\beta\ virtual$ due to an infinitesimal rotation around X- and Y-axis. At the end, the program will determine a $fH\beta\ virtual$ and plot the values.

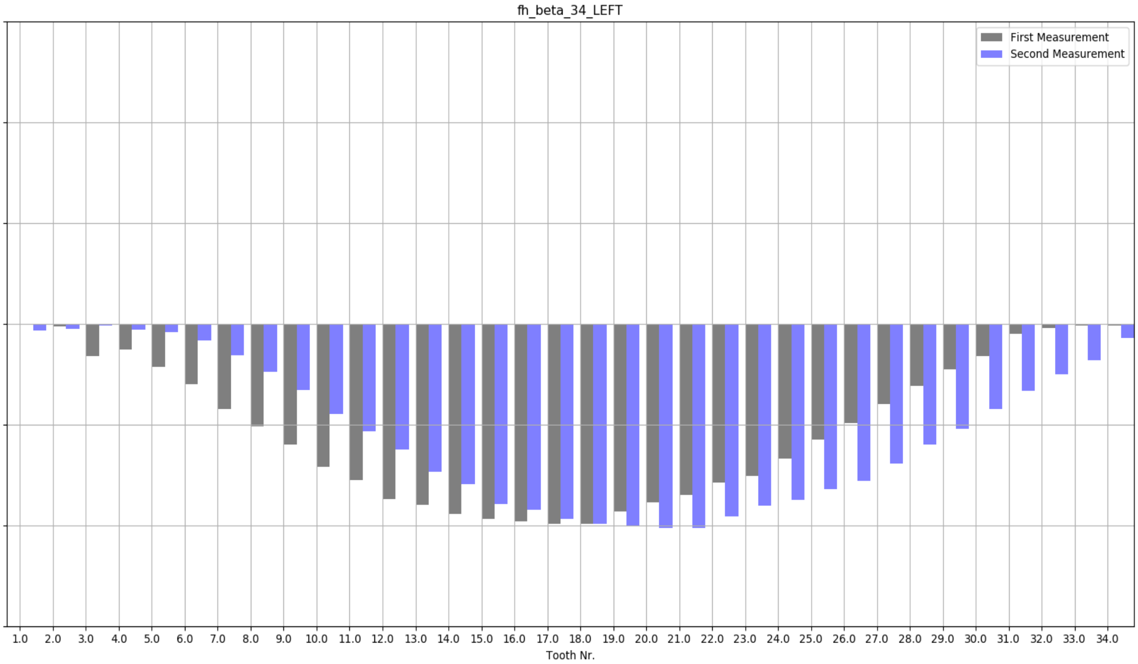


Figure 73 - Example of $fH\beta$ without correction

The first step is to determine the misalignment of gear geometry for both flanks, using the following equation:

$$x/y_{rotation\ left/right} = \frac{\sum fH\beta \cdot f_{x/y}(tooth_{left/right})}{\sum \left(f_{x/y}(tooth_{left/right})\right)^2} \qquad \{3.18\}$$

where the nominator and denominator values are determined with:

$$Angle\ of\ normal\ vector_i(\varphi) = \frac{(\varphi_y - \alpha_{yt}) + (tooth\ nr_i - tooth\ nr_1)}{z \cdot 2 \cdot \pi} \qquad \{3.19\}$$

$$\varphi\ for\ tooth\ nr\ 1 = (\varphi_y - \alpha_{yt}) \qquad \{3.20\}$$

$$f_x(tooth) = cos(\varphi) \qquad \{3.21\}$$

$$f_y(tooth) = sin(\varphi) \qquad \{3.22\}$$

The following step is to determine the misalignment of gear geometry for *X* and *Y* direction, using {3.18} of right and left flank:

$$x/y_{rotation} = \frac{x/y_{rotation\,left}}{2} + \frac{x/y_{rotation\,right}}{2} \qquad \{3.23\}$$

The $fH\beta\ virtual$ is calculated with the values of the previous equation:

$$fH\beta\ virtual_i = fH\beta_i - cos(\varphi) * (x_{rotation}) - sin(\varphi) * (y_{rotation}) \qquad \{3.24\}$$

All previous equations are written in the *Python* language, by this order. The $fH\beta\,virtual$ is calculated for every measured tooth. The nominal value will be compared to the results of this work. This value is determined by the design team and it is specified in gear specifications.

3.4.3 Case Study 1

In the first case study, there are four different measurements, which contains five gears each and only four teeth of each gear will be analysed. It is also measured for right and left flank. To easily identify all this information, the names and numbers of this data are expressed next:

- **Four different measurements**;
- **Gear Numbers**: 32, 34, 48, 54, 102;
- **Tooth Numbers**: 1, 10, 18, 27.

Figure 74 and Figure 75 represent the $fH\beta\ virtual$, for left and right flank of each tooth, expressed in µm. It is only shown the results of the first tooth.

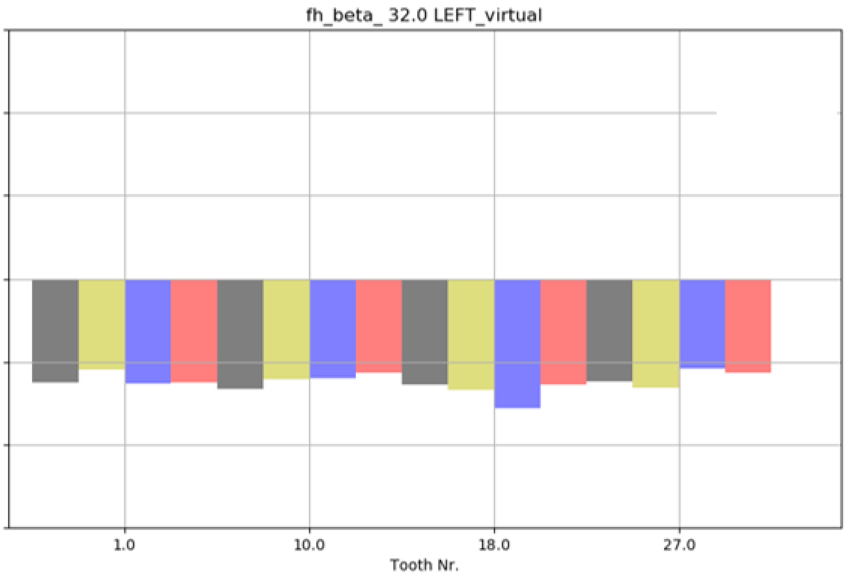


Figure 74 - $fH\beta$ virtual, left flank, tooth nr. 32, case study 1

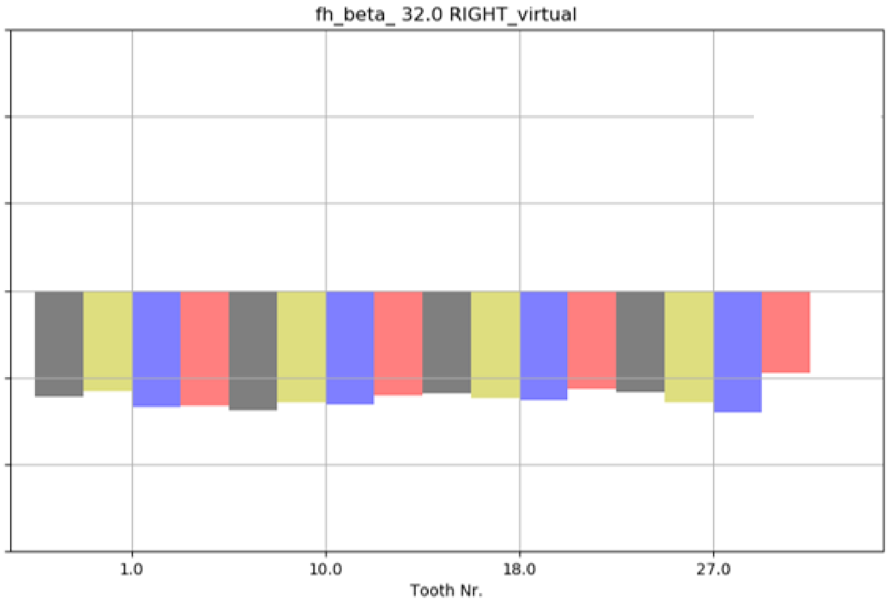


Figure 75 - $fH\beta$ virtual, right flank, tooth nr. 32, case study 1

From these results, it is recognised that the majority of the bars are next to the nominal value (8). These values are totally acceptable.

3.4.4 Case Study 2

The second case study uses the same principle as in the previous case. The gear specifications are equal as in the prior case. Therefore, the other data is the $fH\beta$, which in this case, is obtained from a data file. This file contains two measurements, that were done in all thirty-four teeth of the gear, shown in Figure 76. There are two plots representing $fH\beta\ virtual$ for left and right flank of each tooth. The first and second measurements are illustrated in Figure 77 and Figure 78.

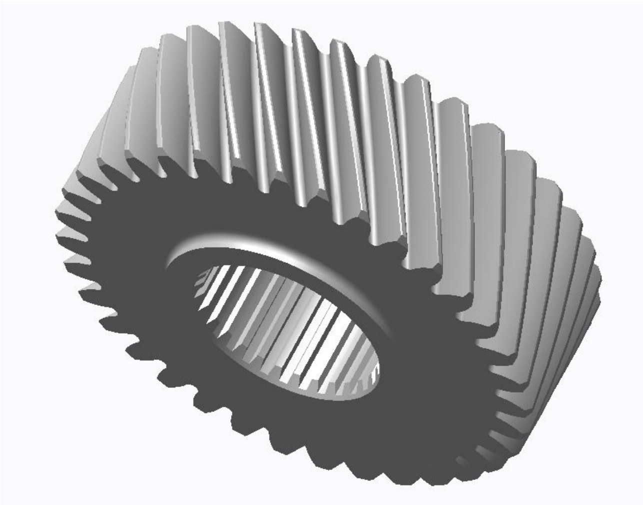


Figure 76 - Gear, Case Study 2

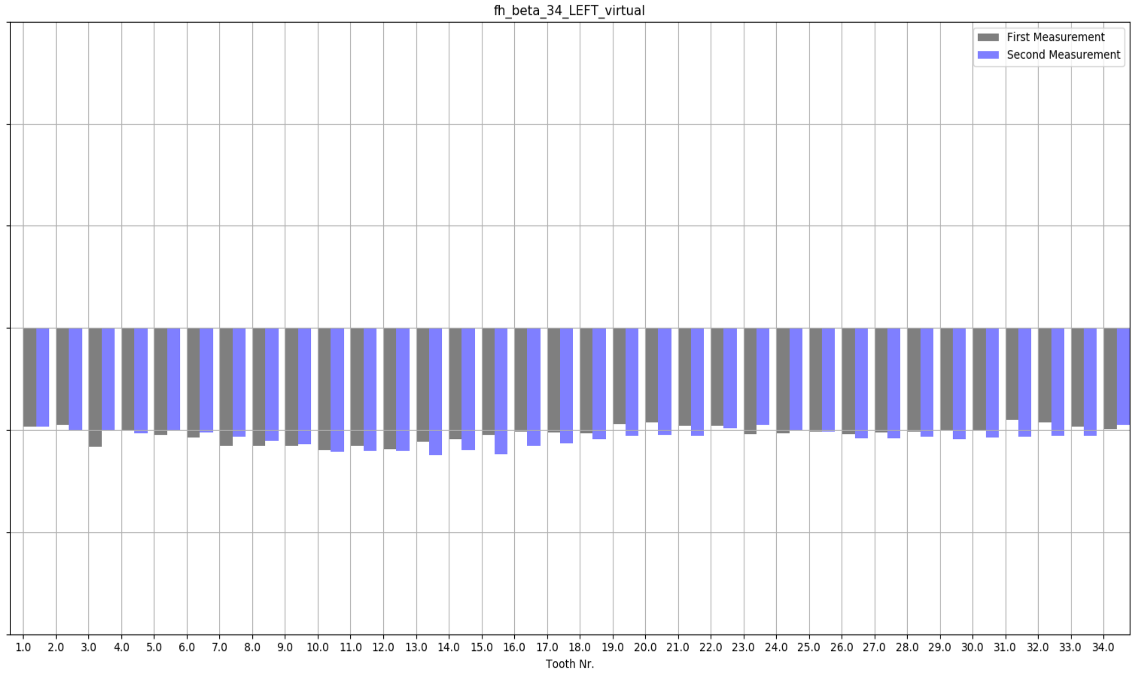


Figure 77 - $fH\beta$ virtual, left flank, case study 2

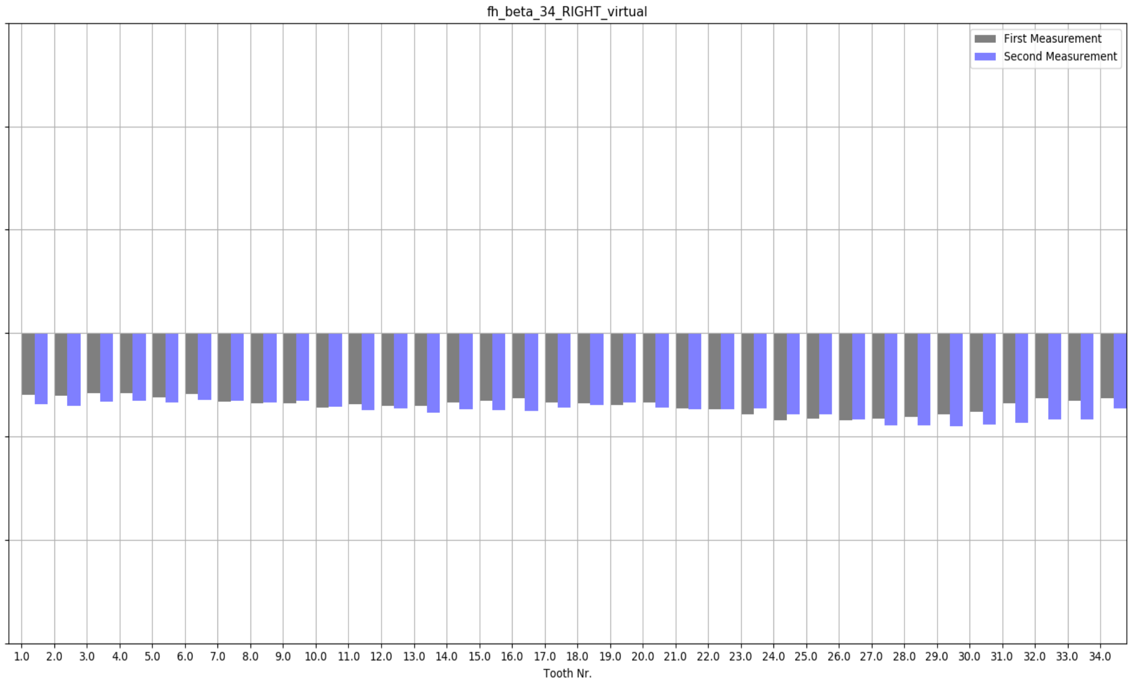


Figure 78 - $fH\beta$ virtual, right flank, case study 2

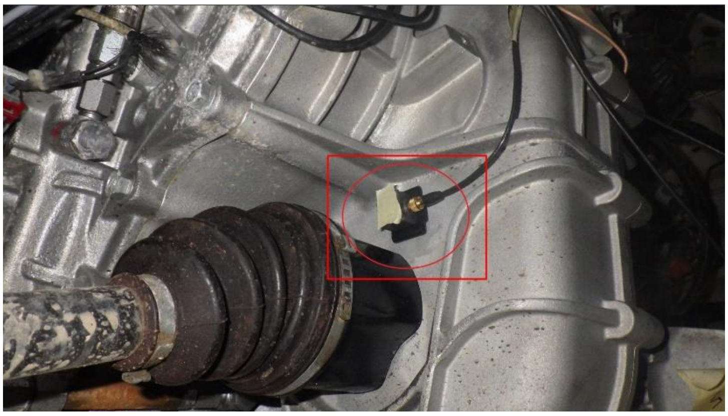
3.5 Road Load Acquisition

3.5.1 Problem proposed

Transmissions are not only simulated. During development, samples of these gearboxes are tested in cars, during road load tests. Before the road test, accelerometers are placed at five different locations of the transmission, which will monitor the loadings in the three axes, *X*, *Y* and *Z*. Those components and locations are shown and identified, with a circle inside a rectangular, in Table 16. The goal of this chapter is to process the data from these accelerometers and predict the number of cycles on these points.

Table 16 - Accelerometers location

Accelerometer	Location	Illustration
1	Top Mount	
2	Casing Front	

3	Driveshaft left	
4	Front Mount	
5	Rear Mount	

These road tests are done in a circuit, that contains a different type of roads. Gearboxes are exposed to twenty-two tests (type of roads). There are four examples of this types of road tests in Figure 79.

Figure 79 - Road tests example

For this chapter, the method to analyse the data was proposed by the company, which is Rainflow Counting. As explained in Literature Review, this technique determines the number of fatigue cycles present in a load-time history. Thus, the purpose of this chapter is to develop a program to read data from the accelerometers measurements files, applying the rainflow counting technique and present the range cycles.

3.5.2 Data files

The road load tests are saved on binary files (*.R32* and *.R64*). The numbers indicate that each value is stored in 32bit or 64bit resolution, respectively. Attached to these files, there are a *.Dat* file, which is the header of the dataset, which contains the information about how to interpret the content of the binaries.

The header file is divided into two types of information. Firstly, there is a description of the data file, the *general header information*. Secondly, there is all the required information to read the individual channels of the data file(s), the *channel header information*. Also, the *channel header* can contain information about several parameters of the individual channels, e.g. minimum value, monotony, units, among others. The structure of the header file of DIAdem is described in Table 17.

Table 17 - Structure of the DIAdem header file

Header file entry	Meaning
DIAEXTENDED {@:ENGLISH	Keyword for DIAdem-data files.
#BEGINGLOBALHEADER *general header entries* *#ENDGLOBALHEADER*	Contains entries regarding the structure of the entire file.

#BEGINCHANNELHEADER *header entries for 1st channel* #ENDCHANNELHEADER #BEGINCHANNELHEADER *header entries for 2nd channel* #ENDCHANNELHEADER • • #BEGINCHANNELHEADER *header entries for nth channel* #ENDCHANNELHEADER	Contains entries for the structure of all the channels which are stored in the data file.

The *general headers* contain general information about the entire data file. In Table 18, there are some possible entries in the *general header*. For this work, the information of the general header is shown in Figure 80.

Table 18 - Possible entries in the *general header*

DIAEXTENDED {@:ENGLISH	Keyword for the type of data set
#BEGINGLOBALHEADER	Keyword for the start of the general header
1, Keyword for the origin of the data set 2, Revision number 101, Description of the data set 102, Comments of the data set 103, Comments on the data set 104, Data 105, Time 106, Description of the comments 110, Time format for time-channels in the case of ASCII-files 111, Value for *NoValues* in the data file 112, Interchange high- and low-bytes 130, Reserve 1 131, Reserve 2 132, Reserve 3 133, Reserve 4	
#ENDGLOBALHEADER	

```
DIAEXTENDED {@:ENGLISH

#BEGINGLOBALHEADER
  1,WINDOWS
  2,@R:200
106,File name:
102,C:\DEWESoft\Data\punch_acc\baan4XL_0000.dxd
106,Number of channels:
102,170
106,Sample rate:
102,5000
106,Store type:
102,always fast
104,28/02/2017
105,14:46:55
110,#dd.mm.yyyy hh:nn:ss
#ENDGLOBALHEADER
```

Figure 80 - *General header* information

The header of a DIAdem file contains also a *channel header*. The number of channel headers depends on the number of channels stored in a data file, which can go up sixty-five thousand channels. It contains information, such as comments on the channel (name, comments, units), other channel characteristics (minimum, monotony), the number of values and the parameters for reading the channels. All these possible entries are shown in Table 19. The first *channel header* presents information about the time and the following blocks contain all signals monitored during the road load test. Figure 81 and Figure 82 show the previous data explanation, respectively.

Table 19 - Possible entries in the *channel header*

#BEGINCHANNELHEADER	Keyword for the start of the first channel header
200,	Channel name
201,	Channel comment
202,	Unit
210,	Channel type
211,	File from which channel data is read
212,	Used internally
213,	Method of storing the data
214,	Data type
215,	Bit masking
220,	No. of values in the channel
221,	Pointer to the first value of the channel
222,	Offset for ASCII block files

Offset for binary block files with header
223, Local ASCII-pointer in the case of ASCII block files
230, Separator character for ASCII block files
231, Decimal character in ASCII files
232, Exponential character in ASCII files
240, Starting value/Offset
241, Step width/Factor
242, Used internally
250, Minimum value in the channel
251, Maximum value of the channel
252, Keyword for *NoValues* in the channel
253, Keyword for monotony
254, Value for *NoValues* in the channel
260, Keyword for the data display at the interference
270, Register variable RV1
... to
275, RV6 for storing the channel-related additional data
280, Register variable Int1
... to
284, Int5 for storing the channel-related additional data in Integer format
300, Reserve 1
301, Reserve 2

#ENDCHANNELHEADER	Keyword for the end of the first channel header

```
#BEGINCHANNELHEADER
200,Time
201,Data1
202,s
210,IMPLICIT
220,123021
240,0
241,0.0002
253,increasing
260,Numeric
#ENDCHANNELHEADER
```

Figure 81 - First channel header

```
#BEGINCHANNELHEADER
200,1 X
201,
202,m/s2
210,EXPLICIT
211,baan4XL_0000_Data1.R32
213,BLOCK
214,REAL32
220,123021
221,1
222,169
253,not calculated
260,Numeric
#ENDCHANNELHEADER
```

Figure 82 - Example of the rest channel header

There are 170 channels blocks on this road load testing, as shown in second entry *102* in Figure 80. However, only the first fifteen channels will be analysed, which corresponds to the three axes (*X, Y* and *Z*) of each five accelerometers. This data is identified by the entry *200*, like for example, shown in Figure 82.

3.5.2.1 Reading Data

This work is divided into two major scripts: one to read the DIAdem files and the second refers to process the data. As explained before, the *headers* file will guide the script to read the binary files. The script is written according to read all lines, that were shown in Figure 80, Figure 81 and Figure 82.

Due to the complexity of reading these binary files with Python language, it was proposed and accepted to use MatLab to read this type of files. However, it was only for reading the data files, organize it in tables and exported to excel sheets. Posteriorly, these excel sheets will be processed with other script and a different language. The MatLab script is divided into two functions, described as follows:

- **Get *headers* and binary files:** Validate the length and the type of data. It will also validate the channel array;
- **Read channels:** Associate channels between *headers* and binary file. It will read the number of the different channels and associate with its category.

In order to recognise the phases of these functions, the following points describe the steps to read the DIAdem files:

1. Choose and open *headers* files;
2. Get channels in the file;
3. Save channels information;
4. Define MatLab data type;
5. Open and read binary files;
6. Show results as a variable '*Ans*'.

The results of this script are represented in variables and each one contains a table of the binary data. These data will be now separate in different excel files. Each file will contain two columns, the time and the signal. As explained above, for each road load, only the five accelerometers signals will be processed. The excel sheet is divided in two columns. Column A represents the time and column B shows the signal.

3.5.2.2 Post-Process Data

It was time to process the excel sheets, using the Rainflow Counting method. In this chapter, the main goal is to process the data. After a deep search about this method and how to write it in *Python* language, it was found a script that matches with our expectations and follows the standard ASTM E1049-85(2005) [52]. The script was analysed and tested to confirm if it could process the excel sheets. It was proposed to the company to use this script, which accepted the solution. The script is divided into different parts, that are easily identified, due to its name. The main parts are described as follows:

- **GUI:** Definition of the graphic interface, containing selectable windows, buttons and a preview window. This GUI is defined below;
- **Reading:** There are two options to read the inputs: with or without the time signal. Thus, there are two sections defined to read one or two columns;
- **Rainflow Counting:** This includes all the process of finding the points, defining the range and count the cycles. This includes the code to process the data and *calculate button*;
- **Export:** There are three options to export data. In the script, the code starts with *'export'*, followed by the variables.

In order to make the script more user-friendly, a program with a GUI was chosen, as shown in Figure 83. The first table is to select between one column or two column input files. It depends on whether the MS Excel ® sheets contain the time. The following selectable tables will not be used. The button 'Read Input File' executes what its name says, which is read the MS Excel ® sheet. It also displays, in a different window, the time history of the signal, as shown in Figure 84.

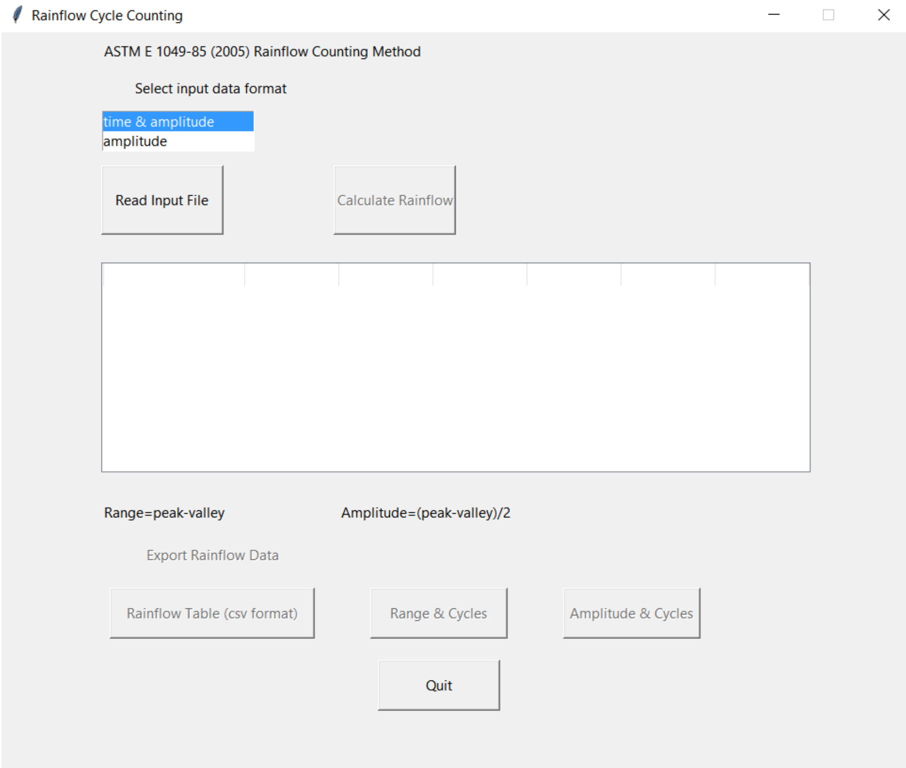


Figure 83 - Rainflow counting script GUI

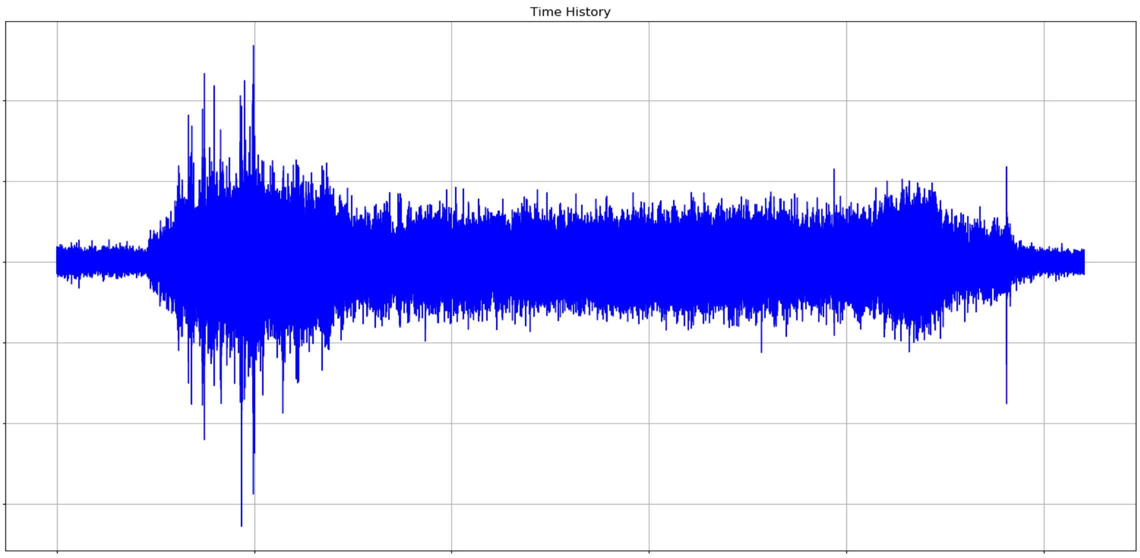


Figure 84 - Example of time history window

The following button, 'Calculate Rainflow', will process the data from the read file. The results will appear on the middle window of the GUI, which will present the Range, Cycle Counts, Average Amplitude, Maximum Amplitude, Average Mean, Minimum, Valley and Maximum Peak. At the bottom of the GUI, it shows three buttons, that can export the tables with the previous Rainflow Counting table, the Range & Cycle or Amplitude & Cycles.

During the process, some information is displayed in the console of the program, such as the number of samples in the signal, the per cent of progression during the Rainflow Counting, the total number of cycles and the maximum range. After exporting again for excel sheet, data is ready to organize and analyse. The following chapter shows the results of the twenty-two road load tests.

3.5.3 Rainflow Counting Results

In this section, it is only presented the results of the post-processed data of the accelerometer one of the first road load test, as shown in Table 20. The twenty-two road load tests will be divided into different headings and named by its designation.

Table 20 - Accelerometer One, Washboard (4X-3K)

Accelerometer 1					
X		Y		Z	
Range (units)	Cycle Count	Range (units)	Cycle Count	Range (units)	Cycle Count
100.00 to 241.70	14	100.00 to 408.49	473.5	100.00 to 509.25	1242.5
90.00 to 100.00	9	90.00 to 100.00	275	90.00 to 100.00	507.5
80.00 to 90.00	19	80.00 to 90.00	416.5	80.00 to 90.00	751.5
70.00 to 80.00	40.5	70.00 to 80.00	690.5	70.00 to 80.00	1009.5
60.00 to 70.00	105.5	60.00 to 70.00	1007	60.00 to 70.00	1488
50.00 to 60.00	237.5	50.00 to 60.00	1672	50.00 to 60.00	2128
40.00 to 50.00	614.5	40.00 to 50.00	2609.5	40.00 to 50.00	2899.5
30.00 to 40.00	1650.5	30.00 to 40.00	4030	30.00 to 40.00	3934.5
20.00 to 30.00	4449.5	20.00 to 30.00	5586.5	20.00 to 30.00	4594.5
15.00 to 20.00	4353	15.00 to 20.00	3205	15.00 to 20.00	2453
10.00 to 15.00	5973	10.00 to 15.00	3281.5	10.00 to 15.00	2874.5
5.00 to 10.00	7860.5	5.00 to 10.00	4365	5.00 to 10.00	3299
0.00 to 5.00	14394	0.00 to 5.00	4633	0.00 to 5.00	2454
Total Cycles	39720.5	Total Cycles	32245	Total Cycles	29636

CONCLUSIONS

4 CONCLUSIONS AND PROPOSALS OF FUTURE WORKS

4.1 Project Gains

In respect to the projects and based on the main goals introduced in the first chapter, this section synthetize those goals, the results and the respective status for the three projects, which are shown in Table 21, Table 22 and Table 23.

Table 21 - Conclusions of the goals and respective results for the improvement of the Hydraulic Block Analysis

Main Goal	Result/Solution/Gain	Status
Analyse the situation of the evolved parts and understand the operation and functionality of each component.	Definition of the case studies and collect all information about the design, assembly, simulation and operation of the projects that were defined.	✓
Study and propose several options to post-process the data, respecting the conditions imposed.	Determine and approval of the two different approaches, related only to the geometrical analysis.	✓
Analyse and present the results of the Case Study 1 for two load cases, using the first method of analysis.	From the illustrations, there were possible to determine the colormap of the distances between the two parts and identify the critical zones, located in the bottom. Similar results for the two load cases.	✓
Analyse and present the results of the Case Study 1 for two load cases, using the second method of analysis.	Determine the scale factor of the displacements in the wall.	✓
Analyse and present the results of the Case Study 2 for two load cases, using the first method of analysis.	Representation of the distance, according to the tolerances of the parts. Identification of critical zones, which are located in the bottom.	✓
Analyse and present the results of the Case Study 2 for two load cases, using the second method of analysis.	Determine the scale factor of the displacements in the wall.	✓
Validation of the post-process results of the Case Study 1.	Comparation of the results with real tested blocks.	✓
Validation of the post-process results of the Case Study 2.	Comparation of the results with real tested blocks.	✓

Implement a user-friendly graphic interface.	Implementation of a graphic user interface, with several options to show the results of the post-process. Define instructions to use this GUI.	✓

Table 22 - Conclusions of the goals and respective results for the improvement of the Gear Analysis

Main Goal	Result/Solution/Gain	Status
Identification the gears and understand the gear measurements files.	Implementation of the method to process the measurement values. Represent the results with bar plots.	✓
Validation of the results for both case studies.	The results were validated by the gear experts. It could also be compared to the nominal value, expressed in gear specifications.	✓

Table 23 - Conclusions of the goals and respective results for the improvement of the Road Load Testing

Main Goal	Result/Solution/Gain	Status
Identification of the problem and investigate the road load tests specifications.	Identification of the specifications, the circuit of the tests and the software used to record the data. Understanding the different type of roads.	✓
Read the road tests files.	Create a reading program (external to the recording software). Export this data and show it in two columns, the time and signal.	✓
Process all data.	Create a post-process program to analyse the previous files. Prediction of the cycle counts, using Rainflow Method. Present the results in tables.	✓
Validation of the results.	Tables with result of each accelerometer of the road tests were validated by the experts.	✓

4.2 Company Gains

Regarding the company gains, the following topics illustrate the contributions of the developed work:

- Study of the different hydraulic block, checking the interferences and predicting the operation of the components, using two different approaches;
- Usage of a user-friendly interface for the programs, so it could be used by everyone, with minor explanations;
- Interpretation and processing of the gear measurements files, showing the results in an easy view;
- Studying several road load tests, in order to determine the fatigue cycles, of each accelerometer, mounted in the transmission.

4.3 Personal Skills

Not only the company had its improvements. There were some personal gaining's developed during the internship, which are explicit as follows:

- Insight in structural FEA;
- Post-processing scripting in Python and MatLab for structural FEA;
- Gear geometry (macro- and microgeometry);
- Geometric measurements techniques;
- Fatigue of Materials;
- Data Analysis for fatigue;
- Insight in CAE techniques and accelerated testing for fatigue;
- Reporting skills;
- Presentation skills;
- Communication skills.

In the end, the internship at Punch Powertrain allowed understanding the automotive industry, regarding the R&D and production departments. It was also important to complement the knowledge acquired during the master's lessons.

4.4 Proposals for future works

Regarding the developed work, there are different necessities and improvements, that can be studied in future works, summarized as follows:

- Improve the analysis, considering more variables (pressures and/or materials) related to the operation of the components;
- Analyse the interferences between the cylinder and the walls of the complete hydraulic block.

REFERENCES AND OTHER SOURCES OF INFORMATION

5 REFERENCES AND OTHER SOURCES OF INFORMATION

[1] D. R. Houser. (2006, 08/10/2018). *Gear Mesh Misalignment*. Available: http://gearsolutions.com/features/gear-mesh-misalignment/

[2] H. Naunheimer *et al.*, *Automotive Transmissions: Fundamentals, Selection, Design and Application*, Second Edition. Springer, Germany, 2010. ISBN: 9783642162138.

[3] W. Callister and D. G. Rethwisch, *Materials science and engineering: An introduction. Materials & Design*, Ninth. Wiley, United States of America, 2013. ISBN: 9781118324578.

[4] D. A. Crolla and B. Mashadi, *Automotive Engineering: Powertrain, Chassis System and Vehicle Body*, First Edition. Elsevier, United Kingdom, 2009. ISBN: 9871856175777.

[5] K. Dutton. (2006, 06/04/2018). *A Brief History of the Car (First ed.)*. Available: http://byronwine.com/files/History%20of%20the%20car.pdf

[6] ACEA. (2017, 08/04/2018). *The Automobile Industry Pocket Guide*. Available: https://www.acea.be/publications/article/acea-pocket-guide

[7] CEBOS. (17/04/2018). *The Biggest Milestones in the History of Automotive Manufacturing*. Available: https://www.cebos.com/blog/milestones-automotive-manufacturing/

[8] C. Clarke, *Automotive Production Systems and Standardisation: From Ford to the case of Mercedes-Benz*. Physica-Verlag, Germany, 2005. ISBN: 3790815780.

[9] INTELLI, *Diagnóstico da Indústria Automóvel em Portugal*, Portugal, 2005.

[10] B. P. Bhardwaj, *The Complete Book on Production of Automobile Components & Allied Products*. NPCS, India, 2014. ISBN: 9789381039335.

[11] Y. Karmokolias, *Automotive Industry Trends and Prospects for Investment in Developing Countries*. International Finance Corporation, United States of America, 1990. ISBN: 0821315927.

[12] J. Brown and C. Rhodes, "The Motor Industry: Statistics and Policy," United Kingdom. 2012.

[13] H. Bezic and T. Galovic, "Trade Performance in the Automotive Industry of the Europe OECD member countries," in *DIEM : Dubrovnik International Economic Meeting*, Croatia, 2015.

[14] T. Ward and P. Loire, "Employment, Skills and Occupational trends in the automotive industry " 2008.

[15] E. Commision. (2017, 06/04/2018). *Automotive industry*. Available: https://ec.europa.eu/growth/sectors/automotive_en

[16] OICA. (2017, 10/04/2018). *OICA - Economic Impact*. Available: http://www.oica.net/category/economic-contributions/

[17] Scotiabank. (2018, 11/04/2018). *Global Auto Report*. Available: http://www.oica.net/category/economic-contributions/

[18] F. Veloso *et al.*, "Can small firms leverage global competition? Evidence from the Portuguese and Brazilian automotive suppliers industries," presented at the 4th International Conference on Technology Policy and Innovation, Curitiba, Brazil, 2000.

[19] P. Nieuwenhuis and P. Wells, *The Global Automotive Industry*. Wiley, United Kingdom, 2015. ISBN: 9781118802397.

[20] B. Klippel, "A Design Methodology for Automotive Component Manufacturing Systems," Massachusetts Institute of Technology, United States of America, 1998.

[21] M. A. Omar, *The Automotive Body Manufacturing Systems and Processes*. Wiley, United Kingdom, 2011. ISBN: 9780470976333.

[22] V. A. W. Hillier, *Hillier's Fundamentals of Motor Vehicle Technology*, 6th Edition. Nelson Thornes, Spain, 2012. ISBN: 9781408515181.

[23] DIN 3990-1:1987-12, *Calculation of load capacity of cylindrical gears; introduction and general influence factors*, 1987.

[24] H. W. Müller, *Epicyclic Drive Trains*. Springer, Germany, 1971. ISBN: 0814316638.

[25] Y.-L. Lee *et al.*, *Fatigue Testing and Analysis: Theory and Practise*. Elsevier, United States of America, 2005. ISBN: 0750677198.

[26] W. Weibull, *Fatigue Testing and Analysis of Results*. Pergamon Press, Belfast, 1961. ISBN: 9780080093970.

[27] J. A. Bannantine *et al.*, *Fundamentals of Metal Fatigue Analysis*, First Edition. Prentice Hill, New Jersey, 1989. ISBN: 9780133401912.

[28] R. C. Rice, *SAE Fatigue Design Handbook*. Society of Automotive Engineers, United States of America, 1997. ISBN: 9781560919179.

[29] N. E. Dowling, *Mechanical Behavior of Materials: Engineering Methods for Deformation, Fracture and Fatigue*, Second Edition. Prentice Hall, New York, 1998. ISBN: 9780131395060.

[30] P. Childs, *Mechanical Design*, Second Edition. Butterworth Heinemann, United Kingdom, 2004. ISBN: 0750657715.

[31] D. G. Ullman, *The Mechanical Design Process*, Fourth Edition. McGraw-Hill United States of America, 2010. ISBN: 9780072975741.

[32] R. G. Budynas and J. K. Nisbett, *Shigley's Mechanical Engineering Design*, Ninth edition. McGraw-Hill, New York, 2011. ISBN: 9780073529288.

[33] A. Golenko, *Fundamentals of Machine Design*. Wroclaw University of Technology, Poland, 2010.

[34] A. Krulikowski, *Fundamentals of Geometric Dimensioning and Tolerancing*, Second Edition. Delmar Publishers, United States of America, 1998. ISBN: 0827379951.

[35] G. Henzold, *Geometrical Dimensioning and Tolerancing for Design, Manufacturing and Inspection*, Second Edition. Elsevier, United Kingdom, 2006. ISBN: 9730750667388.

[36] ISO 2768:1973, *Permissible machining variations in dimensions without tolerance indication*, 1973.

[37] J. E. Shigley and C. R. Mischke, *Standard Handbook of Machine Design*, Second Edition. Mcgraw-Hill, United States of America, 1996. ISBN: 0070569584.

[38] M. Rappaz *et al.*, *Numerical Modeling in Material Science and Engineering*. Springer, Switzerland, 2010. ISBN: 9783540426769.

[39] M. Enelund *et al.*, "Integration of a computational mathematics education in the mechanical engineering curriculum," in *7th International CDIO Conference*, Technical University of Denmark, 2011, p. 17.

[40] A. C. Ugural, *Mechanical Design, An Integrated Approach*. McGraw-Hill, United States of America, 2004. ISBN: 007242155X.

[41] M. Goelke, *Practical Aspects of Finite Element Simulation*, 3rd Edition. University Altair, United States of America, 2015.

[42] L. Critchley. (2017, 27/05/2018). *Computer Simulations in Engineering*. Available: http://www.statisticsviews.com/details/feature/10482673/Computer-Simulations-in-Engineering.html

[43] E. Winsberg. (2013, 15/05/2018). *Computer Simulations in Science*. Available: https://plato.stanford.edu/entries/simulations-science/

[44] S. S. Bhavikatti, *Finite Element Analysis*. New Age International, New Dehli, 2005. ISBN: 9788122425246.

[45] D. V. Hutton, *Fundamentals of Finite Element Analysis*. Mcgraw Hill, United States of America, 2004. ISBN: 0072395362.

[46] C. Rusu. (2015, 28/10/2018). *Why do FEA engineers use 1D, 2D, 3D elements ?* Available: http://feaforall.com/why-do-fea-engineers-use-1d-2d-3d-elements/

[47] A. Kaveh, *Computational Structural Analysis and Finite Element Methods*. Springer, Switzerland, 2014. ISBN: 9783319029634.

[48] S. S. Rao, *The Finite Element Method in Engineering*, 4th Edition. Elsevier, United States of America, 2004. ISBN: 0750678283.

[49] K.-J. Bathe, *Finite Element Procedures*, Second Edition. Prentice Hall, United States of America, 2014. ISBN: 9780979004957.

[50] H. K. Versteeg and W. Malalasekera, *An Introduction to Computational Fluid Dynamics*, Second Edition. Pearson Education, United Kingdom, 2007. ISBN: 9780131274983.

[51] ISO 21771:2007, *Gears - Cylindrical involute gears and gear pairs - Concept and geometry*, 2007.

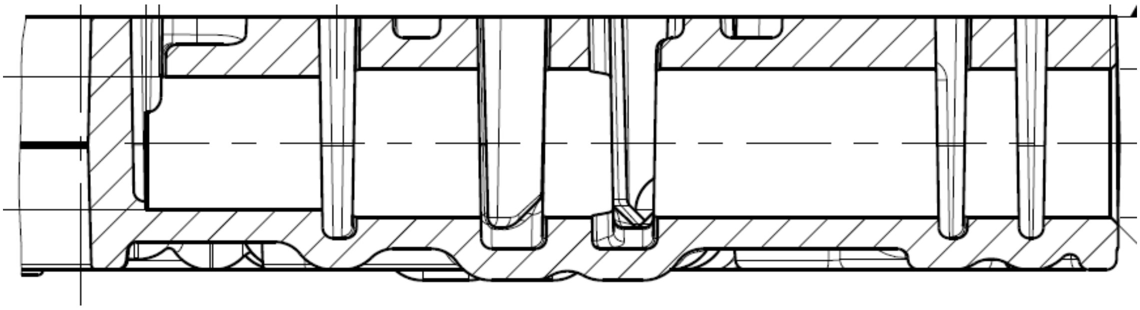
[52] ASTM E1049-E(2005), *Standard Practices for Cycle Counting in Fatigue Analysis*, 2005.

ANNEXES

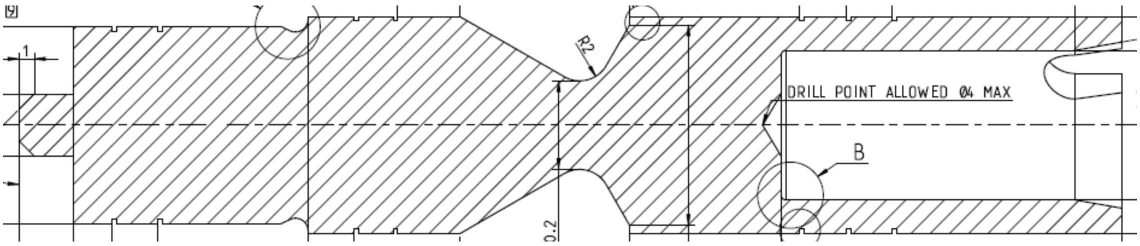
6 ANNEXES

6.1 Hydraulic Block – Drawing for Case Study 1

Manifold, Line:

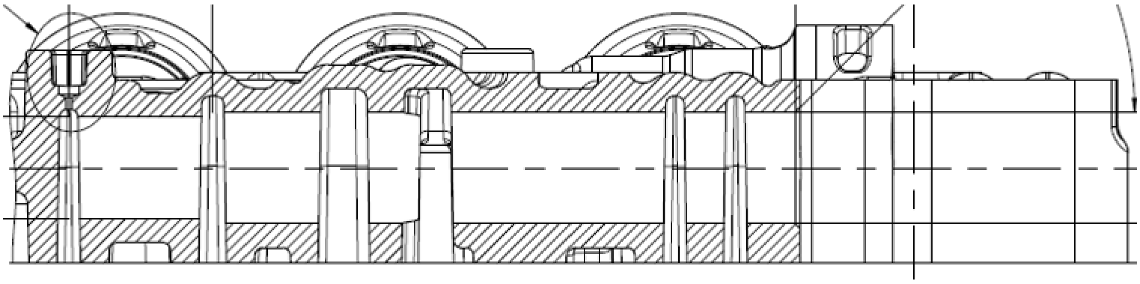


Valve:



6.2 Hydraulic Block – Drawing for Case Study 2

Solenoid Body, Line:



Valve: