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MEASURE OF RADIAL FORCE IN A PNEUMATIC ROD SEALS AND CONTACT PRESSURE CALCULATION

by

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A mi Madre por siempre cuidarme y apoyarme en mis decisiones,
a mi Padre por hacer crecer mi pasión por la Ingeníeria Mecánica,
a mi Hermana por ser parte inolvidable de mi vida
al amor de mi vida, porque has creido y crees en mi,
ves lo que muchos no,TE AMO Valdrianiluz,
gracias por haberme dado otra perspectiva de la vida,
a mis amigos con ustedes he compartido gran parte de mi vida,
gracias a todos por buenos recuerdos, porque recordar es vivir.

*"Fantasy and creativity are important qualities
for the computer simulator!"
Furio Ercolessi.*

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About the software

Software availability

Any reader or programmer interested in downloading the software described in this thesis, for personal and non commercial use, mainly needs a computer, Internet connection, a text editor. The program used for this thesis were SolidWorks, MatLab, Excel, DCS-100 and Latex.

Disclaimer

All the software given in this thesis are provided for educational purposes. The programs are supplied "as are" and, hopefully not but, "with all their faults". The author makes no representations or warranties of any kind concerning the safety, suitability, lack of viruses, inaccuracies, typographical errors, or other harmful components that could be in the software. There are inherent dangers in the use of any software, and you as user are solely responsible for determining whether these programs are compatible with your equipment and other software installed on your equipment. You are also solely responsible for the protection of your equipment and backup of your data, and the author will not be liable for any damages you may suffer in connection with using, modifying, or distributing these programs.

Abstract

Nowadays, the tribology studies, are important in a mechanical field because gives an explanation of how bodies interact themselves when are in contact with lubrication. The tribology system developed in this thesis expose what is happening in the seal while is in contact with the rod surface and with the lubricant that might be between them, obtaining their frictional behaviour. In general, a reciprocating seals have two requirements that should be guarantee:

1. the friction should be constant and as low as possible.
2. and they must maintain tightness during their cycle life.

Therefore a measurement of the radial force exerted in the seal is needed. In the mechanical laboratory at the Politecnico di Torino there is a special test bench that allows to calculate that force in an indirectly way through a radial force meter. The contact pressure is calculated by the following formula $p(z) = \dfrac{dF}{d \cdot dt \cdot V}$, "V" is the seal speed and "d" is the rod diameter. The last Test Bench was modified according to guarantee, as constant as possible, feeding pressure in the seal, the pneumatic bearing was removed and replaced by a piece called "sleeve guide" which has two sliding bearing that don't require lubrication, avoid the air leakages but increase the friction in the system. However the system operate quieter and occupy less radial space. A small perforation was done in the seal holder to allow pressurized air supply through a Micro rapid fitting to pressurize the seal. The tests were started, obtaining the test data to calculate the smooth signal by to semi-automatic post-processing methodology through Matlab and Simulink, which were compare with two methods "Spline" and "Polynomial Fit".

After this, a contact pressure was calculated from the smooth signal and shown them, presenting a certain tends and some problems.

Chapter 1

Introduction

This chapter intends to point the place in the Engineering where this thesis occurs and tries to excite curiosity in the reader providing a review of some significant studies about the tribology, pointing out the trigger for actual studies. Then a brief explanation of what a tribology does is specified, and finally, how it applied this about the seals and why.

1.1 Tribolgy

The science that is responsible for the study of friction, lubrication, and wear of interacting surfaces, generally is done in motion.

1.1.1 Seals

All reciprocating seal has two requirements: its friction should be constant and as low as possible and maintain tightness during their service life.

Then in order to maintain this conflict parameter under control, it is had to know what happens in the sealing contact. how it interacts the seal with its metallic counterpart? and how the lubrication influence the friction onto the seal contact?

The radial force is directly proportional to the contact pressure then it is necessary to detect this force. Therefore, a radial force meter is required.

1.2 Radial force meter

In the mechanical laboratory at the Polytechnic of Turin there is a radial force meter test bench, that was characterized by the low friction guide or air bearing that guarantee as low friction as possible. There are some test done with this test bench and the results are presents in the laboratory.

But there are some problems related to this test bench. Then some modifications are necessary to achieve certain parameters. This thesis is aimed to evaluate the radial force in an experimental way without interposing any intrusive measuring device. In fact is obtained by commercial load cells which are detect the small disturbances made by the seal to the special rod, obtaining signal that represent the seal.

This signal is filtered and properly fitted obtaining a smooth function, after this, is calculated the pressure contact by time derivative and the rod diameter and seal's speed.

1.2.1 Problematic

In this work it will be studied the the problematic present in the test bench and it is the incapacity to maintain a certain pressure in the Seal-holder and how it avoids the air leak in the system?, why it is important to guarantee this parameter in the seal holder? and how will be the contact pressure in comparison by the results that it is had in this moment in the laboratory? will there be some different?.

Chapter 2

Theoretical background

In this chapter will be reviewed what is the tribology, its importance, the Friction ,then an overview of how the friction is applied in engineer studies and how is possible to measure these forces with certain types of tests benches, the test bench that is present in the Mechanical laboratory at Polytechnic of Turin. Also, in this section it will be present the seal that were used, the type, the brand and its data sheet.

2.1 Tribology

The Tribology is the part of the science that is responsible for the study of wear, friction and lubrication , and how interacting surfaces and other tribo-elements in relative motion in natural and artificial system. The term is based on the Greek word for rubbing, although the term itself was not coined until 1964.

The tribology has collaborative efforts of researches from fields including mechanical engineering, manufacturing, materials science, chemistry, physics, mathematics, computer sciences, etc. To summarize it is not an isolated science.

The most important pillar of tribology is the system analytical and system related thinking.

Friction and wear are not material properties. These are responses to a specific tribological system which typically includes a bearing, seal, shaft and lubrication combination and as such are influenced by a wide range of factors.

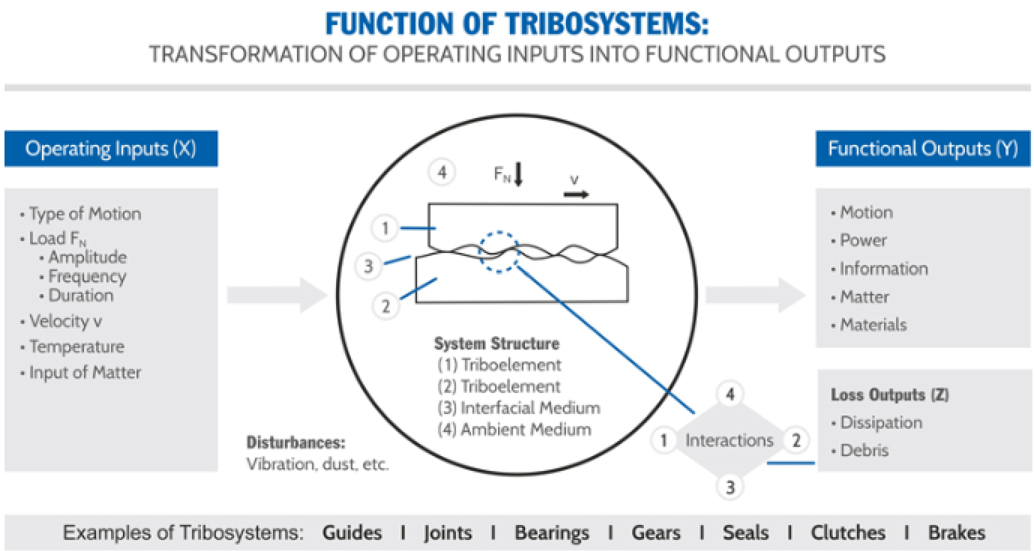


Figure 2.1: Tribology System. Taken from:[?]

The different factors that can change the combination of the system could be summarized in two sections, as:

STRUCTURE

Ground Body And Counter Body (which are the tribo-Elements)

1. Material Property:
    - Hardness.
    - Deformation Behaviour.
    - Adhesion Tendency.
    - Structure of the Material.
2. Geometrical Properties:
    - Topography.
    - Contact Ratio.
    - Shape.
    - Geometrical Dimensions.

Interfacial Medium

1. Agregate State Liquid and Gaseous:
    - Type (Lubricant, Gases, Grease).
    - Content.
    - Humidity.
    - Viscosity.
    - Compatibility.
    - Burning Point.
2. Aggregate State Solid:
    - Type (Abrassive, Particles, Solid Lubricant.)
    - Composition.
    - structure.
    - Deformation Behaviour.
    - Hardness.
    - Dispersion.

Ambient Medium

1. Agregate State Liquid and Gaseous:
    - Type (Lubricant, Gases, Grease).
    - Content.
    - Humidity.
    - Viscosity.
    - Compatibility.
    - Burning Point.

COLLECTIVE STRESS:

1. Load:
   - Type:
     - Static.
     - Dynamic.
   - Load Value:
     - High.
     - Low.
   - Time Dependency:
     - Constant.
     - Periodical.
     - Intermittent.
     - Pulsating Loads.
     - Impulsive.
2. Type of Motion:
   - Type
     - Sliding.
     - Rolling.
     - Impact.
     - Rolling with Slippage.
   - Load Value:
     - High.
     - Low.
   - Time Dependency:
     - Continuos.
     - Oscillating.
     - Reciprocating.
     - Periodical.
     - Intermittent.
3. Temperature:
   - Type
     - Ambient Temperature.
     - Friction Induced Temperature.
     - External Heating.
     - External Cooling.
     - Temperature Gradients
   - Time Dependency:
     - Constant.
     - Periodical.
     - Irregular
     - Intermittent

To conclude the tribological system as is enumerated, the System Structure is determined by the property of the substantial elements including the base, opposing body and ambient. And the Collective Stress includes the technical and physical load parameters including Load, sliding speed and duration along the movement and temperature conditions stressing the system.

2.2 Friction, Wear and Lubrication

In this section it will be defined concepts that are important to understand the interaction between two surfaces:

2.2.1 Friction

Simply is the force of resistance to motion between two bodies, it could be one in movement or both are in movements. The magnitude of this resistance is function of the materials, geometries and surface features of the both bodies, the operating conditions and environment. Generally speaking, friction increases with load and surface roughness and is possible to minimize using lubricant.

Macroscopic level it could be used the basic laws of friction from Physicist Charles-Augustin de Coulomb. This relationship is linear and directly proportional to the normal force and are related throughout coefficient friction.

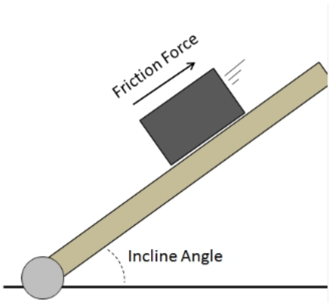


Figure 2.2: "Macroscopic Friction. Taken from: [?]

On the other hand, the real frictions occurs at a microscopic level, which means tribological theories on friction also involve the topography. The mechanisms responsible for the energy transforming process in the near surface area include (as shown):

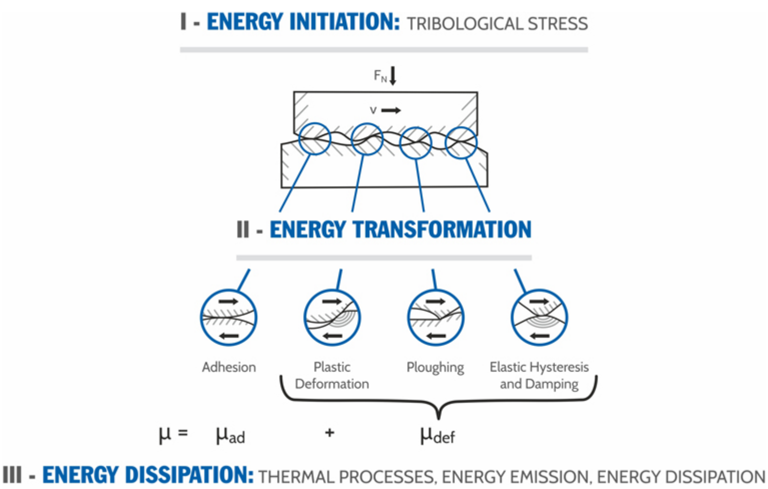


Figure 2.3: "Microscopic Friction.And the process of the energy transforming.Taken from: [?]"

2.2.2 Wear

Wear is the material loss generally due to sliding among two surface. It is defined as wear mechanisms to all the Physical and chemical processes in which there are change in material and shape in the friction partners due to the contact area of a sliding pair.

These wear mechanics include:

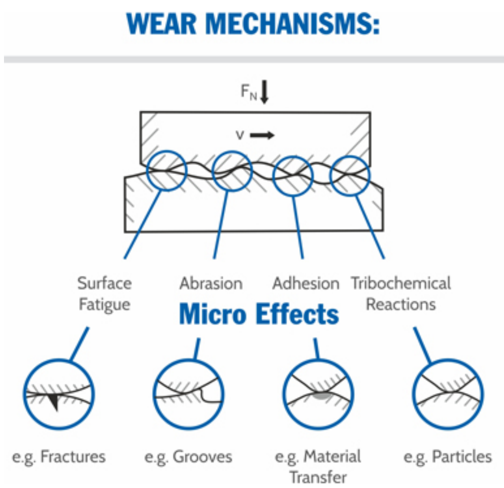


Figure 2.4: Wear Mechanisms.Taken from: [?]

2.2.3 Lubricants and Lubrication

Mainly used to minimize friction and the wear separating two sliding surfaces. they are often liquids (oil and added chemicals, best known as additive). However, there are come applications where lubricants can be gases, greases, or even solids.

Tribologists classify friction according to the following:

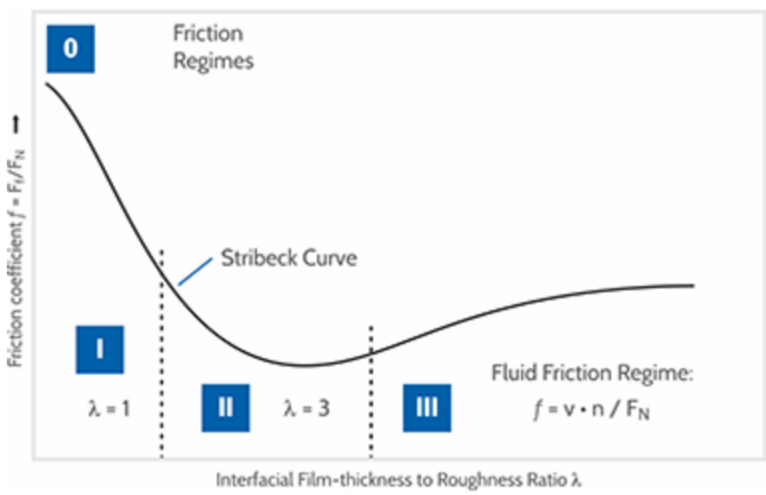


Figure 2.5: Wear Mechanisms.Taken from: [?]

- Zone 0: there is not lubrication, and the surfaces are in direct contact, known as Solid friction.
- Zone I: the surfaces are covered with a molecular lubricant film that has no load carrying capacity, but also in this case there is a Solid Friction.

- Zone II: is the combination of the solid and hydrodynamic friction. Is known as Mixed Friction.
- Zone III: This zone is called as hydrodynamic friction, and is due to the fluid between the surfaces does not permit the contact between them, reducing losses.

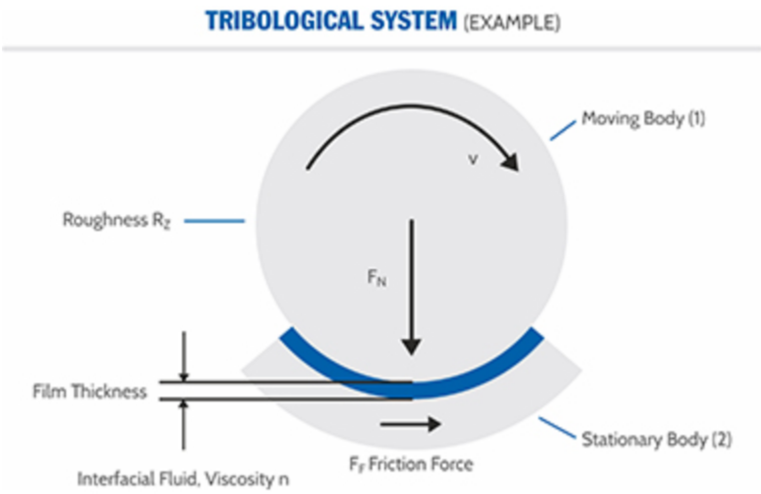


Figure 2.6: Trybology System Example with hydrodynamic friction.Taken from [www.ggbearings.com]

2.3 Tribology system: Seal

The trybosystem that it will be studied in this thesis is the seal.

The seal is a component that control the interchange of fluid between two regions sharing a common boundary, preventing the leakage and consequently the contamination of the environment in where it is working.

2.3.1 Seal Classification

Seals are subdivided into two great categories statics and dynamics.

- Static: Provide sealing between surfaces which do not move relative to each other.
- Dynamic: Provide sealing, but can be subdivided into rotatory and reciprocating seals.

The studies that will be developed in this thesis is dedicated to the Dynamics seals, but specifically reciprocating.

2.3.2 Reciprocating Seals

Provide sealing in relative reciprocating motion along the shaft axis. Between the inner and outer element. They are subdivided into **Rod Seals**, **Piston seals** and **Wiper**, as shown in the imagine:

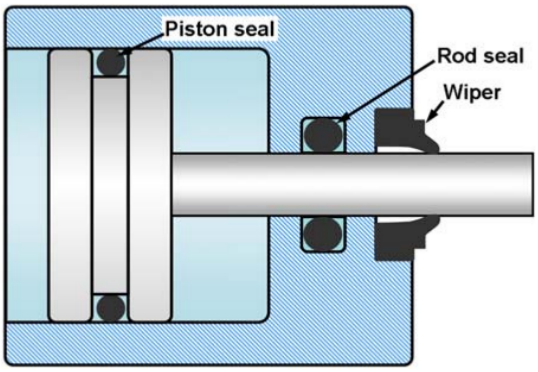


Figure 2.7: Reciprocating Seal example

The friction present in this type Seals is very high at the start of its operation and depends on the preceding down-time. If it sees the image when the seal slides goes from the dry side to oil-side the film thickness is much higher and the friction is lower on the other hand when the actuator is moving inward (in-stroke), from the oil-side to the dry-side the film thickness is very thin in conclusion the friction is high.

In all reciprocating seals is necessary to fulfil two requirements:

1. their friction should be constant and as low as possible.
2. they must maintain tightness during their lifetime.

Then if it wants to optimise these conflicting properties, it is necessary to know what happens in the sealing contact. The interaction of the seal surface, rod surface and the lubricant determines the frictional and its functional behaviour. In pneumatic applications greased contact prevail.

2.3.3 Elastomeric Seal Materials

Elastomer are a class of polymeric material with a high elasticity adapting to the shape according to the case and the pressure against it. A polymer is a comprising of repeating structural units, or monomers, connect by covalent chemical bonds. The elastomer present a phenomenon depending of the time and the strain, and its name is viscoelasticity. When is in undergoing deformation. These types of materials resist against shear flow and strain linearly with the time, when a stress is applied and return to their original state once the stress is removed.

The advantages of elastomer as sea material:

- Low elasticity modulus, then they are extremely deformable without giving high contact stresses.
- They are resilient and thus can resist the vibration and irregularities of the sealed surface.
- They are cheaper.
- Ther are easily stretched to fit into housing and piston groves.
- They present a Poisson's ratio close to 0.5, hence the material behaves is more similar to a liquid under pressure, transferring any applied pressure hydrostatically, creating its own sealing force automatically in proportion to the pressure.

The disadvantages of the elastomeric seals:

- The behaviour of the seal are not always predictable.
- The chemical and temperature resistance is poor compared with other engineering materials.

Chapter 3

Measurement of Radial Force

There are some ways that allow to take over the radial force, which can be expressed:

- Direct measurement through numerical analysis of finite elements.
- Indirect measurement through the examination of radial force.

It will be develop the second methodology in order to obtain the radial force. It is proceed to explain a radial force meter. But firstly it necessary to define the seal that will be study in this thesis. It has been taken Freudenberg Seals, as shown in the figure:
??).

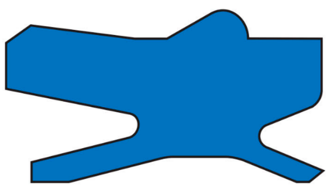


Figure 3.1: Freudenberg Seal Transversal Section.
Take From: [**?**]

Figure 3.2: Double lips seal. Taken from: [**?**]

This seal is known as a double lips because has two parts which are in contact with the rod. This lips apply a radial force and it is the important parameter for global sealing performance. Is possible to obtain a good tightness if is applied high radial force in the seal but in counterpart the high contact pressure exerted in the lip has a consequence and it is more friction and wear. It must obtain a compromise that guarantees tightness even in the most unfavourable operation conditions in its lifetime, but keeping friction at lowest level possible.

Then to obtain the measure, is mounted the seal on a rod which is divided in two sections. The seal presses it and a general radial force is derived. In this study the two sector have 180° each.

Seal geometry in this study is rather complex. As it can see in the Fig. 2.3. The seal has two lips, one of which has an automatic sealing. Seeing the transversal section, the left side is pressurized and is possible to obtain this phenomenon. It was used this radial force meter for this investigation because is of special interest. For that reason two load cells are mounted parallel to the special rod, and they have the objective to take the disturbance signal of the seal which is in contact. These load cells are sensitive only to the horizontal force. Then the seal goes down from the upper rod onto the special rod, and is possible to drawn the overall force.

"If the seal motion occurs at constant velocity V, the contact pressure distribution along the rod it could be obtained as a function of the force time derivative (F(t)), the rod diameter (d) and the seal velocity (V)" $G.Belforte$

In Addition to this, if the axial gap between the two rods could be infinitely small the pressure distribution under a single lip could be resolved with good precision and might be expresses like this:

$$p(z) = \frac{1}{d} \cdot \frac{dF}{dt} \cdot \frac{1}{V} \tag{3.1}$$

This equation is applied along the rod As shown:

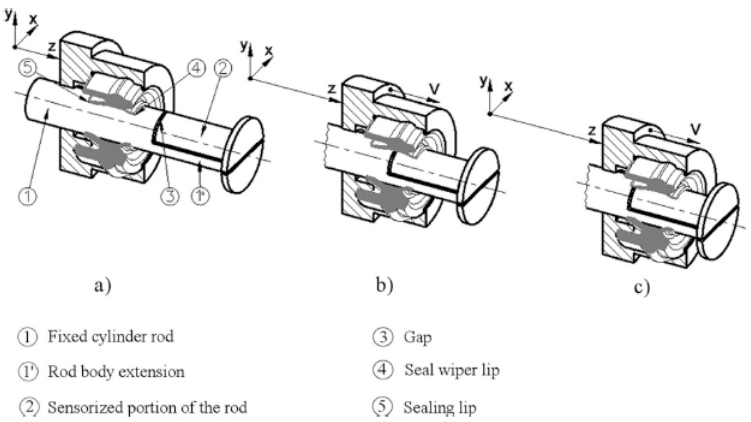


Figure 3.3: Rod and Seal

The resultant of the contact pressure distribution around the rod is constant when the seal is not in contact with the special rod, instead, the contact area between the seal and the sensitized lip increases, the sensors detect an increasing radial force until the maximum value is reached.

3.1 Radial Force Meter

In this subsection it will be explained the Radial Force meter that is present at the Mechanical Laboratory in the Politecnico di Torino. In order to obtain the contact pressure in an indirect way, it was design as follow:

1. **Seal Holder.**
   Piece that permits to pressurize the left lip of the seal.

2. **Pneumostatic Bearing.**
   Used to obtain a low friction even if in low velocity condition.

3. **Main Rod.**
   This is the part fix which allow the linear movement of the seal holder. It has an extension part in where is coupled the special rod.

4. **Special Rod.**
   This is the piece that couple exactly in the main rod.

5. **Load Cells.**
   Have the objective to measure the radial force in the stroke of the seal onto the special rod.

6. **Precision Screws**
   Piece very important in the test bench, because has the task to regulated the gap (h1) between the two rods.

7. **Pneumatic Guide Bearing**
   Also called low friction bearing, has the main objective to guarantee that the radial force exerted in "y-direction" read by the load cells are done in a correctly way.

Through the Load Cells and the electronic boards, is possible to take over the different points that represent the Phenomenon in this case of study how it changes the force along the seal and how is its contact pressure distribution. But this Radial Force meter has another compounds that make possible to take over all points. The united compounds are called Radial Force meter test bench.

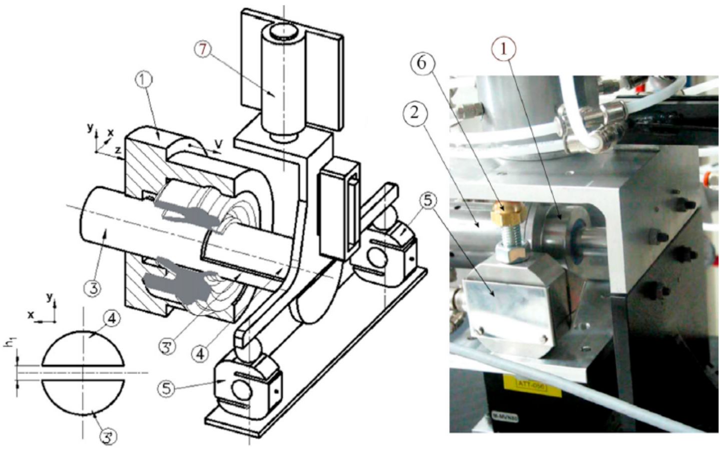


Figure 3.4: Radial Force Meter. Taken from Paper Measure of the Radial Force

In the figure 3.4 is known as measuring portion that is composed by the components that was mentioned. But this compound for itself is useless, it is needed another pieces that permit the correct signal take over. Then the union of these pieces is the Test Bench, that it is had the Mechanical laboratory at the Polytechnic of Turin.

3.2 Test Bench

Test Bench, is conformed by different system that as well are conformed by several pieces. In this subsection it will be studied those systems and explains some important parts.

3.2.1 Base

The base of the test bench is conformed by the numbers 1 and 2, as it can be seen in the fig. 3.5 the number one is the lower base and the number two is lateral base.

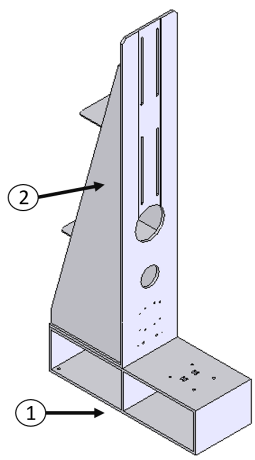


Figure 3.5: Test Bench Base

1. The Lower Base, maintain the pneumatic bearing in position and has the micro-metric set-up, this last one, is important because has the function to maintain the mobile part as parallel as possible to the fixed rod (or fixed part).

2. The Lateral Base, has the guides to put the base of mechanical actuator, the vertical linear stage (Newport-MVN80), and position the electronic part, board and the electrical fed.

3.2.2 Energizer part

This part of the test bench is characterized for the linear movement of the seal and its compounds by the Pneumatic Mechanical Actuator. The velocity is regulated by the throttle valve with retention, which is positioned both in the feed and in the discharge. As it can be seen in the following figure

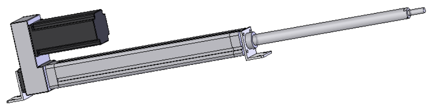


Figure 3.6: Taken from design thesis 2009

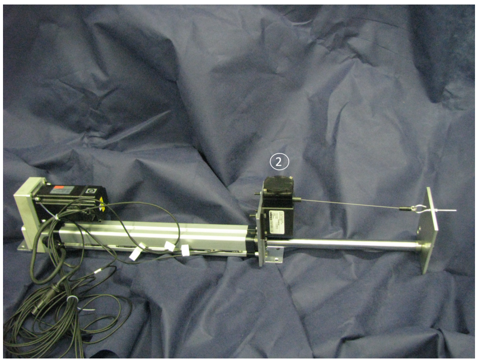


Figure 3.7: Taken from thesis 2009

In this subsection also is mounted the velocity transducer (denoted with the number 2) in order to measure rod velocity of the actuator, because this will be a important parameter to study.

3.2.3 Systems assembled

These systems assemble constitute the Test Bench. These system were made in SolidWork and a schema is achievable that will be shown as follow:

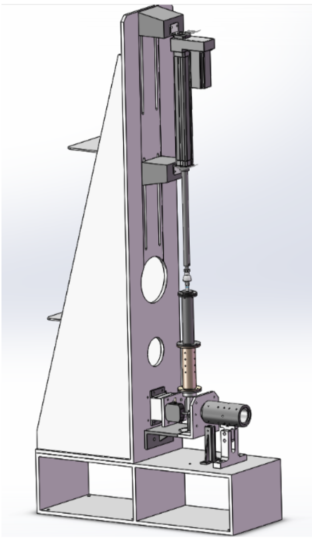


Figure 3.8: Test Bench Assembled

As can be seen in the figure 3.8 the radial force meter also is included although is not explained in the subsection of systems.

3.2.4 Fed system

The Mechanical Laboratory of the Polytechnic of Turin has an air compressed system well distributed, in different points of the laboratory there are air flow regulators that can permit to regulated the pressure in the system. There are different systems that are fed with air compressed between them:

1. **Pneumatic guide bearing.**
   In order to have the lowest friction this part is fed it with air compressed . This method permits that piece can to levitate and the friction could reduce as more as possible.

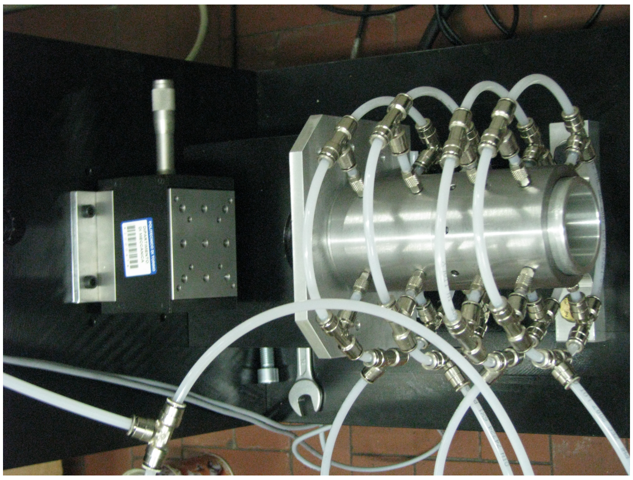


Figure 3.9: Pneumatic Guide Bearing

2. **Pneumatic Bearing**
   Is the same principle that the last piece. But in this case is mounted in the rod, and its function is to guarantee that the axial force it will be exerted only by the seal in study.

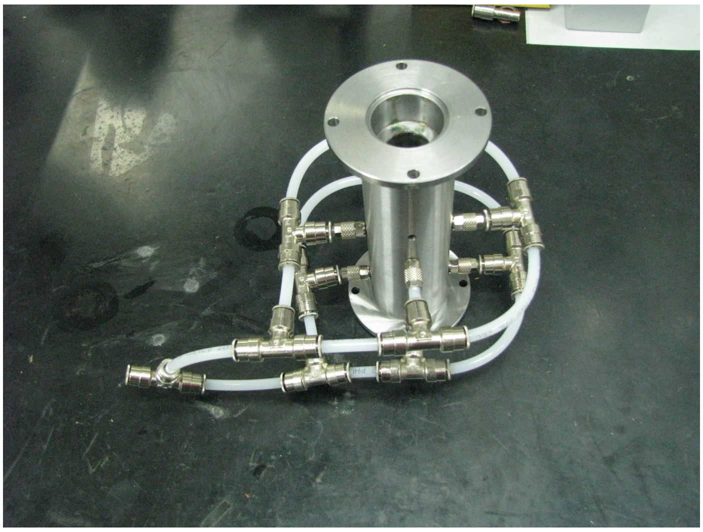


Figure 3.10: Pneumostatic Bushing

3. **Pneumatic actuator**
   The main function is the linear movement of the seal, and its velocity is regulated throughout valves in the outstroke and instroke. The velocity is observed directly in a computer because the transducer has internally the gain between [V] and [mm/s].

3.2.5 Signal Recording

firstly, it started in the radial force meter in where are positioned the **Load Cells**
these last ones register the perturbation that suffer the mobile part specifically the special rod because this is pressed by the seal, then the contact by the mobile part and the special screw tends to increase and this force is read by the electronic board. Through a computer program **DCS 100A**
is register in an Excel sheet the time in [s], The force in [V] and the velocity in [mm/s]. These are the parameter that it will be taken in consideration in this thesis.

These test will be made varying the Fed Pressure and the rod velocity. These are two parameter to take in consideration in order to observe how change the contact pressure on the seal.

Then it will be explained steps that permit to obtained the force in [N], and starting from here how is possible to calculate the contact pressure.

3.2.5.1 Data Recorded

The all data from the acquisition board will be saved in .xlxs format (Excel sheet) and it will be processing in Matlab. Then an example of this sheet is represent as follows:

Table 3.1: Data Recording

Time [s]	Force [V]	Force [V]	Velocity [mm/s]
0	1.211908	3.2808	6.128756
0.001	1.20573	3.278199	6.129406
0.002	1.210607	3.285352	6.129406
0.003	1.208981	3.272346	6.129406
0.004	1.206055	3.282751	6.129081
0.005	1.209306	3.284702	6.129081
0.006	1.206705	3.279174	6.129406
0.007	1.209957	3.291205	6.128756
0.008	1.205405	3.279174	6.129406
0.009	1.214184	3.277224	6.129081
0.01	1.209632	3.2808	6.129081
0.011	1.215484	3.275273	6.129406
0.012	1.213858	3.283076	6.128756
0.013	1.220361	3.279174	6.129406
0.014	1.21776	3.278524	6.129406
0.015	1.220361	3.279825	6.129406
0.016	1.221662	3.276573	6.129406
0.017	1.214834	3.278524	6.129406
0.018	1.216785	3.275273	6.129731

NOTE: The table shows a part of the all data that was taken from the load cells, the velocity from the velocity transducer

After this is applied a formula, the relationship between the volts and Newton. As two load cells are present in the laboratory the force is split. Then the equations are present as follow:

$$F_1 = 5,9449 \cdot X[\frac{N}{V}] - 0,4492[N] \tag{3.2}$$

$$F_2 = 11,514 \cdot X[\frac{N}{V}] + 1,6878[N] \tag{3.3}$$

Chapter 4

Test Bench Modifications

In this chapter will be developed and explained the modifications that were made in the test bench in order to maintain most controlled the main parameters, as the fed system pressure. As it could be seen in the previous test bench, the Seal was feed directly by the air bearing, and there was not a pressure gauge that could read the effective pressure that was exerted it. Also the Air Bearing represented a leakage source then when the feed pressure was increased the noise produce by itself increase, making an uncomfortable environment. Another problematic source is the difficult to maintain the same contact of the screws with the mobile part, if this contact has a gap between the screws there will be a momentum, that will be represented to the increase of a signal and the decrement of another signal

4.1 Modifications

All modification were made in SolidWork that is a solid modelling computer-aided design (CAD) and Computer-Aided engineering (CAE) in where is possible to model system and see its respond by a certain parameters. It can be designed several pieces and after that do an Assemble a see the entire system. The modification that will be developed in this section are enumerate as follow:

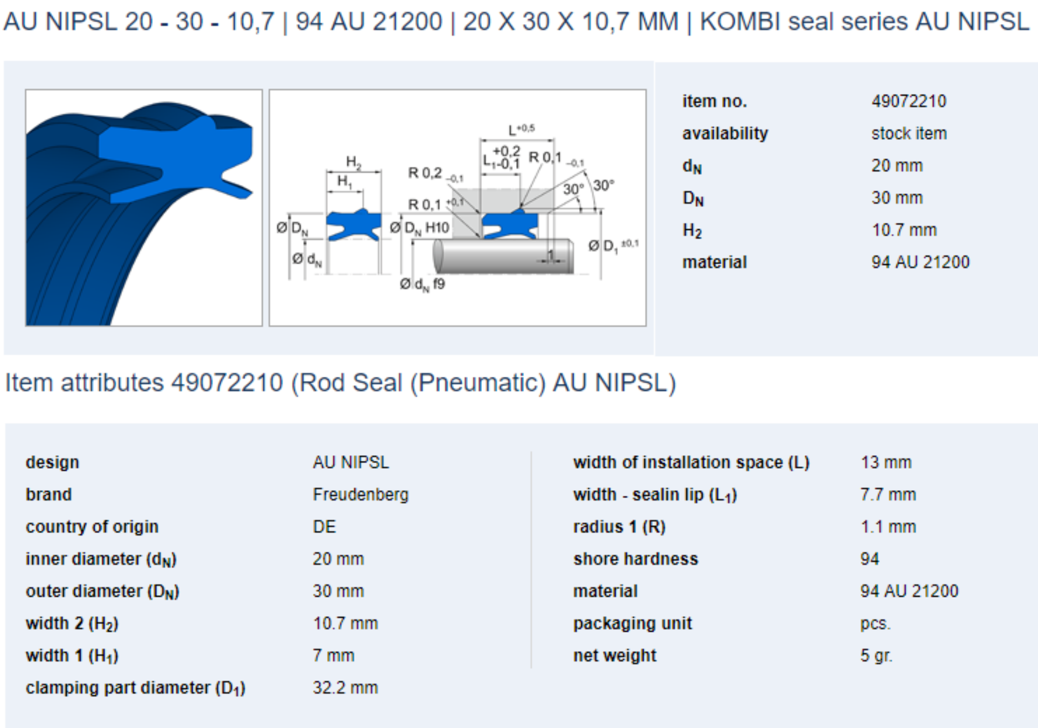
1. In order to guarantee a best way to pressurized the seal-holder, the modification that has suffered was open a hole in where would be attached a **Super-rapid Fitting** from "Camozzi" as near the seal as possible.

2. The study will be focused in a particular seal as can be seen in the figure 5.5 and has a complex shape and also the seal-holder is. Generally this materials are elastic but by their complexity is very difficult to introduce it and also to pull-out it. To counter this is modify the internal seal holder, making an rectangular part with a specific length in order to do more easier works with the seal.

3. The thesis will be developed focussed in the measure of the Radial force then the axial force or friction is not an influence parameter that take in consideration. Then in order to achieve that there will are not leakages, the air bearing is removed from the test bench and is searched to have a close volume designing a Sleeve-Guide.

4.1.0.1 Seal-Holder

Using SolidWork the seal-holder was modified, it is started searching the different brands that sell the double lips seal, between them were **Freudemberg** and **Parker** in this thesis it will work with a Freudenberg seal because is more commercial and its webpage is posted how to design the seal-holder. Also Parker catalogue was used because explain better how to make easier to pull-out and introduce the seal. Following the previous steps, it is begin searching in the Freudenberg official site the seal having this:


AU NIPSL 20 - 30 - 10,7 | 94 AU 21200 | 20 X 30 X 10,7 MM | KOMBI seal series AU NIPSL

item no.	49072210
availability	stock item
d_N	20 mm
D_N	30 mm
H_2	10.7 mm
material	94 AU 21200

Item attributes 49072210 (Rod Seal (Pneumatic) AU NIPSL)

design	AU NIPSL	width of installation space (L)	13 mm
brand	Freudenberg	width - sealin lip (L_1)	7.7 mm
country of origin	DE	radius 1 (R)	1.1 mm
inner diameter (d_N)	20 mm	shore hardness	94
outer diameter (D_N)	30 mm	material	94 AU 21200
width 2 (H_2)	10.7 mm	packaging unit	pcs.
width 1 (H_1)	7 mm	net weight	5 gr.
clamping part diameter (D_1)	32.2 mm		

Figure 4.1: Freudemberg Seal-Holder Design. Taken From: https://ecatalog.fst.com/seals

Doing reference to the figure 4.1 it is started to make a drawing in Solid-Work respecting the main measure. In other hand also is design the rest of the seal holder following the original. Doing a Solid revolution starting from the draw, it is obtained the required seal holder:

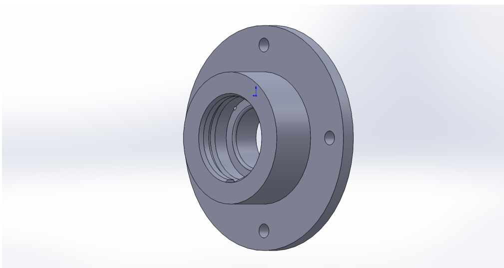


Figure 4.2: Seal-Holder Front view. Doing with SolidWork 2018 Student Edition

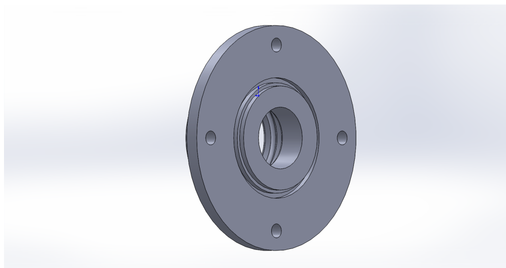


Figure 4.3: Seal-Holder Back view. Doing with SolidWork 2018 Student Edition

This is the base to star to do the another modifications. As had been said, it must to guarantee the pressure in the Seal, then the feed hole should be as near as possible. The decision to make a hole in the seal-holder was taken.

But there is other decision to take in consideration is the diameter of that hole, hence a research of the Super-rapid fitting has done. Between of all brands has been chosen "**Camozzi**", because in their catalogues offer a **Super-rapid fittings** Series 6000, model 6512 3-M3 Micro Metric-BSP male Connector, in conclusion the seat is smaller (3 mm). Looking like this:

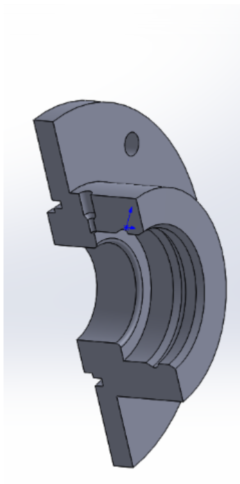
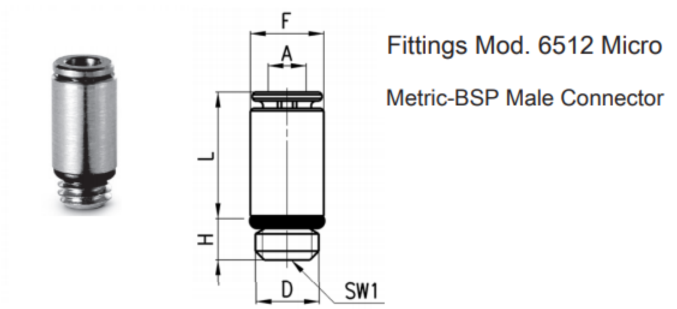


Figure 4.4: 90 degree cut Seal Holder. It was made with SolidWork 2018 Student Edition

As can be seen in the figure the hole is near to the seal, but is not in contact with the seal-holder vertical part. It is positioned to 45^o with respect to the seat of the fixing screws in order to don't interference in the Seal-Holder and sleeve assemble. This design ensure a read pressure more accurate. The air fed is done through Super-rapid fitting and the data sheet is as shown:



DIMENSIONS								
Mod.	A	D	F	H	L	SW1	Weight (g)	
6512 3-M3	3	M3	5.8	2.5	10.2	1.5	1	⋆
6512 3-M5	3	M5	5.8	3.5	10	2	1	•
6512 4-M7-M	4	M7	9.4	5	17.5	2.5	5	•
6512 4-1/8-M	4	G1/8	11.2	5	13	2.5	9	•, Y
6512 6-M7-M	6	M7	10.4	5	17	4	7	•
6512 6-1/8-M	6	G1/8	11.2	5	14	4	7	•, Y
6512 8-1/8-M	8	G1/8	12.4	5	18.5	5	10	•, Y
6512 10-1/4-M	10	G1/4	14.8	6	21	7	16	•

⋆ = with gasket
• = with O-Ring

Figure 4.5: Super-rapid fitting. Taking from:

The dimension are shown in the data sheet, value of A is important to taking in consideration because the fed-pipe must be the same value, or another solution could be use to use amplifier junctions which have the function of amplifying the feed hole, allowing them to place inner tubes with a larger diameter.

Sequentially, it was made the rectangle in the internal seal holder using the Parker's catalogue as follow:

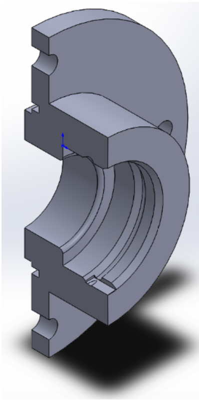


Figure 4.6: Dis-malting recess. It was made with SolidWork 2018 Student Edition

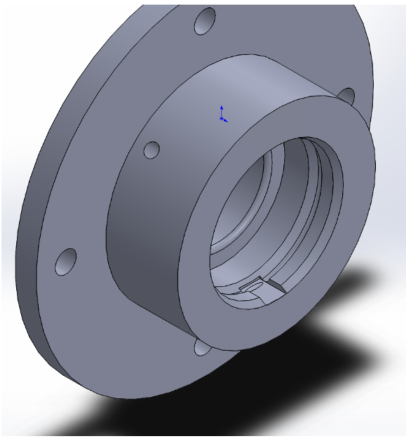


Figure 4.7: It was made with SolidWork 2018 Student Edition

In case the seal-wiper set needs to be exchanged, this can be accomplished if a dismantling recess has been made as can be seen in the figure (detail "X").

Finally the Seal-Holder modified is looking like this:

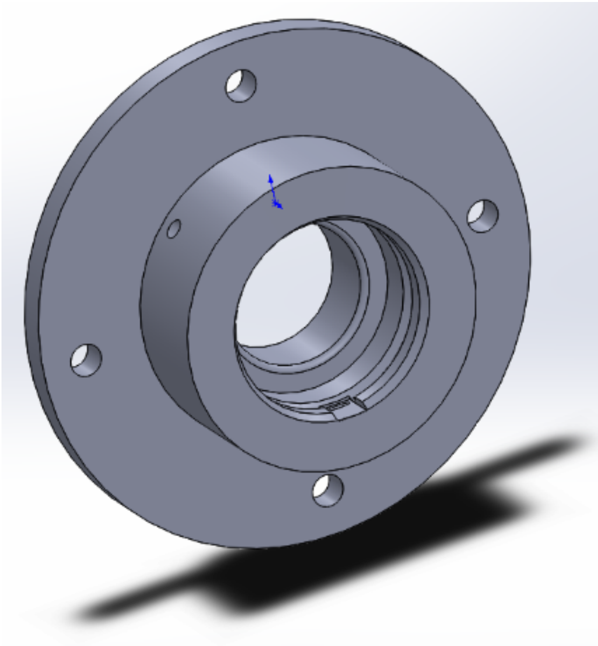


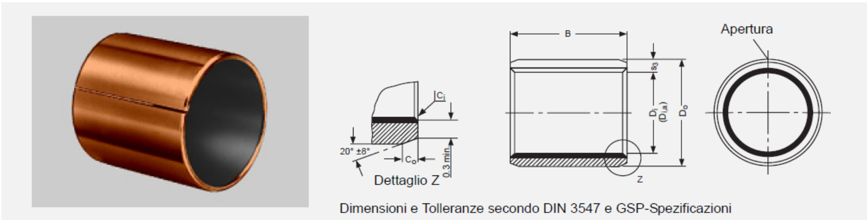
Figure 4.8: Seal-Holder Design.It was made with SolidWork 2018 Student Edition

4.1.0.2 Sliding bearing

Following the numbering and taking in consideration only the radial force, it will be designed a Sliding bearing holder in where could be guaranteed a close volume in order to don't have air leakage in the system, this with the intention to study the fed pressure as a parameter to characterize the seal on study. Working with Solidwork, it has been taken the original Air-Bearing because in the New test bench the dimension has maintained constant. Then the modifications have started closing the holes that fed the air-bearing. Instead of air, the guide of the seal-holder it will be done by the Sliding bearing, the lasts ones will be positioned inner the piece. The brand with which work was been GGB bearing.

Searching in its catalogue in the section of "**Boccole cilindriche DUB"**", it was taken in consideration the following Sliding Bearing:

8.5 Boccole cilindriche DUB



Tutte le dimensioni in mm

Smussi sul Dia. Int. Ci e Dia. Est. Co

Spessore parete boccola s_3	C_o (a) lavorato	C_o (a) avvolte	C_i (b)
0.75	0.5 ±0.3	0.5 ±0.3	-0.1 fino -0.4
1	0.6 ±0.4	0.6 ±0.4	-0.1 fino -0.5
1.5	0.6 ±0.4	0.6 ±0.4	-0.1 fino -0.7

Spessore parete boccola s_3	C_o (a) lavorato	C_o (a) avvolte	C_i (b)
2	1.2 ±0.4	1.0 ±0.4	-0.1 fino -0.7
2.5	1.8 ±0.6	1.2 ±0.4	-0.2 fino -1.0

a = Smusso Co tornito o rullato (a discrezione GGB)

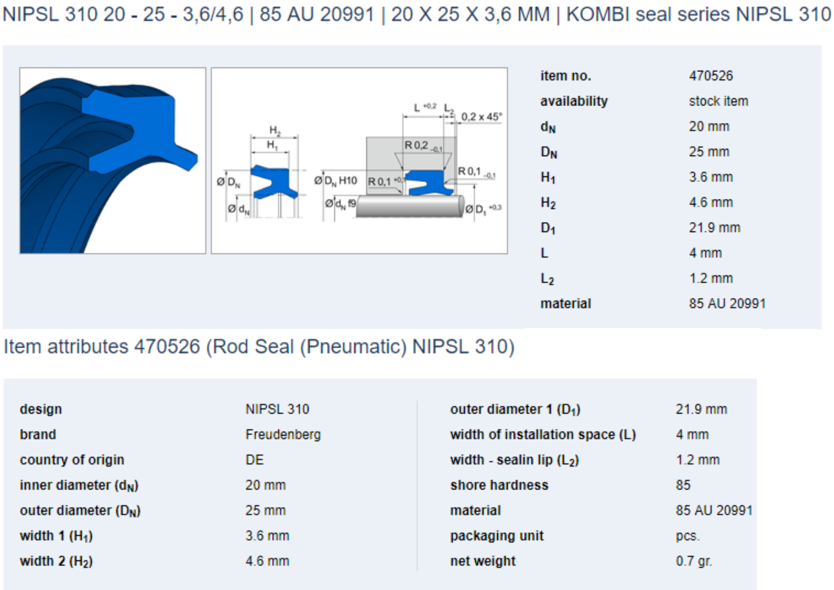
b = Ci può essere un raggio o uno smusso secondo ISO 13715

Rif.	Diametro nominale D_i	Diametro nominale D_o	Spessore parete boccola s_3 max. min.	Larghezza B max. min.	∅ Albero D_J [h6, f7, h8]	∅ Albero D_J max. min.	∅ Sede D_H [H6, H7]	∅ Sede D_H max. min.	∅ interno $D_{i,a}$ dopo mont. in H6/H7 Sede max. min.	Gioco C_D max. min.
2015DUB	20	23	1.505 1.475	15.25 14.75	f7	19.980 19.959	H7	23.021 23.000	20.071 19.990	0.112 0.010
2020DUB				20.25 19.75						
2025DUB				25.25 24.75						
2030DUB				30.25 29.75						

Figure 4.9: Sliding Bearing. Taking from: GGB bearings Catalogue

Taking information by this catalogue is proceed to design the inner part of the sliding bearing holder for its seat. After that and following the idea of close volume, it was taken a decision to put inner of this piece another seal that will have not other function but to avoid the leakage of air in the system.

The same rod seal brand (Freudemberg) was taken, searching one have the same diameter but with an only lip, as shown:



NIPSL 310 20 - 25 - 3,6/4,6 | 85 AU 20991 | 20 X 25 X 3,6 MM | KOMBI seal series NIPSL 310

item no.	470526
availability	stock item
d_N	20 mm
D_N	25 mm
H_1	3.6 mm
H_2	4.6 mm
D_1	21.9 mm
L	4 mm
L_2	1.2 mm
material	85 AU 20991

Item attributes 470526 (Rod Seal (Pneumatic) NIPSL 310)

design	NIPSL 310	outer diameter 1 (D_1)	21.9 mm
brand	Freudenberg	width of installation space (L)	4 mm
country of origin	DE	width - sealin lip (L_2)	1.2 mm
inner diameter (d_N)	20 mm	shore hardness	85
outer diameter (D_N)	25 mm	material	85 AU 20991
width 1 (H_1)	3.6 mm	packaging unit	pcs.
width 2 (H_2)	4.6 mm	net weight	0.7 gr.

Figure 4.10: Sliding Bearing seal. Taking from: Freudenberg bearings Catalogue

Then with this information is proceed to making in SolidWork a seat for this seal. Obtaining the following figures:

Figure 4.11: Sliding Bearing holder. It was made with SolidWork 2018 student edition

Seeing the figure 4.11 the numbers represent

1. Is the first sliding bearing seat.
2. Is the second sliding bearing seat.
3. Sliding bearing seal-holder.

4.1.0.3 Modified parts Assembly

In order to understand better the close volume meaning, in this subsection will be posted the modification parts assemble.

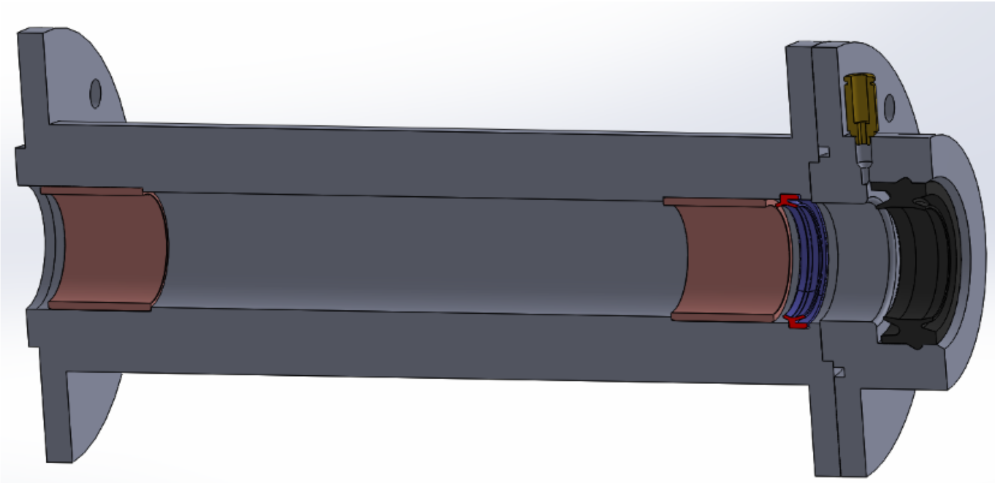


Figure 4.12: Assemble view. It was made with SolidWork 2018 student edition

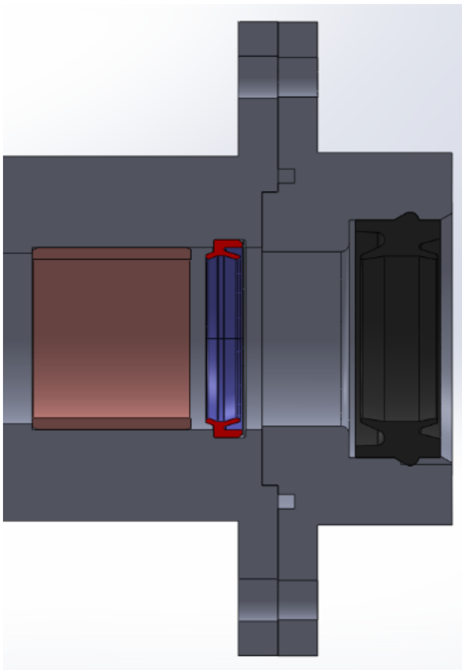


Figure 4.13: Close volume. It was made with SolidWork 2018 student edition

As can be seen in the figure 4.13 between the two seals there is a small volume, guaranteeing that will not have leakages. The Sliding bearing work as a guide for the system, being self-lubricated is not necessary to lubricate it.

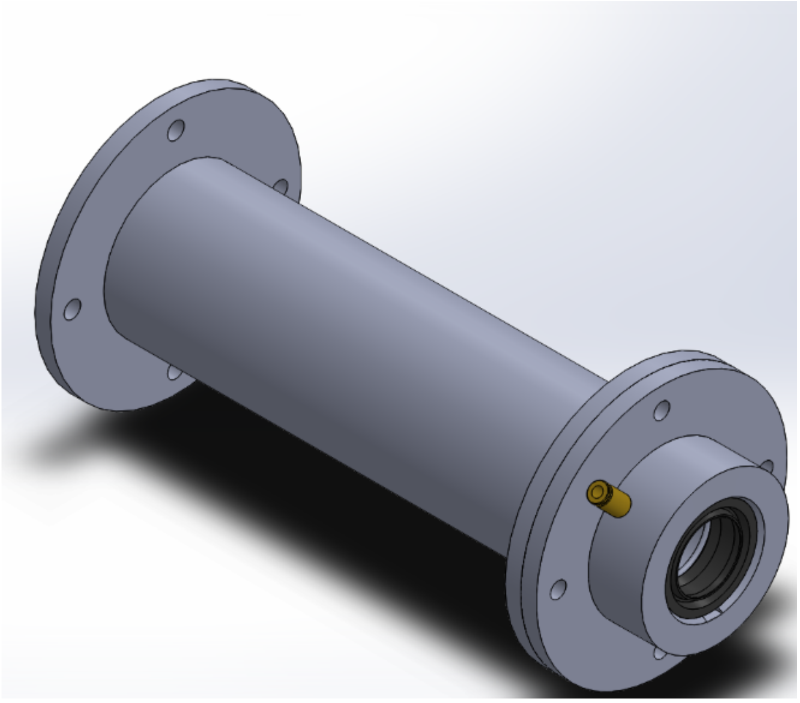


Figure 4.14: 3D modified parts view. It was made with SolidWork 2018 student edition

These parts were developed due to the problematic presented in the section ??.

4.2 Load cells

When it had been started to do the set-up of the test bench and the test were started, the load cells registered a signal with a lot peaks. Firstly it was thought that could be the noise present in any signal, but then filtering it, the signal continued presenting these peak.

It was been taking the decision to test only one a load cells the results that obtained did not present this peaks. To summarize, the parallelism between the two load cells were not guarantee and hardily the same contact from the load cells screws with mobile part of the air bearing were not fulfilled. The last problematic can be seen in the next figure:

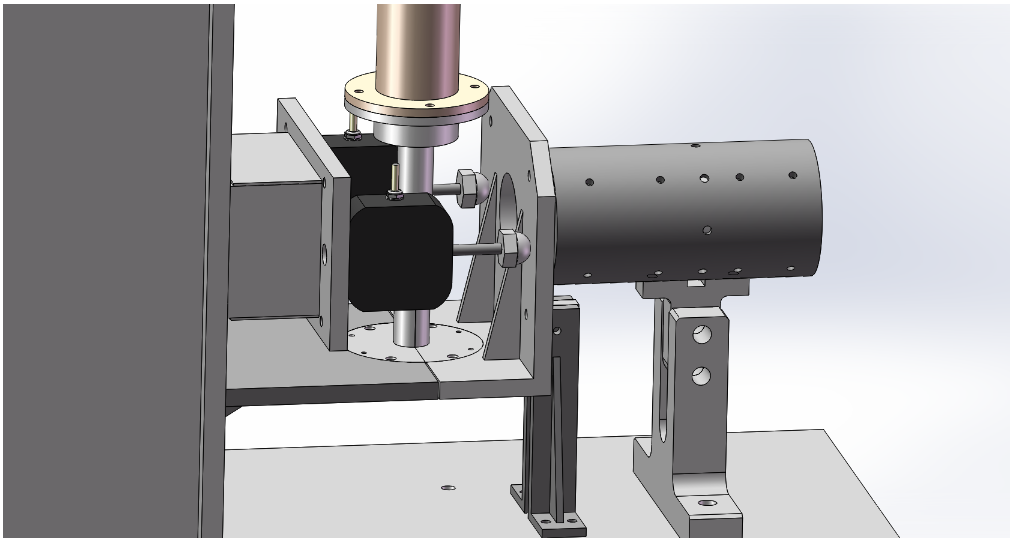


Figure 4.15: Load cells problematic. It was made with SolidWork 2018 student edition

This problematic could be explain the decrease of the force signal that was appreciated in the figure **??**.

To conclude in the new test bench assembly will work with a only one cell, because eliminate that strain decrease in the force signal.

4.3 Modified Test Bench

The original test bench was used as a reference, only the previously aforementioned parts were added,thus replacing the ones that were previously there.

As can be seen in the following figures:

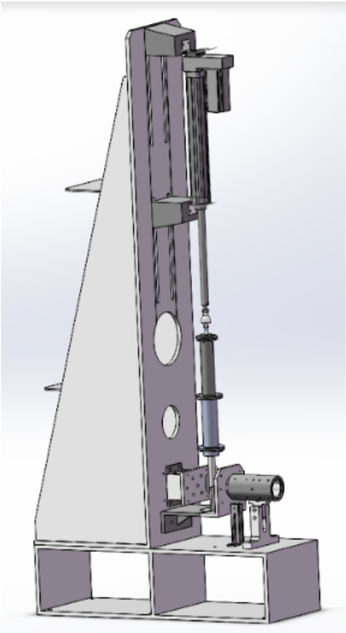


Figure 4.16: New Test Bench. It was made with SolidWork 2018 student edition

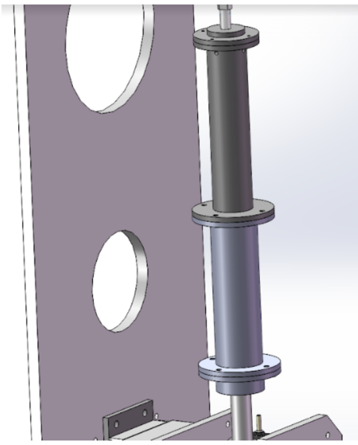


Figure 4.17: Modified parts on the Test Bench. It was made with SolidWork 2018 student edition

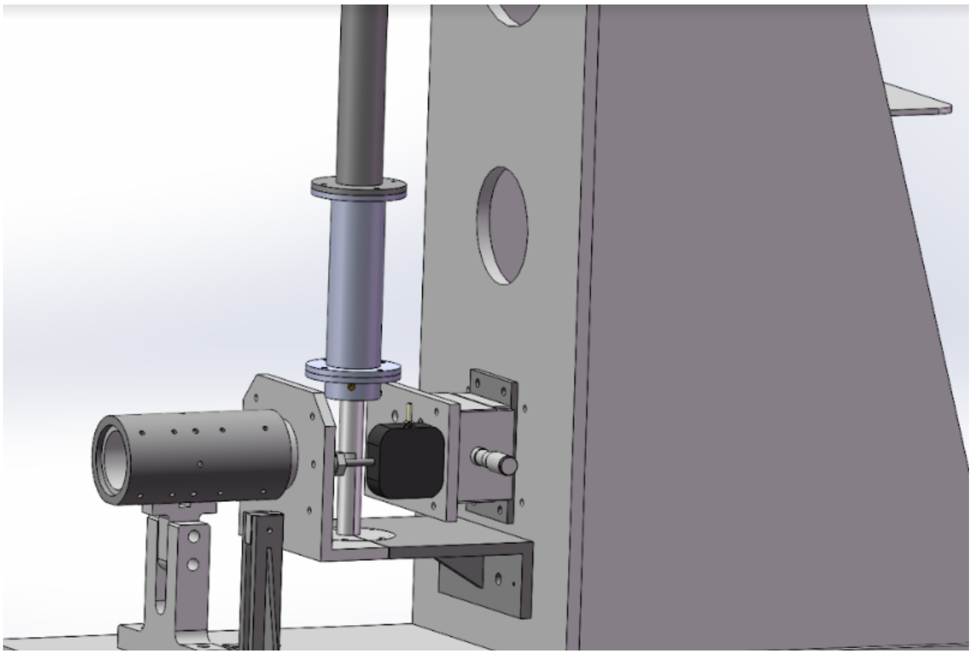


Figure 4.18: New test bench load cell. It was made with SolidWork 2018 student edition

Chapter 5

Test

In this chapter first of all, will be described the previous procedures to do a several tests in order to obtain the radial force signal in different conditions, after that it will be explained how is study and develop the best fitting curve obtaining the signal without peaks (noise). Hence, first it is introduced the **Matlab** environment. Matlab is a programming platform designed specifically for engineers and scientists. The heart of Matlab is its language,a matrix-based language allowing the most natural expression of computational mathematics. And the **SimuLink** environment is a graphical programming environment for modelling, simulating and analysing multi-domain dynamical system.

5.1 Load cell characteristic

It is well known that the transducer generally read an electrical signal disturbance (variations) and convert it a physical quantity variation.

In this thesis will work with a Load cell **(S/N:S162JT)** with the following characteristics:

The fabricator did not attach the load cell physical characteristic, but it can be obtained through a series of steps.

1. A precision screw is connected to the load cell with the aim to put it on weight previously known.
2. The load cell wiring is connected to a Voltmeter in order to read the stationary volt.
3. With weights of 5 kilos each ones are put on the load cell and read the voltage by the voltmeter, and it goes increasing of 5 in 5 until arriving at 30 kilos and reading the voltage in each one.
4. It is repeated the previous procedure but starting from 30 kilos to 5 kilos.
5. The procedure it will be done three time in order to have a good data to make an average characteristic.

The last step could be summarized in the following figures:

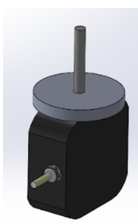


Figure 5.1: Made with:[?]

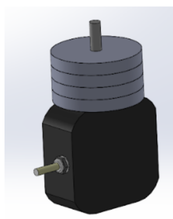


Figure 5.2: Made with: [?]

The all data were registered in an excel sheet, as shown:

Table 5.1: Test 1

1	2	3	4	5	6
[Kg]	[Kg]	[mV]	[Kg]	[Kg]	[mV]
0.63	0.63	2.71	0.63	0.63	2.707
5	5.63	2.612	5	5.63	2.61
10	10.63	2.516	10	10.63	2.513
15	15.63	2.417	15	15.63	2.413
20	20.63	2.319	20	20.63	2.316
25	25.63	2.22	25	25.63	2.218
30	30.63	2.122			

NOTE: The 1^{st} test that was made in order to characterize the load cell

Table 5.2: Test 2

1	2	3	4	5	6
[Kg]	[Kg]	[mV]	[Kg]	[Kg]	[mV]
0.63	0.63	2.707	0.63	0.63	2.713
5	5.63	2.611	5	5.63	2.616
10	10.63	2.513	10	10.63	2.518
15	15.63	2.424	15	15.63	2.42
20	20.63	2.321	20	20.63	2.322
25	25.63	2.224	25	25.63	2.24
30	30.63	2.128			

NOTE: The 2^{nd} test that was made in order to characterize the load cell

Table 5.3: Test 3

1	2	3	4	5	6
[Kg]	[Kg]	[mV]	[Kg]	[Kg]	[mV]
0.63	0.63	2.714	0.63	0.63	2.711
5	5.63	2.615	5	5.63	2.612
10	10.63	2.517	10	10.63	2.515
15	15.63	2.417	15	15.63	2.417
20	20.63	2.319	20	20.63	2.319
25	25.63	2.226	25	25.63	2.222
30	30.63	2.124			

NOTE: The 3^{th} test that was made in order to characterize the load cell

5.1.0.1 Average test

Table 5.4: Average Test

1	2	3	4	5	6
[N]	[mV]	[N]	[mV]	[N]	[mV]
6.174	2.710	6.174	2.710	6.174	2.710
55.174	2.613	55.174	2.613	55.174	2.613
104.174	2.515	104.174	2.515	104.174	2.515
153.174	2.419	153.174	2.417	153.174	2.418
202.174	2.320	202.174	2.319	202.174	2.319
251.174	2.223	251.174	2.227	251.174	2.225
300.174	2.125	300.174		300.174	2.125

NOTE: Average test, the column with [N] were calculated using the weight formula, that could write like this $W = m \cdot g$, in where m is the mass and the g is the gravity. The column 5 and 6 are the average of the all data registered.

After this, it has been done the fitting of the average points. Using Excel to do a fitting, it will be obtained:

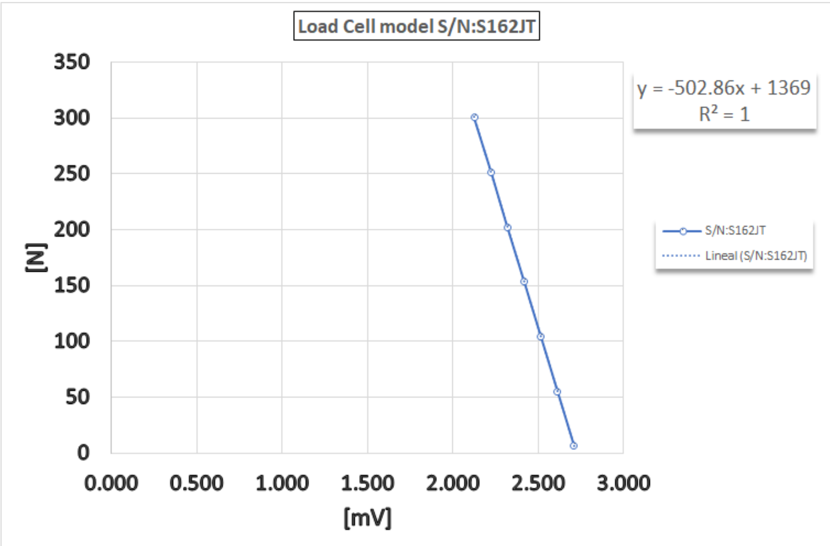


Figure 5.3: Load cell Characteristic. ??

Re-writing the equation is looking like this:

$$F[N] = -502,86 \cdot x[N/V] + 1369[N] \tag{5.1}$$

5.2 Steps before to start recording the signal

First of all, it started with the lubrication of the rod, because all tests were done with this characteristic. After this the system is fed (with air compressed) mainly by the pneumatic actuator, so a forward stroke and return were made in order to lubricate the two seals and avoid grip. The last step was repeated three times. At the end of testing process the rod is cleaned.

A manometer was put as near as possible to the seal holder in order to read the pressure in the close volume. The different tests that were made in the laboratory, can be seen as following:

Table 5.5: Tests done

Test	V[mm/s]	P[bar]
1	1	0
2	1	2
3	1	4
4	1	6
5	5	6
6	10	6
7	50	6
8	100	6

NOTE: It posted the different test that were done. It has the intention to calculate the Contact pressure and the radial force with these tests, determining the seal behaviour

In order to guarantee the velocity posted in the table 5.5 the pneumatic throttle valve was used, then different test were began and through the program DCS100 the velocities were read and monitored until to have approximately the request.

After this the Tests can be started and recording the interests parameter. For any main prove is repeated the same test three times. The aim of this is calculated an average test.

5.3 Signal Processing

The DCS100 program save the recording data in excel sheet, in each column a physical parameter is saved, In the first column is present the acquisition time, in the second column is present the force exerted by the seal which one is read directly in volts from acquisition board, through the characteristic curve of the load cell is possible to obtain the signal force [N], and in the third one is present the velocity directly in [mm/s] because the speed transducer has its gain and calculate it by itself. The load cell **(S/N:S162JT)** has characteristic equation:

$$F[N] = -502,86 \cdot x[N/V] + 1369[N] \tag{5.2}$$

After doing this it is defined three variables: **Time**, **Force** and **Velocity**. Remembering that for each Test it was repeated three times to obtain an average signal, consequently it will have three same variables. For example, it will have three acquisition time denoted by t_1, t_2, t_3.

5.3.1 Filtred signal

For any signal that is recording by the acquisition board is prone to has noise that could not represent the phenomenon studied therefore filter the signal is the first step in order to obtain a smooth and continuous signal. Simulink has a library in where put different types of filter and it is only necessary to defined: type, Design method, filter order and the passband edge frequency.In this thesis it had worked with filter Besself, low-pass frequency with an order 5 and varying the passband edge frequency for any test. As shown in the Figures:

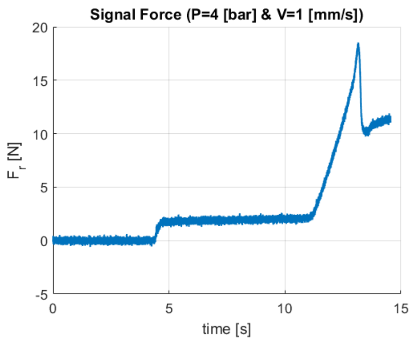


Figure 5.4: Noise present in the Force Signal

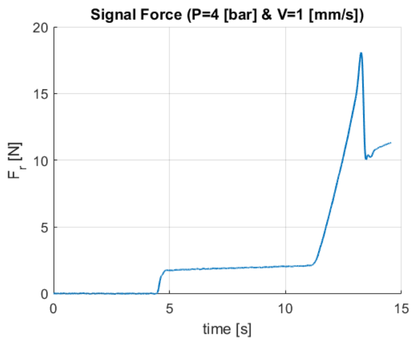


Figure 5.5: Force Signal Filtered

5.3.2 Shifting signals

Firstly it necessary to found the most greatest acquisition time in the three test, this in order to avoid choosing a very short time and miss valuable information from another test. Defining these variables, a simulation in Simulink is started. Obtaining three graph with equal conditions.

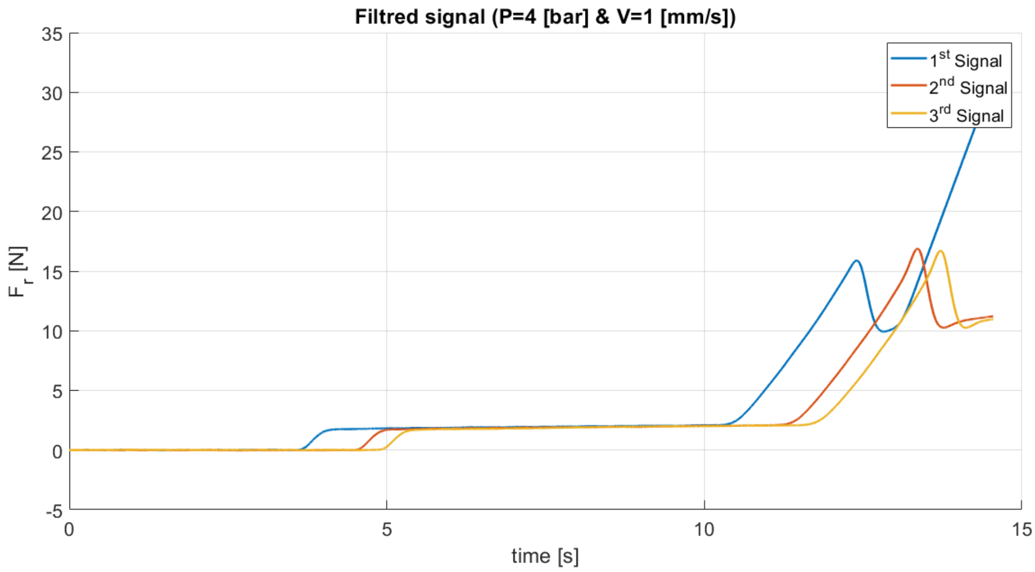


Figure 5.6: The Three signals in equals condition

It is highlighted in the 5.6, the different between the three graph, and it is due to the starting time recording data that could change for each person that work in the test bench, as is shown it. In order to put these graph in the same time they are shifted it, at the same time that is 0 sec. Then the procedure is as listed:

1. It is identify the four part that compound the entire signal
2. Identify the part that the seal is in contact with the rod.
3. Identify the moment that begins the signal has increased.
4. put a range between the two main parts of the signal, at the time in where the signal is outside of this range is recorded this time.

Having this time that it will be called **T1**, **T2** and **T3** according to each case. After this, said time is subtracted to each point that makes up the time column and a new point will not make up part of the new time column until the difference would be greater than zero. With this condition it is able to shift the signal to zero and place the three graphs at the same time. As shown in the next graph:

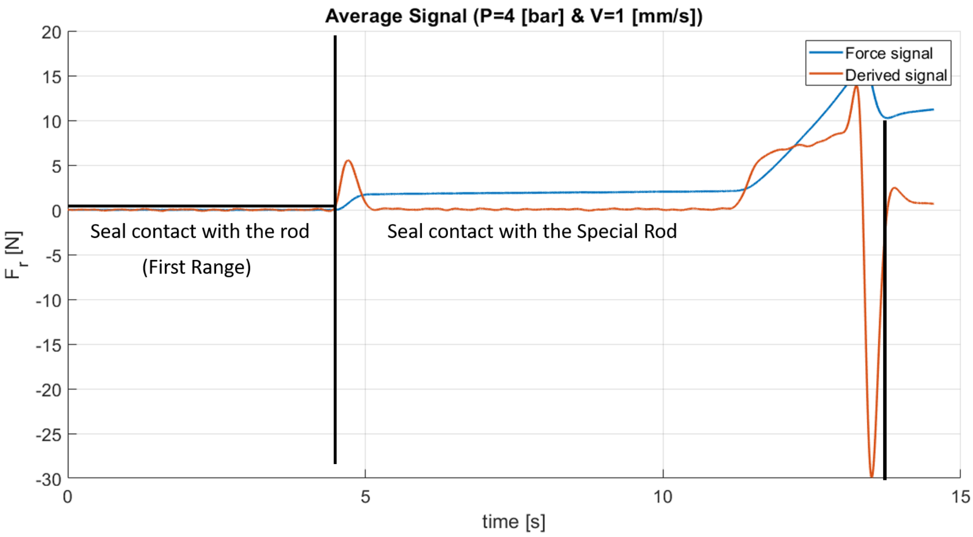


Figure 5.7: Seal contact with the rod and the special rod

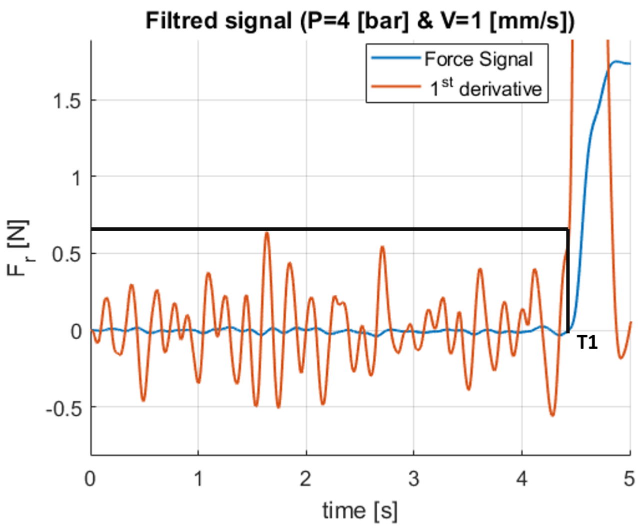


Figure 5.8: First range

And it is applied this equation in Matlab:

$$t_1 = F1.time(:,1) - T1 \tag{5.3}$$

In order to Shift the signal to zero this equation 5.3 is used in a Matlab environment in a cycle for and with a If condition, then when $t_1 \geq 0$ means that T1 value is reached and it was eliminated the seal contact with the rod.

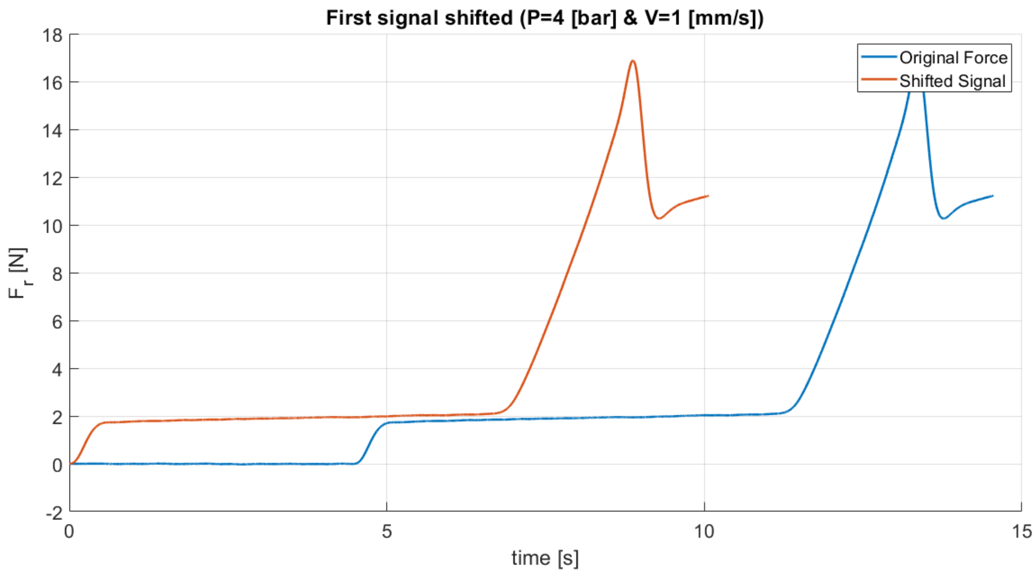


Figure 5.9: Shifted Signal

The same procedure is applied to the second and the third signal. It is possible to obtain the following figure:

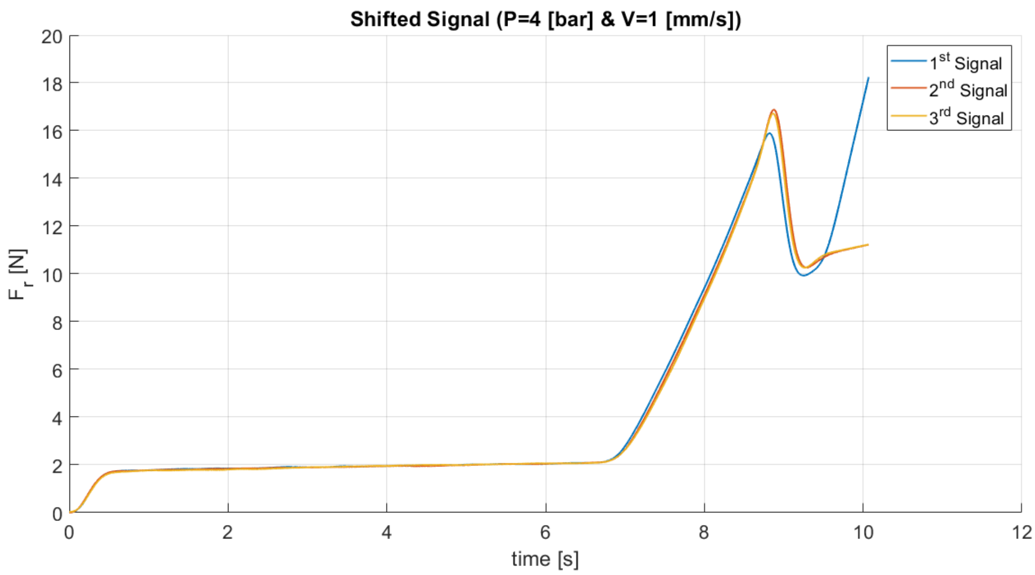


Figure 5.10: The three shifted signal

5.3.3 The three main signals

It will be developed the separation of the force signal and the first derivative signals in order to fitted the average signal. Then the aim is obtain a smooth signal without peaks. It started from the last step (The three signals allied) as in the figure 5.10; the next step is made an average, obtaining only one signal that will fitted.

Then a simulation is started with the condition to obtain the average signal as can be seen:

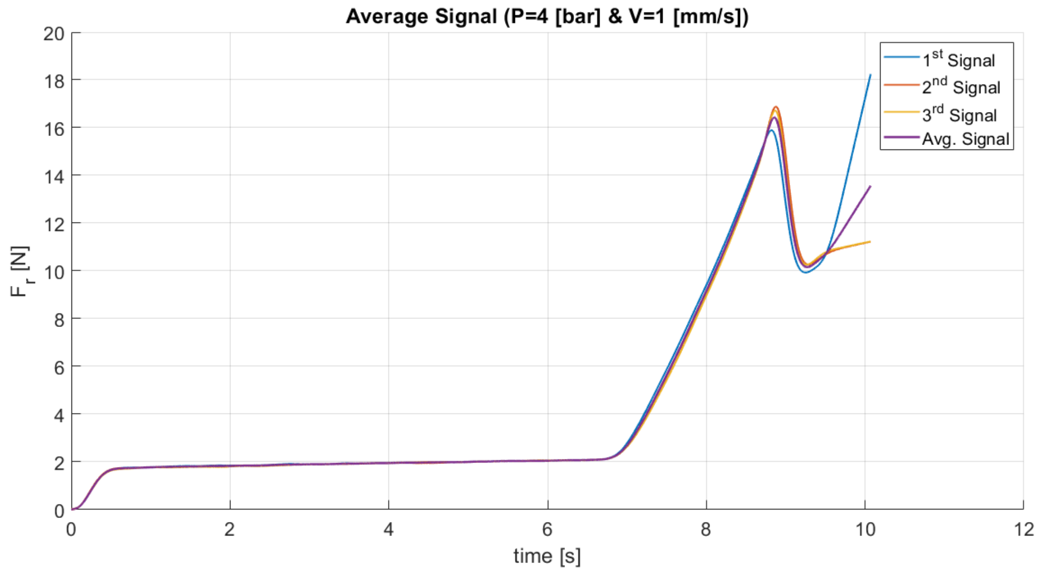


Figure 5.11: Average Signal

The violet one is the average signal then it was working and separate in three parts. These parts is showed:

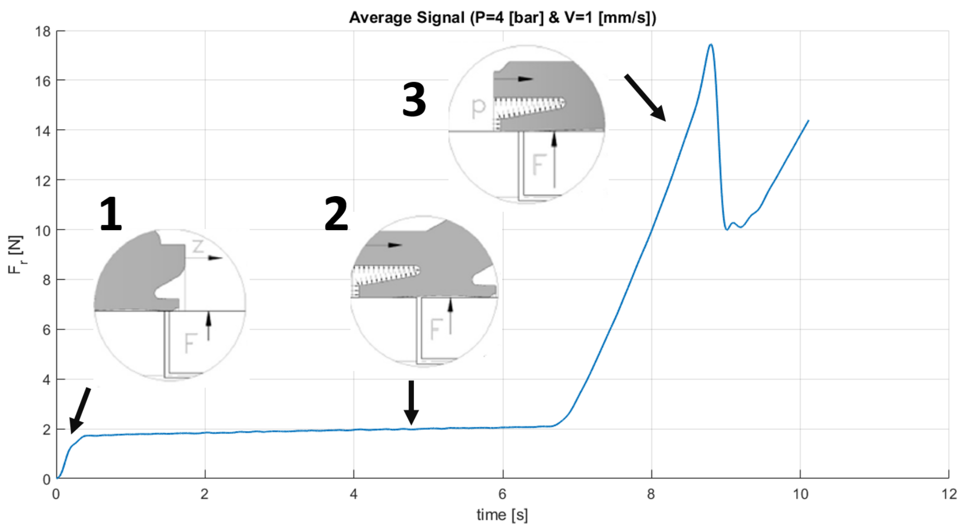


Figure 5.12: Three main parts

Then it starts in the same simulation using the **cycle If**, **Max** and Simulink functions, in order to find specifics times points.

5.3.3.1 The first part

In this subsection it will be defined the range in which is possible to get the first part of the main signal. After this it is starting seeing in which part the signal stop to increase and the first peak is observed and it tends to stay constant. This is indicators that the second part has started.

Consequently using a max function and one If block, in where it is putting the range definite as is shown in the next figure:

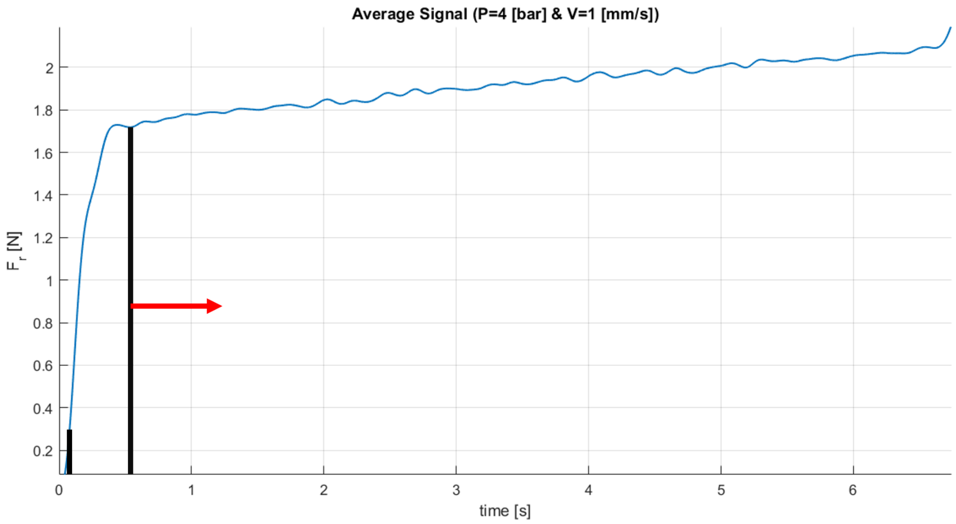


Figure 5.13: The first Range

in the figure 5.13 The black lines represent the first range and its maximum value will be called t_{o1}, this time is used in another simulation and will be the stop time. As follows:

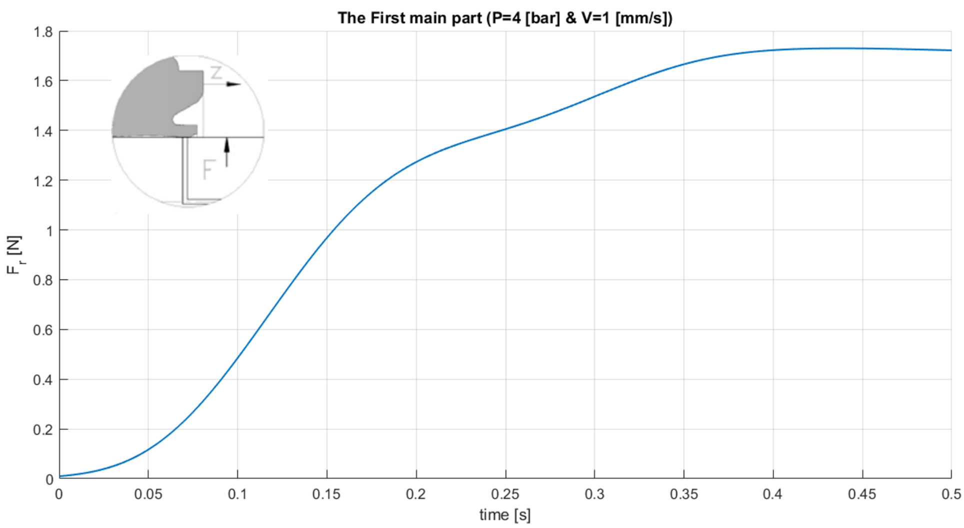


Figure 5.14: The first Part

When the first lip is moving and got touch the special rod the force signals tends to increase and in a small time interval pass from 0[N] to $\approx 1,98[N]$

5.3.3.2 The Second part

Continuing with the same previous idea, it started defining the range using the derivative signal, as follows:

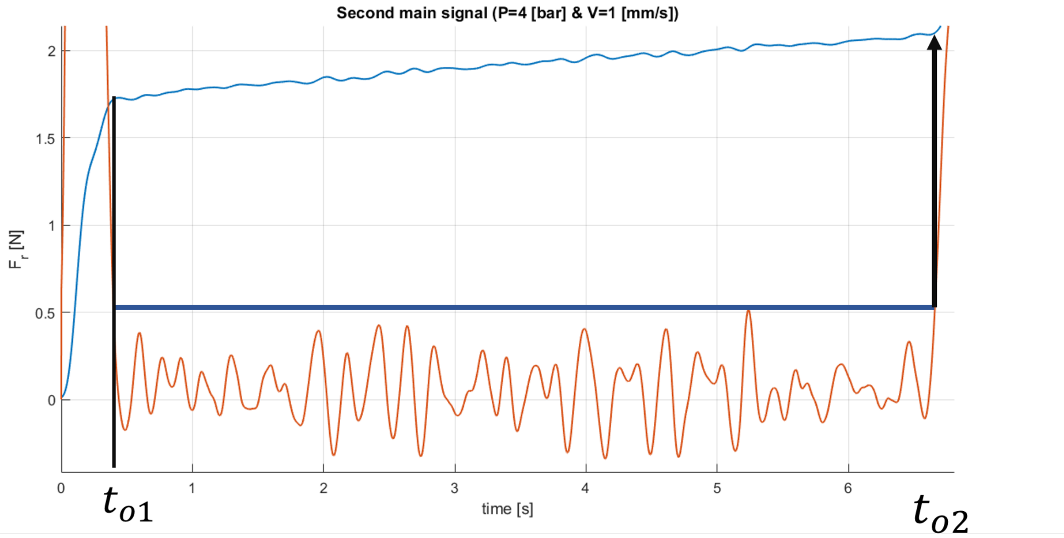


Figure 5.15: The Second Range Part

Working with the derivative signal, is highlighted the peaks and it has chosen the highest, its value define the range, when the signal overcome that range value is registered and saved it in a variable that will be called t_{o2}. Subsequent of this another simulation in Simulink is started, but put in the start time simulation t_{o1} and the final simulation time it put t_{o2}.

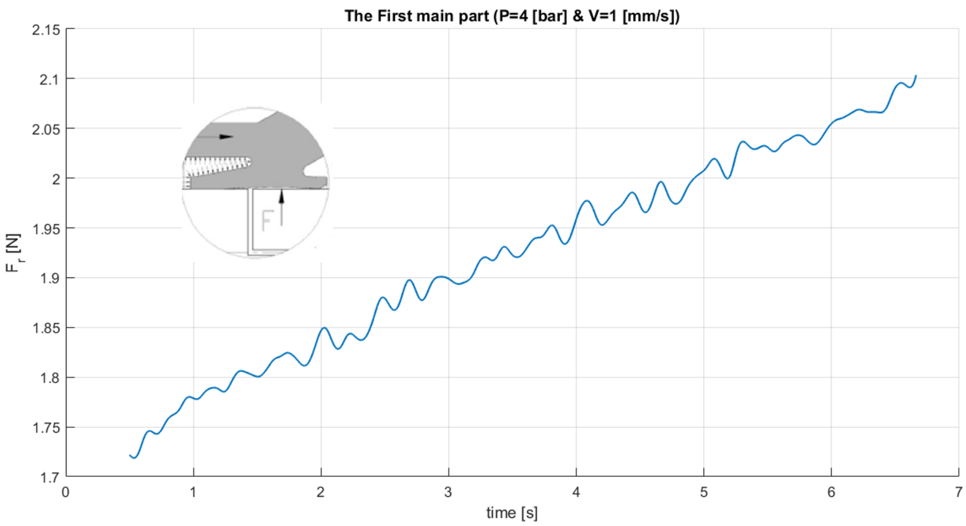


Figure 5.16: The Second Part

As showing in the figure 5.16 a small increasing is notated, this is occurs because it is in the seal center that has a small curvature which avoid the contact between the seal and the rod. But in the second lip, is pressurized and tends to push the lip against the rod, and this explain the slight increase.

5.3.3.3 The Third part

Similarly as the previous steps, it will be definite the third part of the main signal, it began using the simulink blocks, the most important were IF and the Max value, it put the range between 8,5 and 9, this range obviously depend of each test hence is different in any case. The block return the max values,then in Matlab environment Using a "for" cycle and "if" cycle, is possible to reached with the time value t_{o3} and t_{o4}. As shown in the graph:

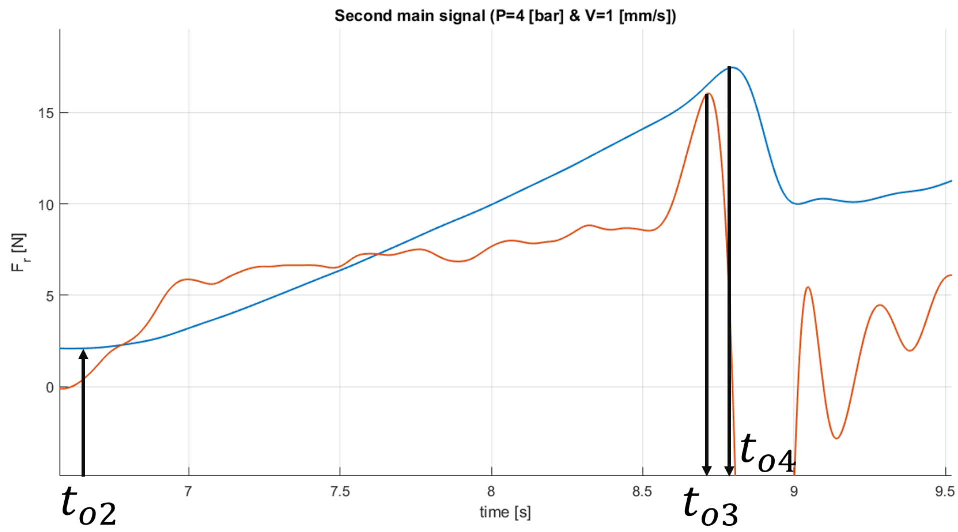


Figure 5.17: The Third range

Successively taking the t_{o4} and begin another simulation in Simulink putting in the start simulation time t_{o2} and in the final simulation time t_{o4}, with this define it can launch the entire simulation, and the third signal that it will be obtained, is as Follow:

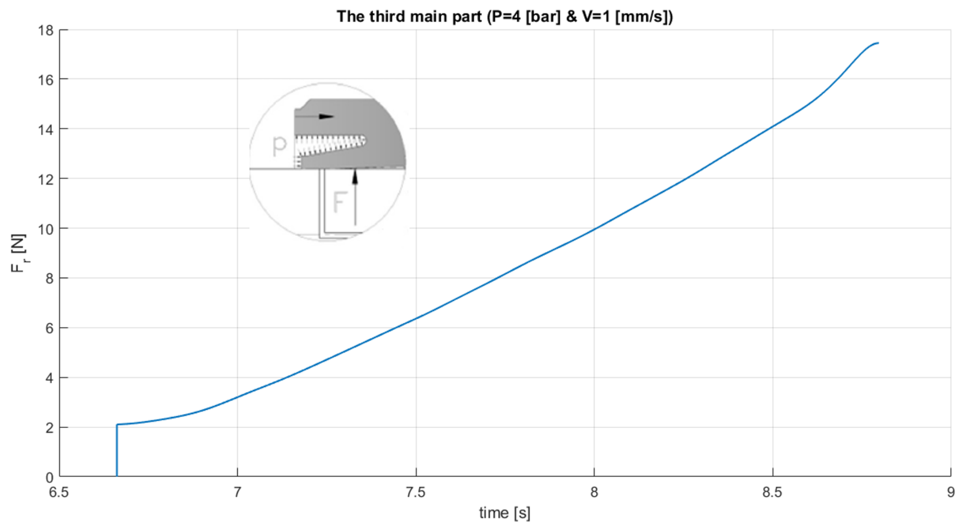


Figure 5.18: The Third Part

As evidenced in the figure 5.18 is the part that present the highest increase of the three parts, and is evident because there is an extra pressure from the second lip, furthermore the pressure from the supply line represent an extra pressure in the system and this is translates into an high increase of the contact pressure from the seal against to the rod.

5.4 The polynomial fitted

It will be developed the way to obtain the Polynomial fitted in order to obtain a smooth signal as much as possible. In the Matlab Library is present the function: **polyfit (x-value,y-value, Polynomial order)** which return the values of the polynomial coefficients. There is another function in Matlab that allows to evaluate the Polynomial, its name is: **polyval(p,x-value)** and return the vector that contains the y-values of the polynomial fitted.

Following the previous ideas Matlab has done the three polynomial of the each part in order to fitted the main signal, the Polynomial graphs shown:

5.4.1 First part fitted

6-degree Polynomials in the first parts were used to fit the signal.

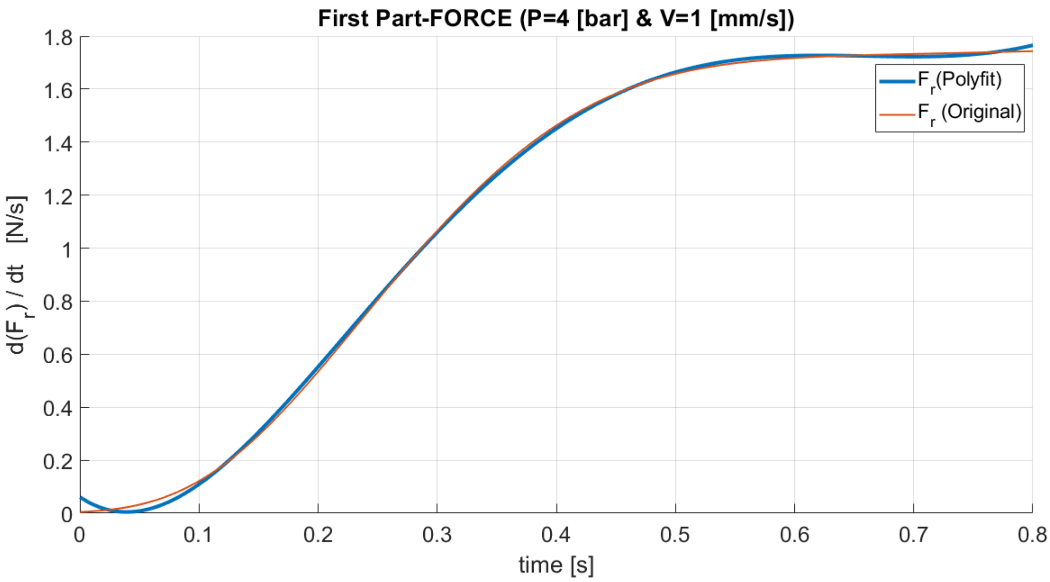


Figure 5.19: First Polynomial Fitted

As it can see in the figure 5.19 the polynomial fitted is well.It Tends to follow the first signal and has a coefficient of determination $r^2 = 0,999$, it could be conclude that the variance of the dependent variable is predictable in the range in where is the first-main part. The Polynomial equation is the following:

$$p_1(x) = -25,59 \cdot x^5 - 88,15 \cdot x^4 - 101,68 \cdot x^3 + 44,49 \cdot x^2 - 3,0424 \cdot x + 0,0614$$

5.4.2 Second part fitted

1-Degree Polynomials were used in order to obtain the fit in this section because analysing the force signal acquired in the laboratory, the slight increase that has the signal it could be highlighted as a line.

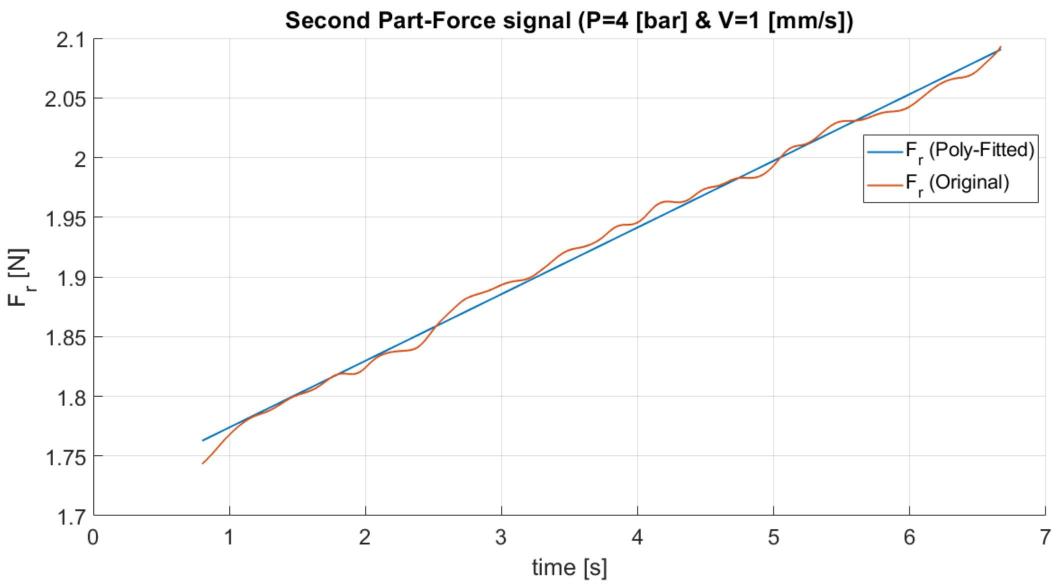


Figure 5.20: Second Polynomial Fitted

The 1-degree polynomial has a coefficient of determination $r^2 = 0,9985$. As a result the line that fit the signal it could be used to smooth it.The equation of the line is:

$$p_2(x) = 0.0559 \cdot x + 1,718$$

5.4.3 Third part fitted

6-Degree Polynomials were used in this subsection. But firstly it is necessary to explain this part because is used another procedure in order to obtain the Polynomial. Using as reference the figure 5.17, the signal is stopped at time t_{o4} because is the point in where the contact pressure in the seal is negative and that part does not have sense. Stopping the simulation in the maximum value of the force signal and proceeding to make the fit, in the ending part the polynomial tends to give some errors. Then, it was solved extending the force signal some milliseconds more in order to have more information and the Polyfit did not make mistakes and have a better behaviour.

As can be seen in the fig. 5.21 the blue polynomial function continues fitted until a specific time. The coefficient of correlation value is $r^2 = 0,9986$, then the Polyfit is a good way to represent the signal. The equation of the polynomial:

$$p_3(x) = -2,94 \cdot x^6 - 114,39 \cdot x^4 - 1776 \cdot x^3 + 1367,4 \cdot x^2 - 5323,4 \cdot x + 8220,2$$

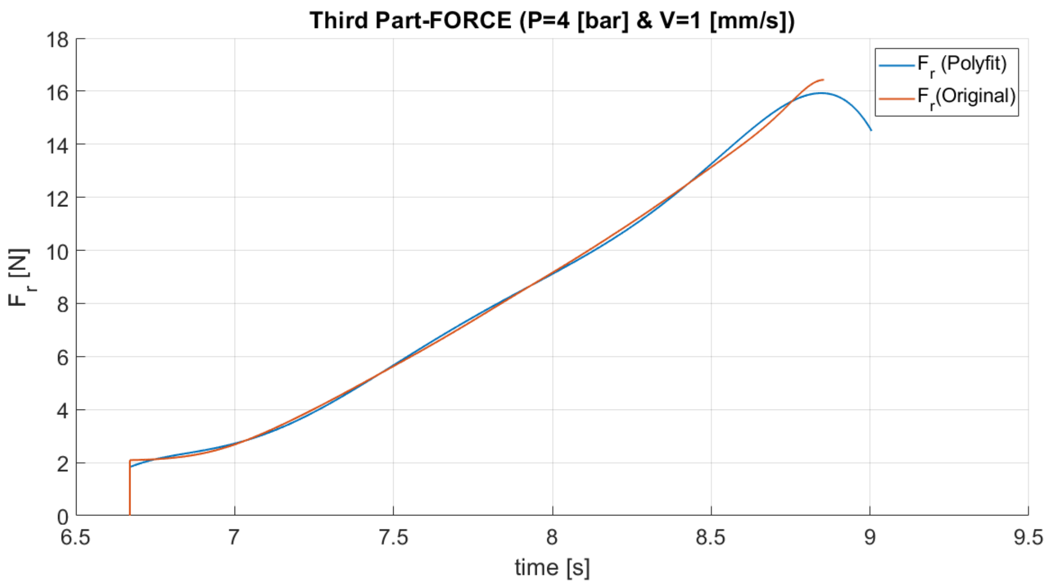


Figure 5.21: Third Polynomial Fitted

5.4.4 Main signal Poly-fitted

At the moment it has three polynomials that combined represent the phenomenon, this union is done through of **for,if Matlab cycle** and it can obtain the follow figure:

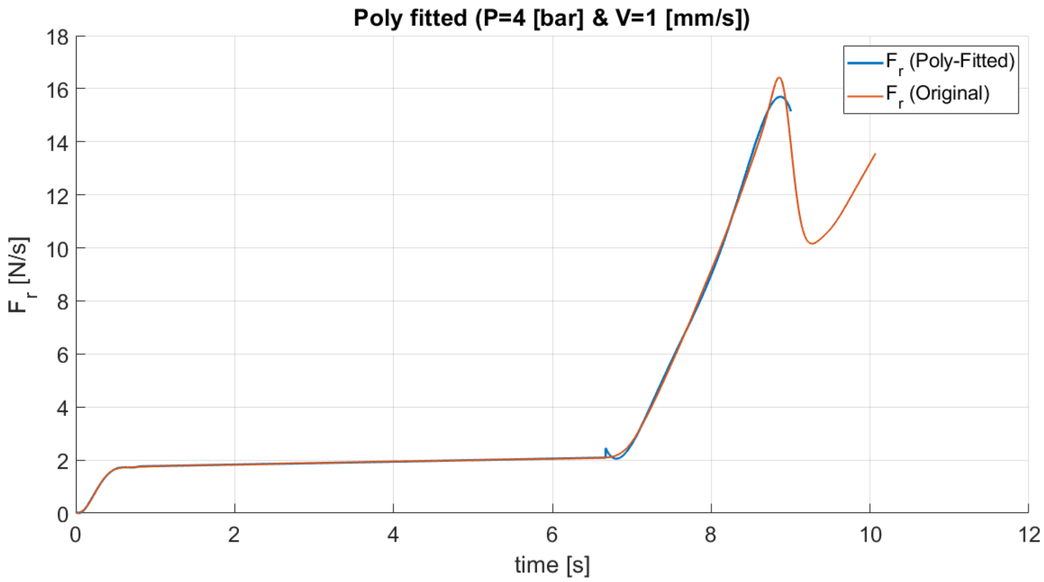


Figure 5.22: Polynomial Signal Fitted

The first and the second part were well fitted because the two signal are overlapped, the third one also is well fitted but nevertheless is highlighted that there are parts that stand out of the tends line. In general terms, the polynomial fitted is a well way to represent the phenomenon. As can be seen:

5.4.5 Derived Main Force Signal

In where the problematic that can be seen in the figure 5.23 and it is, the continuity of the main polynomial signal, an outstanding part at the beginning of the third one because the join between

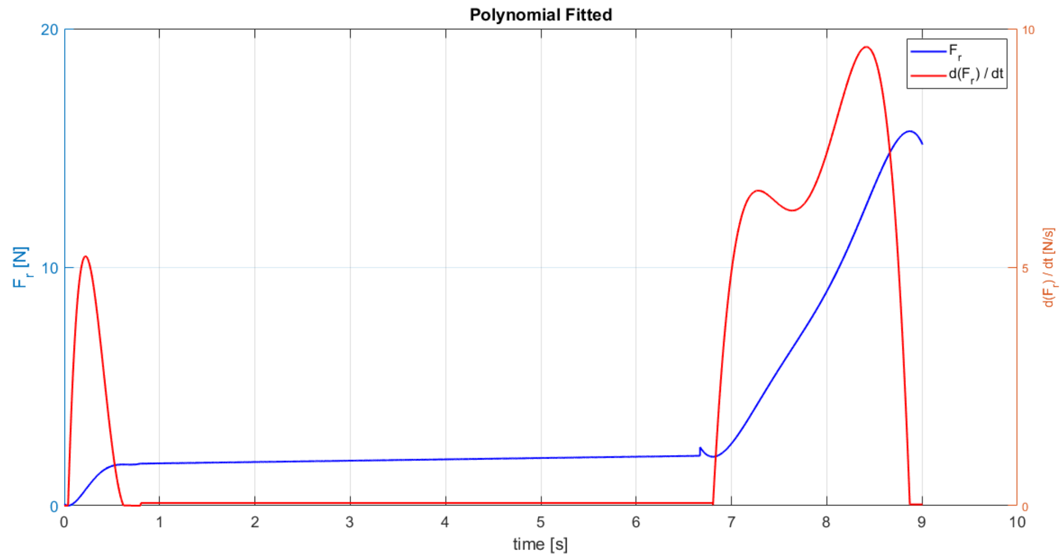


Figure 5.23: The Main fitted Phenomenon

the second one and the third one there is a gap, when derived, represent a step and its value tends to the infinity ($\rightarrow \infty$), hence a condition was put in order to have a continuity signal without peak that was the first condition. Then in the derived signal could has values of 0 for this reason. And at the end of the contact pressure signal there will be a zeros value and this was explained in the subsection third part fitted.

5.4.6 Polynomial Contact Pressure

It will be posted the contact pressure calculated by the polynomial fitted main force signal. Calculated by the equation 3.1:

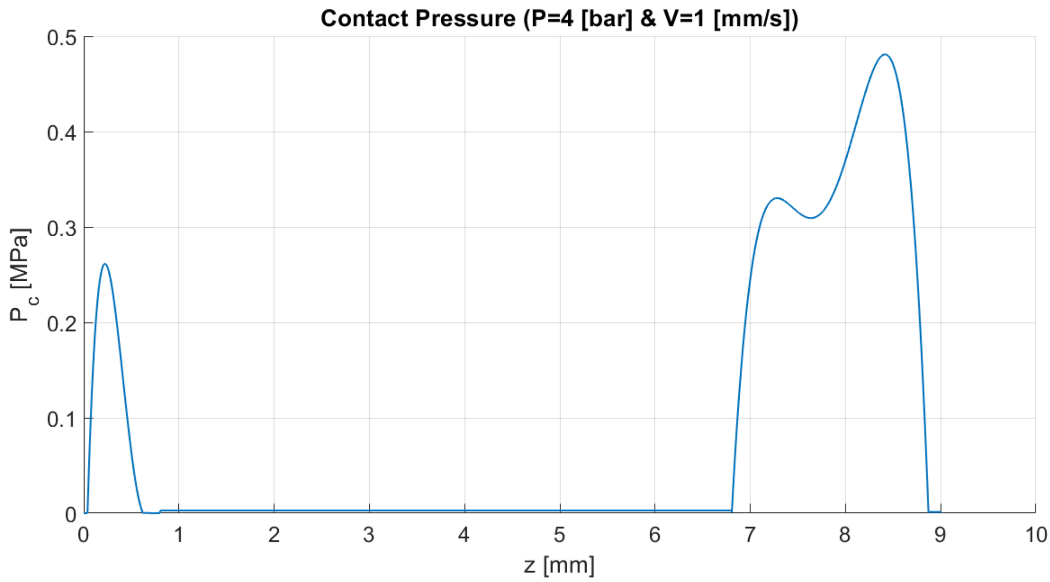


Figure 5.24: Poly-fit Contact Pressure

The figure 5.24 is the aim of this thesis. This is the contact pressure that can suffer the seal along the rod with a conditions seeing in the heading of the graph. This will be calculated for several conditions posted in the table 5.5.

5.5 The Spline fitted

Motivated of the Polynomial fitted problematic that was the continuity, is explored another way in order to obtain a smooth signal. It is well known that if it has continuity in the derived function, it will be continuity in the integrated function therefore it will be fitted it with the spline method .

The spline interpolation is a special type of piecewise polynomial, is used because avoid the Runge's phenomenon. That is a problem of oscillation at the edges of an intervals with polynomials of high degree.

Then in the library of Matlab is present this function Spline, in where it puts the x-axis and y-axis points and the x-vector in where the spline it will be the spline interpolation called query points. Between any points that it were chosen a cubic polynomial is used to fitted the signal using this function.

The main signal is derived and divided in three parts, the different graphs are shown as follow:

5.5.1 First part derived signal spline

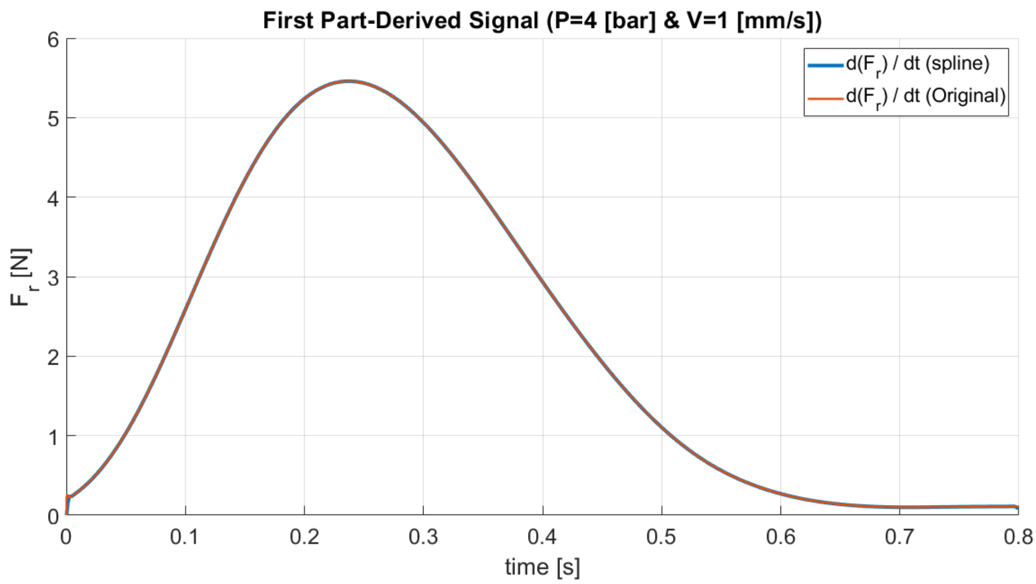


Figure 5.25: First part derived-Spline fitted

In the figure **??** it is not highlighted the red one because the blue one is more width and those graph are overlapped. Then the spline fitted tends to follow the graphs.

5.5.2 Second part derived-signal spline

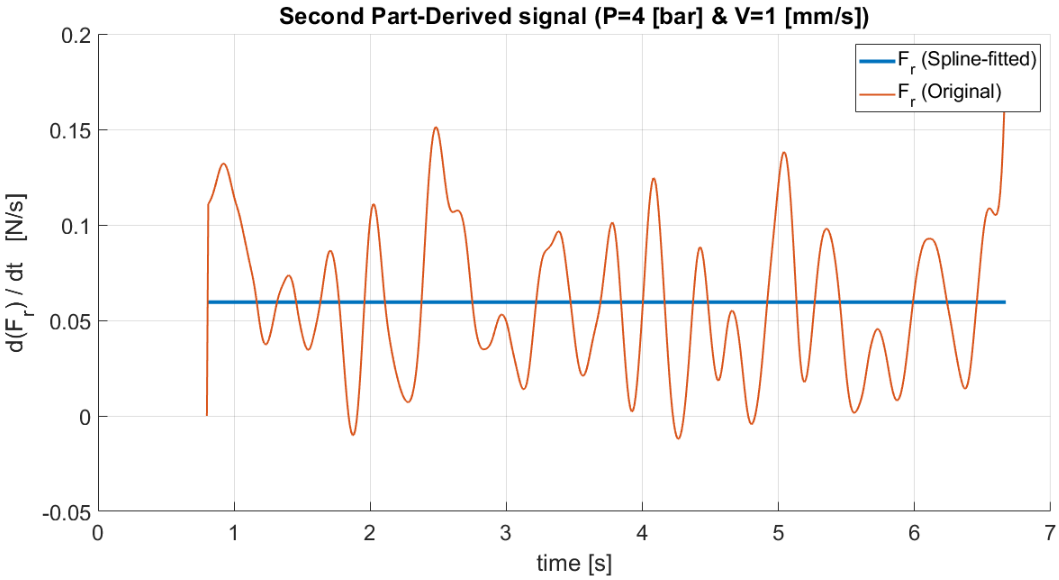


Figure 5.26: Second part derived-Spline fitted

There is more noise in this graph but in general terms that part is a constant line or polynomials of degree 0, because its integer part is a line that have slight-increase.

5.5.3 Third part derived-signal spline

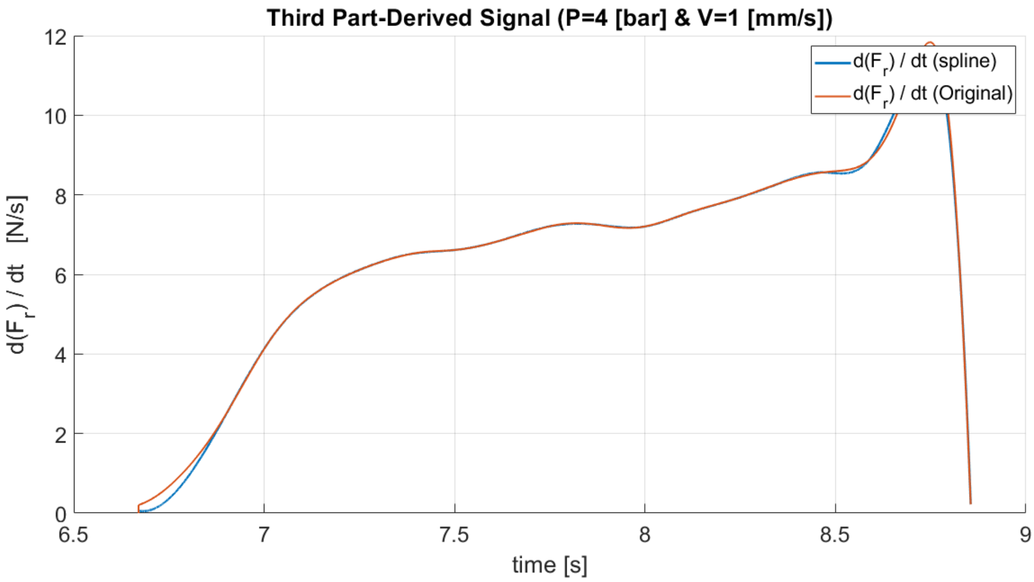


Figure 5.27: Third part derived-Spline fitted

5.5.4 Main signal Spline-fitted

Following the same idea that in Polynomial-fitted signal, these three ”signals spline-fitted” should be united.

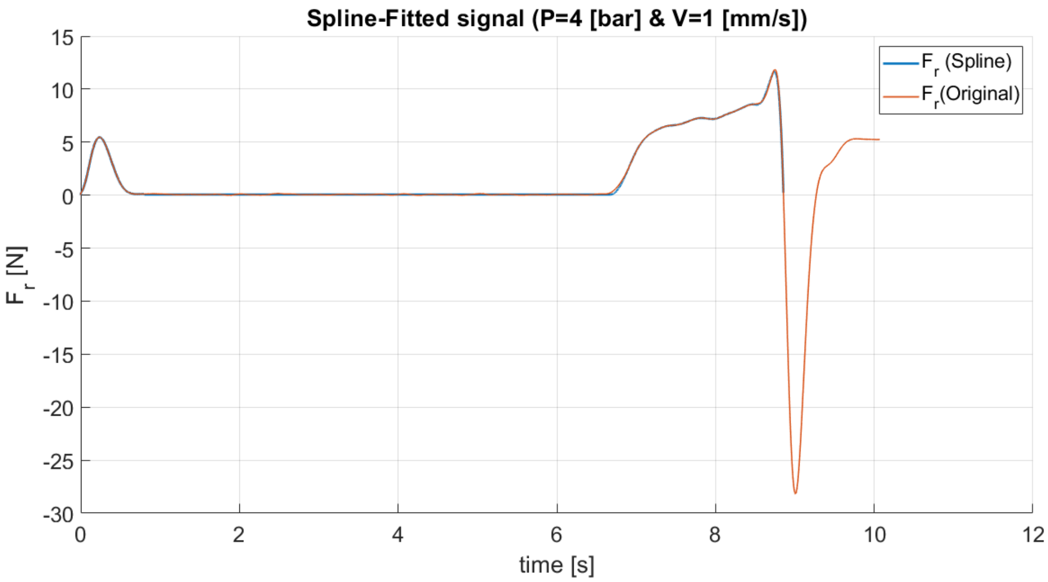


Figure 5.28: Spline-fitted Signal

Then in order to obtain the force signal, this value are integrated as follow:

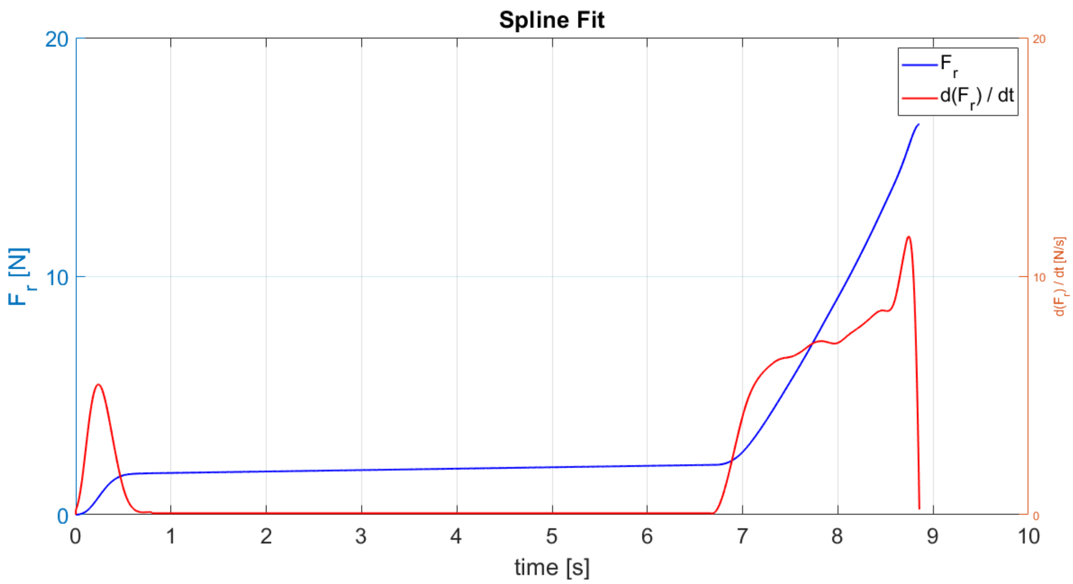


Figure 5.29: Spline-fitted Force Signal

Practically is the same original function except for the second part that was fitted by a line.

5.5.5 Pressure Contact Spline-fitted

Following the same Idea of the Polynomial-fitted and using the same equation 3.1 it is obtained the following figure:

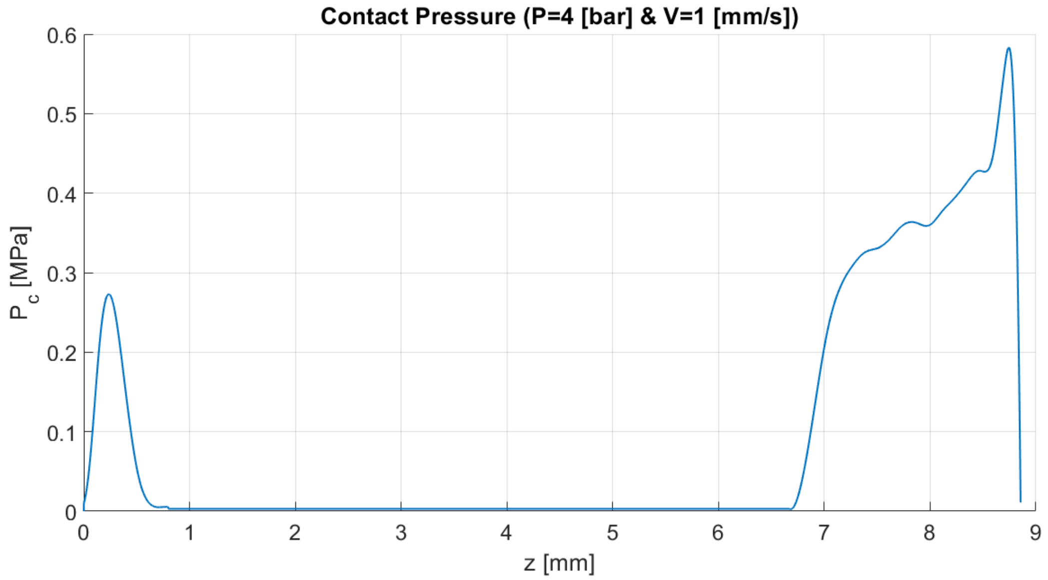


Figure 5.30: Spline-fitted Contact Pressure

The figure 5.30 is similar to the original derived force signal because the spline interpolation tends to overlapped the signal.

5.6 Polynomial interpolation vs Spline Interpolation

It will be developed a comparison between the two method used in this thesis, firstly of all it starts graphing the two signals in the same graph. Seeing the figure ?? it can be highlighted that the two

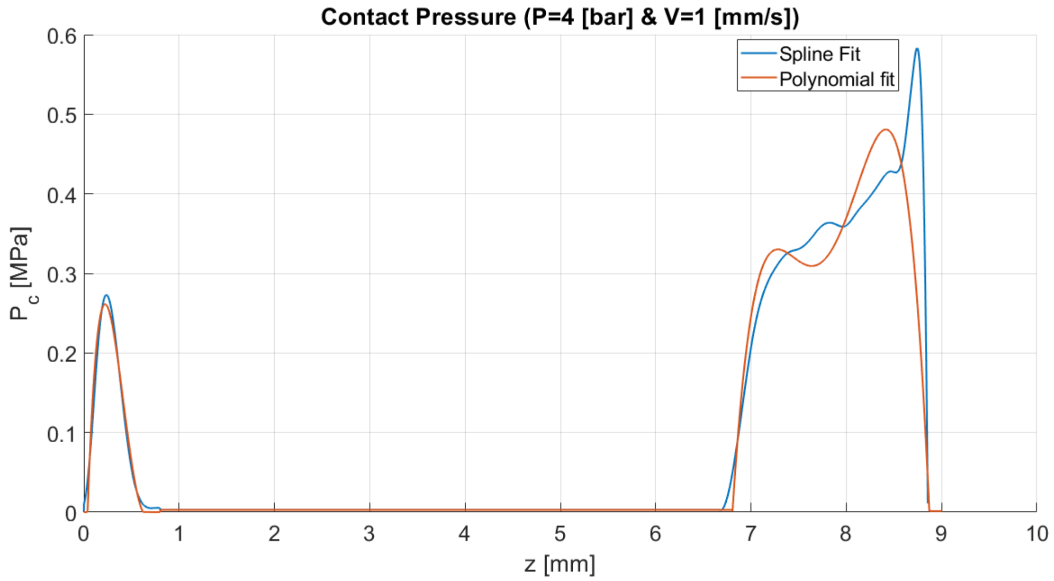


Figure 5.31: Contact Pressure Comparison

signals have more or less the same slope, almost arriving at the same pressure point a decreased at the same slope. In the second part there is not difference between the two interpolation. In the third part there is more difference, starting with polynomial fit is well known while the degree-polynomial increase the Runge's Phenomenon becomes more pronounced and the error also increase. The physical error is approximately to 0.1 [MPa]. But in short intervals time is difficult to well approximated the signal. But in general term the two signal at least have the same slope.

Chapter 6

Results

In this chapter, they will be posted the different tests were done in the laboratory. And will be divided into three sub-chapters in where there will be the Polynomial-fit, Spline-fit and varying the day. The last one is developed in order to understand what happen if the same prove that are done in different days with the same steps to start the test have difference between them.

6.1 Test done varying the Pressure and the Velocity

In this subsection it will be posted the Results obtained in the all test:

6.1.1 P=0[bar] V=1[mm/s]

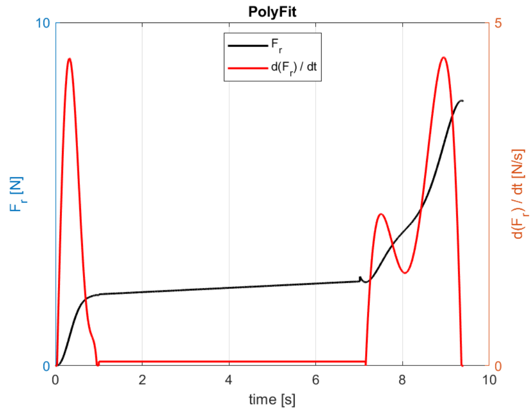


Figure 6.1: Poly-fit P=0[bar] V=1[mm/s]

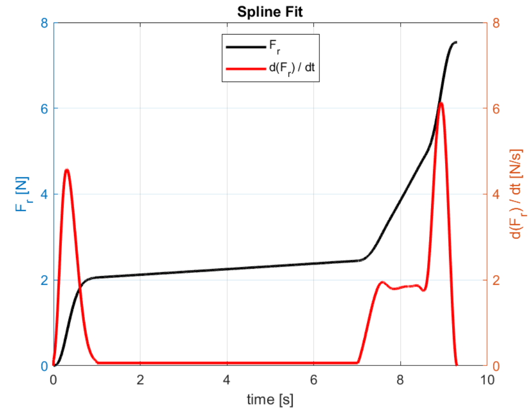


Figure 6.2: Spline-fit P=0[bar] V=1[mm/s]

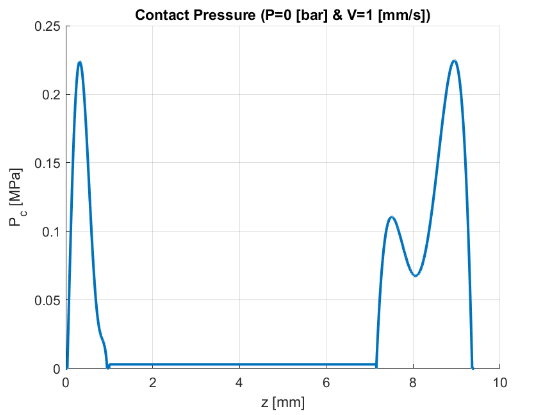


Figure 6.3: Poly-fit Contact Pressure P=0[bar] V=1[mm/s]

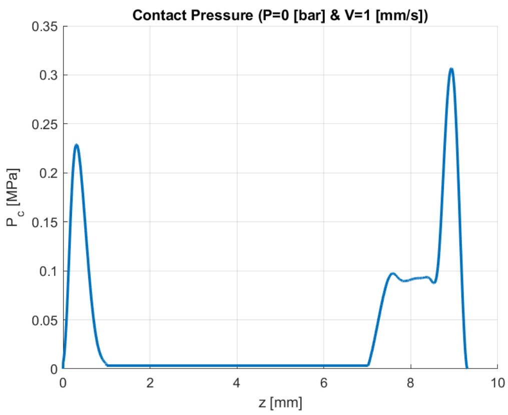


Figure 6.4: Spline-fit Contact Pressure P=0[bar] V=1[mm/s]

6.1.2 P=2[bar] V=1[mm/s]

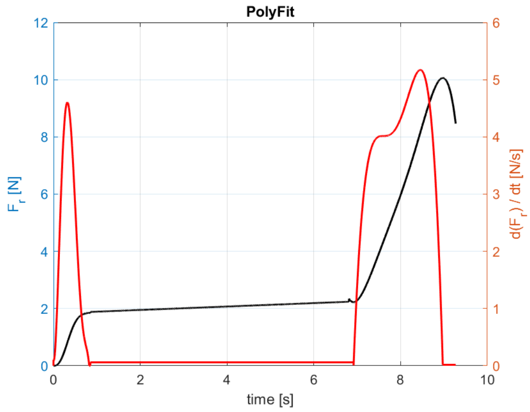


Figure 6.5: Poly-fit P=2[bar] V=1[mm/s]

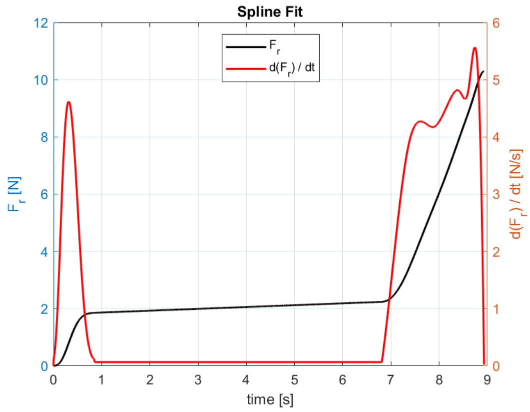


Figure 6.6: Spline-fit P=2[bar] V=1[mm/s]

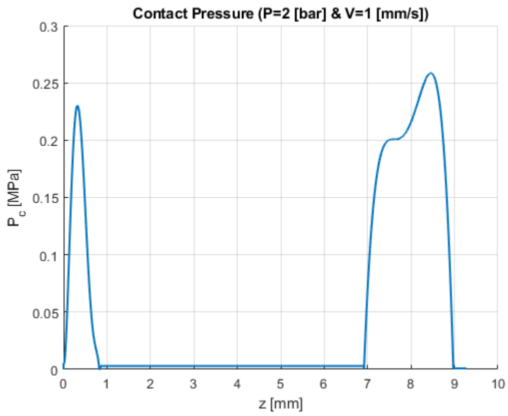


Figure 6.7: Poly-fit Contact Pressure P=2[bar] V=1[mm/s]

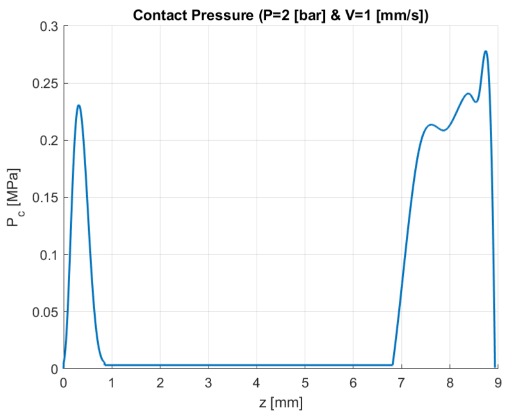


Figure 6.8: Spline-fit Contact Pressure P=2[bar] V=1[mm/s]

6.1.3 P=4[bar] V=1[mm/s]

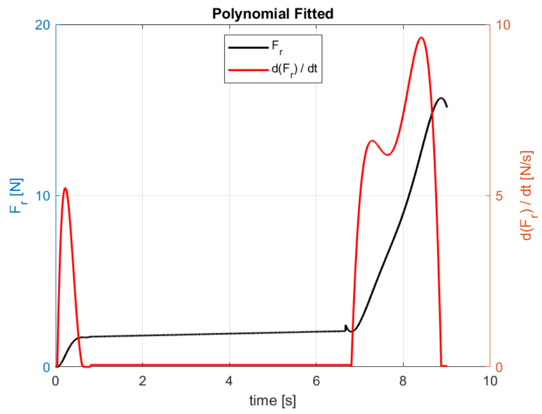


Figure 6.9: Poly-fit P=4[bar] V=1[mm/s]

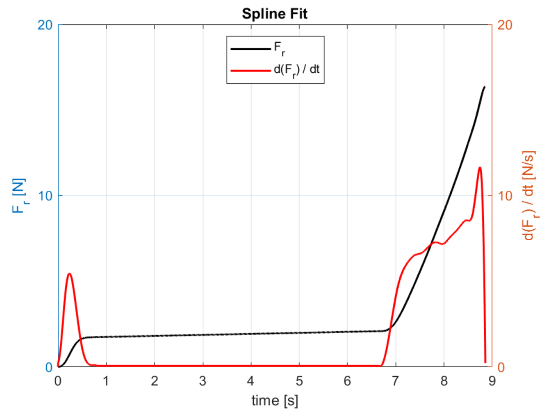


Figure 6.10: Spline-fit P=4[bar] V=1[mm/s]

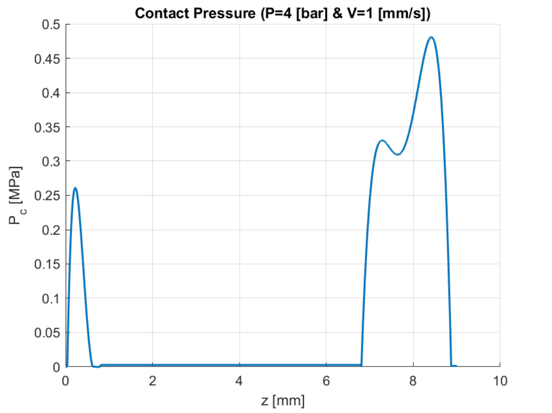


Figure 6.11: Poly-fit Contact Pressure P=4[bar] V=1[mm/s]

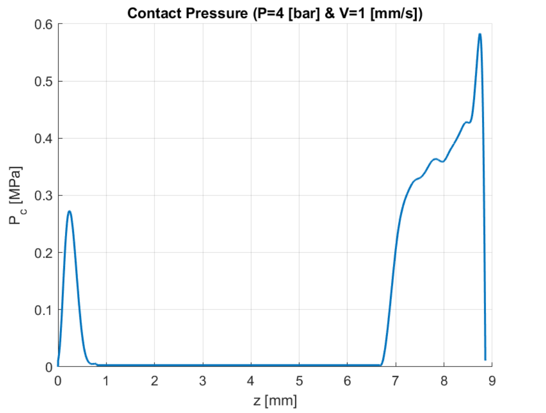


Figure 6.12: Spline-fit Contact Pressure P=4[bar] V=1[mm/s]

6.1.4 P=6[bar] V=1[mm/s]

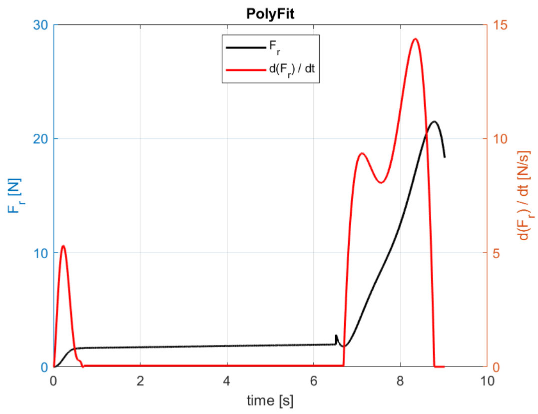


Figure 6.13: Poly-fit P=6[bar] V=1[mm/s]

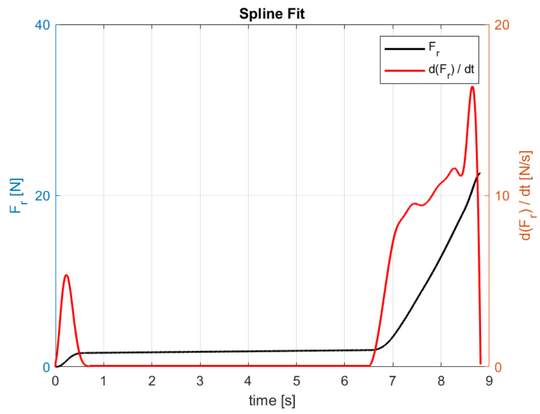


Figure 6.14: Spline-fit P=6[bar] V=1[mm/s]

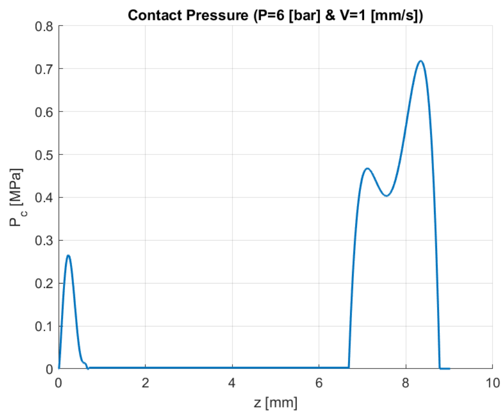


Figure 6.15: Poly-fit Contact Pressure P=6[bar] V=1[mm/s]

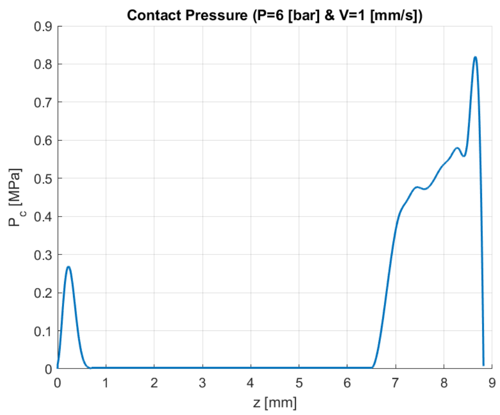


Figure 6.16: Spline-fit Contact Pressure P=6[bar] V=1[mm/s]

6.1.5 P=6[bar] V=5[mm/s]

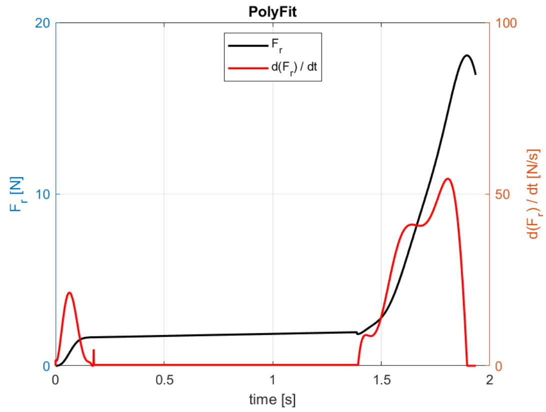


Figure 6.17: Poly-fit P=6[bar] V=5[mm/s]

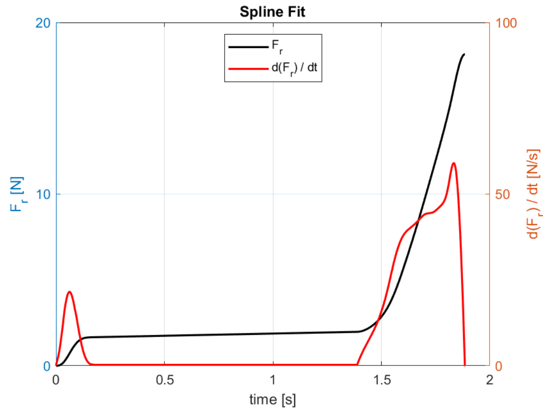


Figure 6.18: Spline-fit P=6[bar] V=5[mm/s]

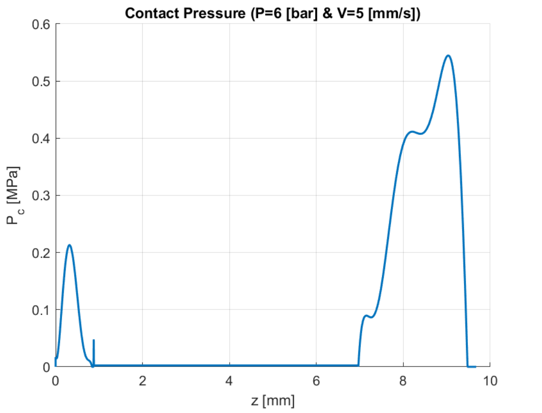


Figure 6.19: Poly-fit Contact Pressure P=6[bar] V=5[mm/s]

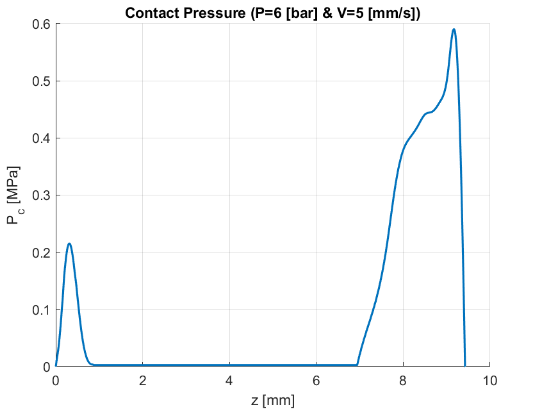


Figure 6.20: Spline-fit Contact Pressure P=6[bar] V=5[mm/s]

6.1.6 P=6[bar] V=10[mm/s]

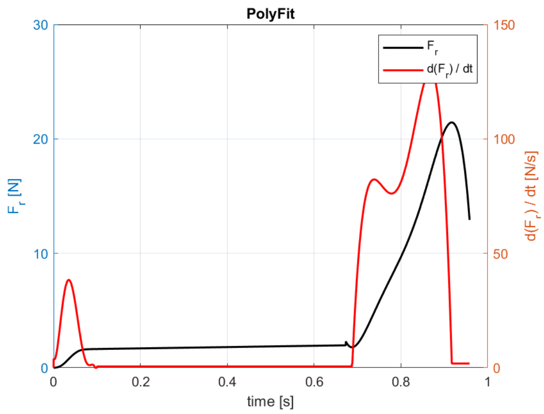


Figure 6.21: Poly-fit P=6[bar] V=10[mm/s]

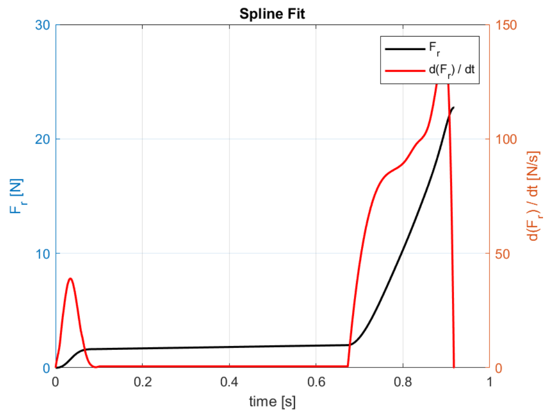


Figure 6.22: Spline-fit P=6[bar] V=10[mm/s]

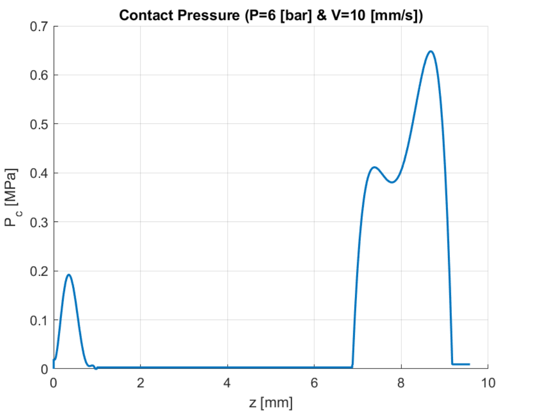


Figure 6.23: Poly-fit Contact Pressure P=6[bar] V=10[mm/s]

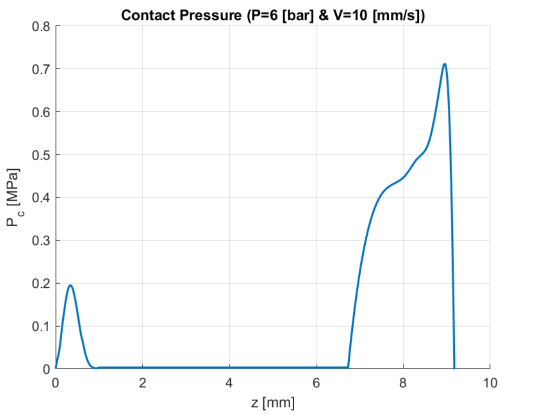


Figure 6.24: Spline-fit Contact Pressure P=6[bar] V=10[mm/s]

6.1.7 P=6[bar] V=50[mm/s]

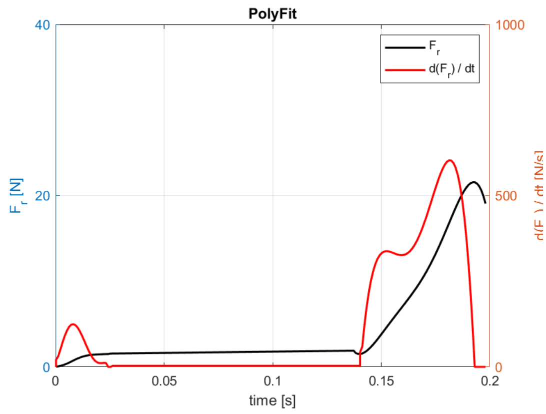


Figure 6.25: Poly-fit P=6[bar] V=50[mm/s]

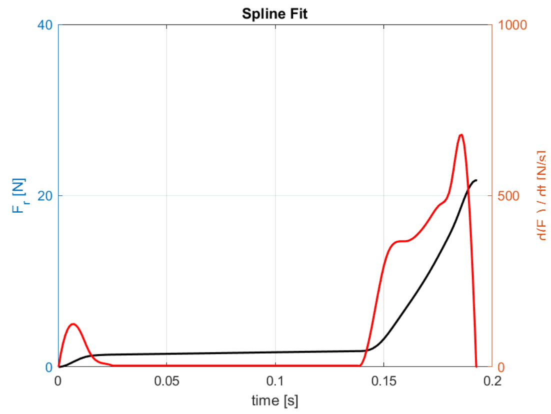


Figure 6.26: Spline-fit P=6[bar] V=50[mm/s]

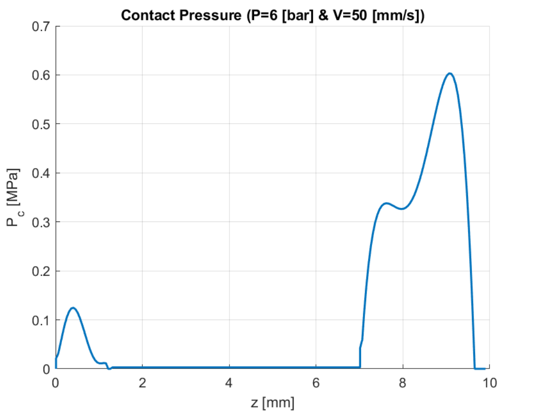


Figure 6.27: Poly-fit Contact Pressure P=6[bar] V=50[mm/s]

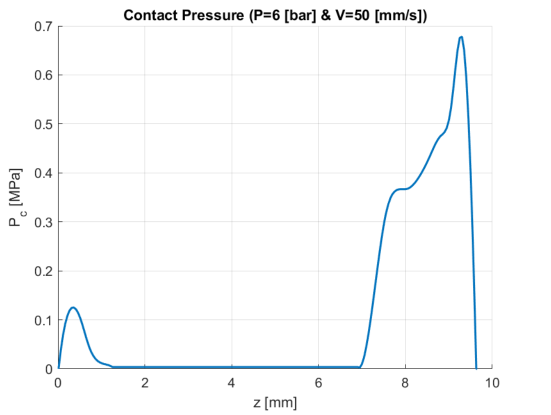


Figure 6.28: Spline-fit Contact Pressure P=6[bar] V=50[mm/s]

6.1.8 P=6[bar] V=100[mm/s]

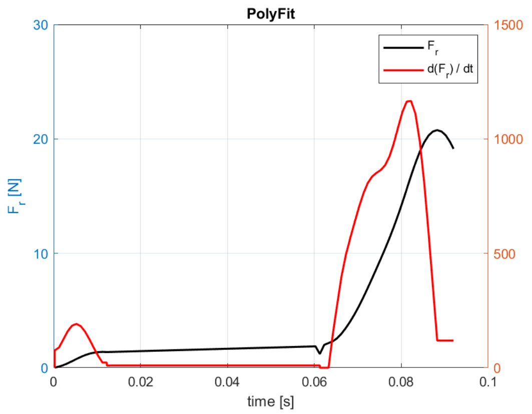


Figure 6.29: Poly-fit P=6[bar] V=100[mm/s]

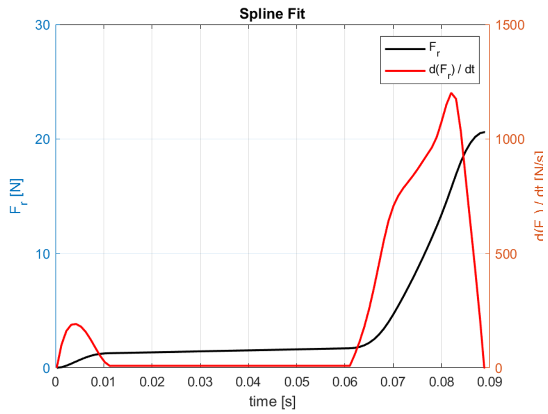


Figure 6.30: Spline-fit P=6[bar] V=100[mm/s]

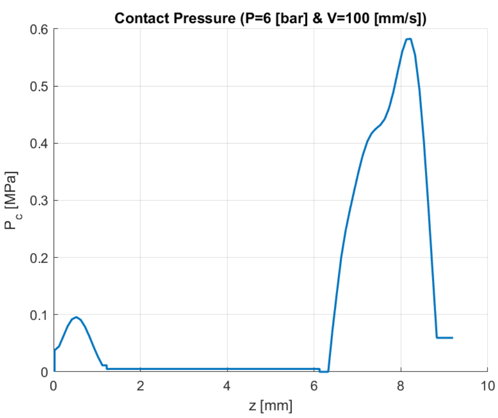


Figure 6.31: Poly-fit Contact Pressure P=6[bar] V=100[mm/s]

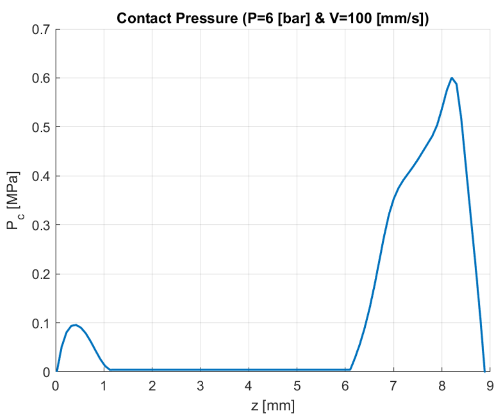


Figure 6.32: Spline-fit Contact Pressure P=6[bar] V=100[mm/s]

6.1.9 Constant Pressure and Varying Velocity

In this section will be attached the test in a same graph in order to understand what is change between the proves.

6.1.9.1 Polynomial-fit

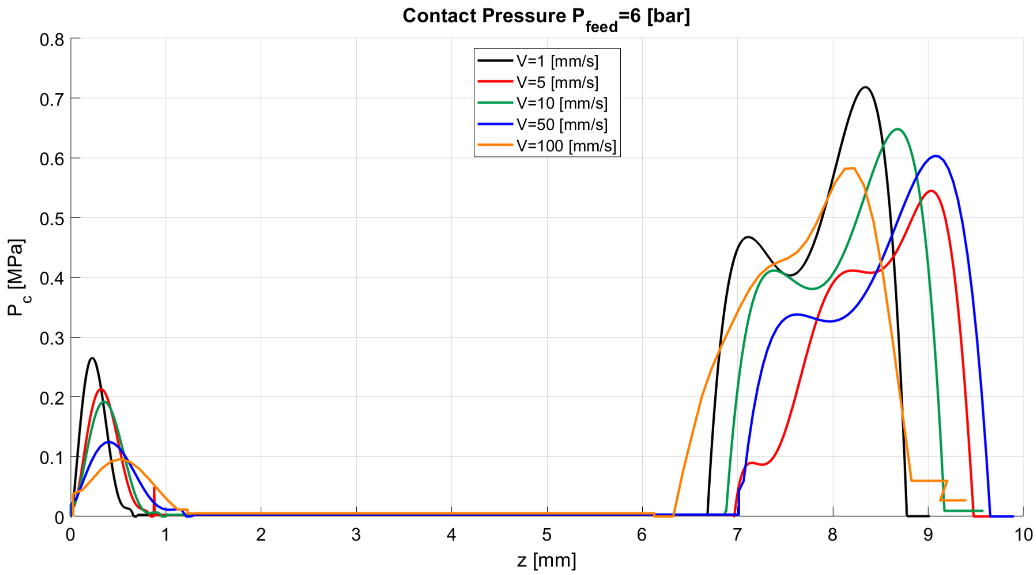


Figure 6.33: $P_{feed} = 6[bar]$ Varying the Seal Velocity

6.1.9.2 Spline-fit

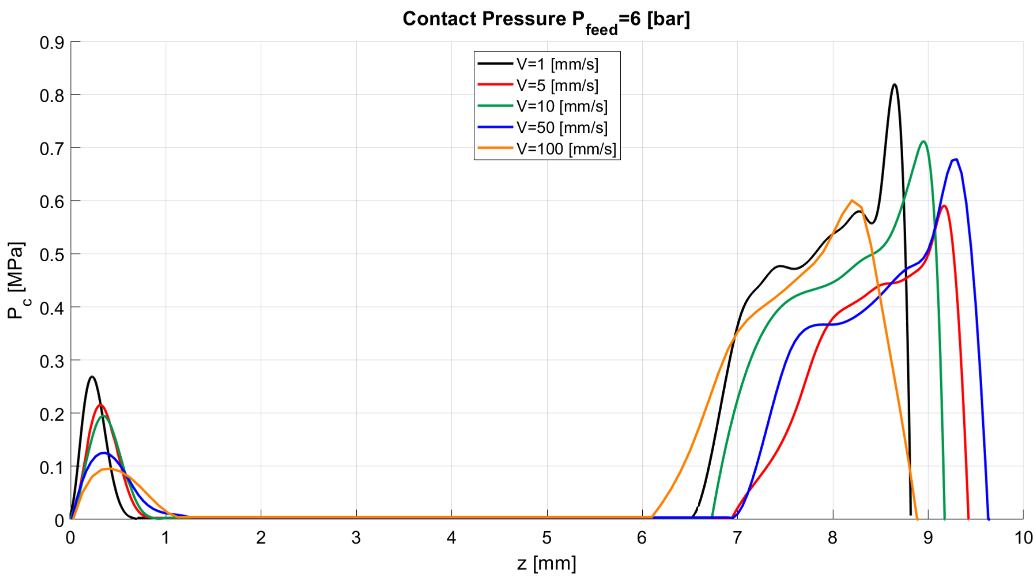


Figure 6.34: $P_{feed} = 6[bar]$ Varying the Seal Velocity

6.1.10 Constant Velocity and Varying the Pressure

6.1.10.1 Polynomial-fit

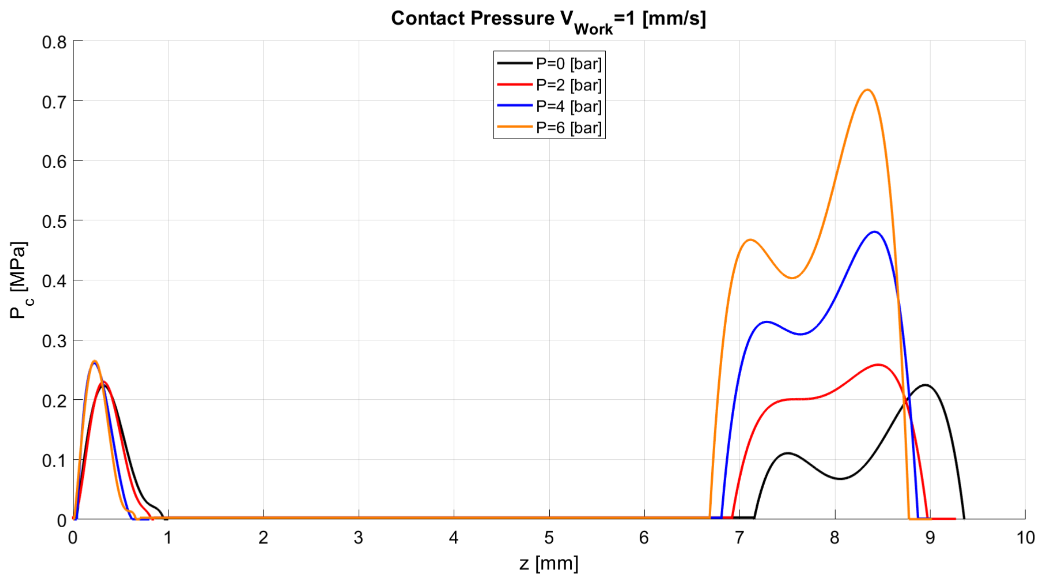


Figure 6.35: $P_{feed} = 6[bar]$ Varying the Seal Speed

6.1.10.2 Spline-fit

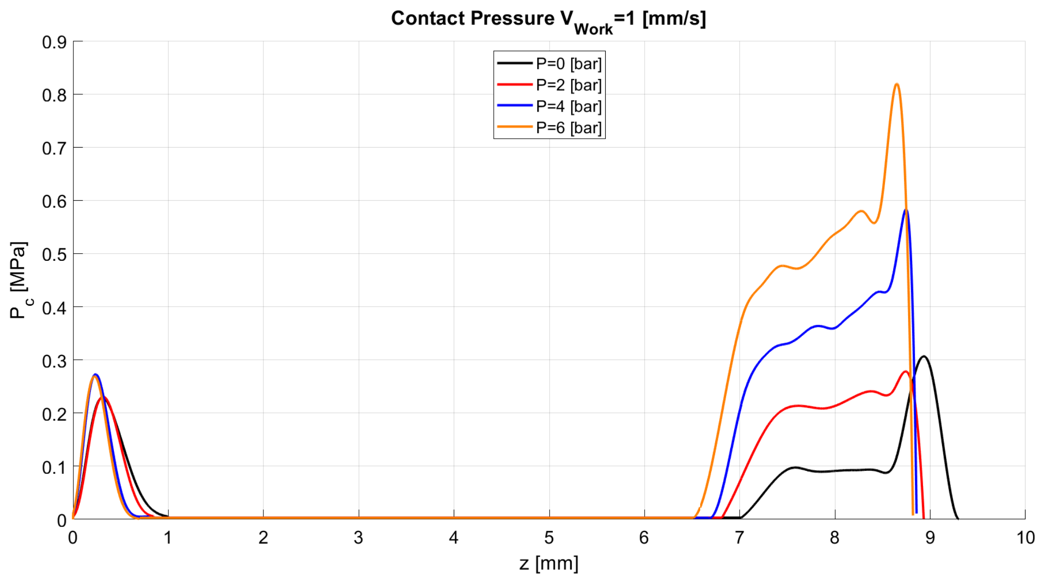


Figure 6.36: $P_{feed} = 6[bar]$ Varying the Seal Speed

6.2 Additional Tests

In this section will be exposed a complementary tests which were done in a different day in order to analyse how it would change in a time gap.

6.2.1 Constant Pressure and Varying the Velocity

6.2.1.1 Polynomial-fit

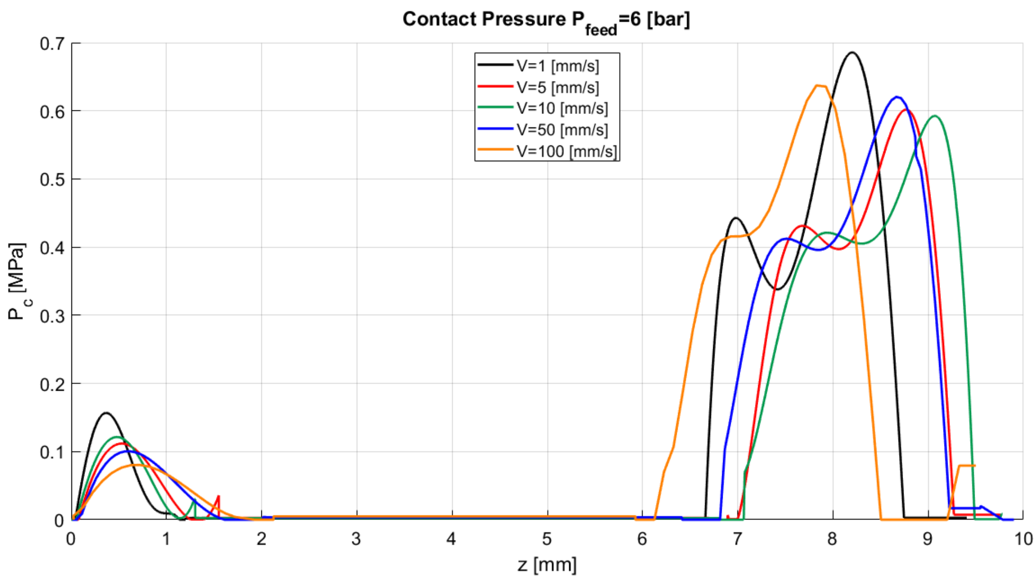


Figure 6.37: $P_{feed} = 6[bar]$ Varying the Seal Velocity additional test

6.2.1.2 Spline-fit

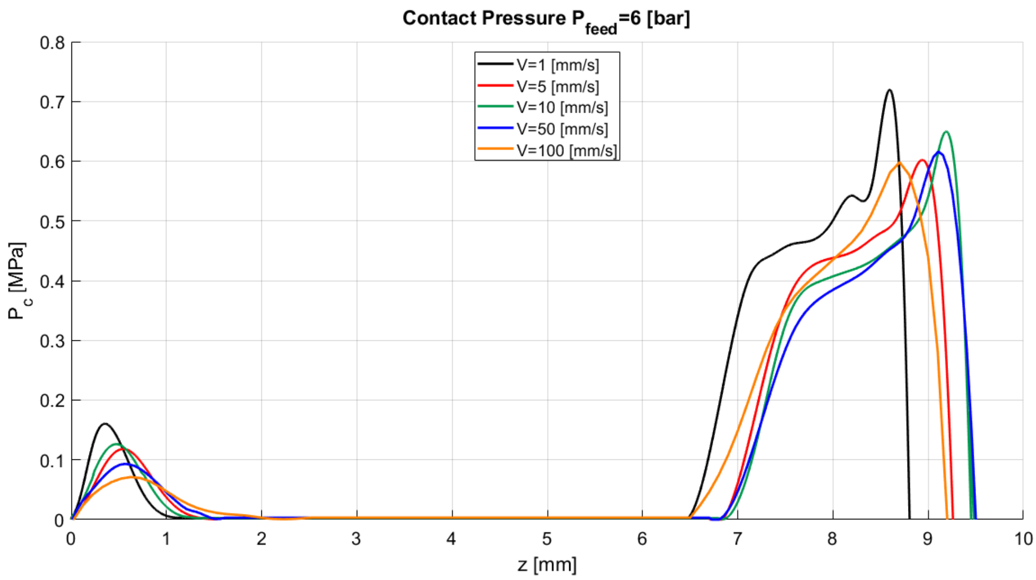


Figure 6.38: $P_{feed} = 6[bar]$ Varying the Seal Velocity additional test

6.2.2 Constant Velocity and Varying the Pressure

6.2.2.1 Polynomial-fit

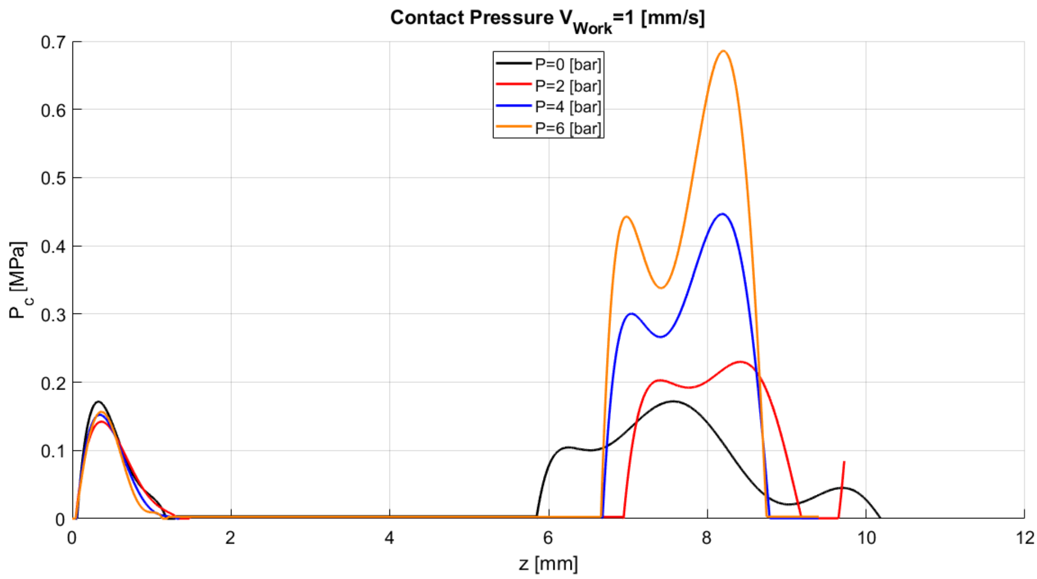


Figure 6.39: $P_{feed} = 6[bar]$ Varying the Seal Velocity additional test

6.2.2.2 Spline-fit

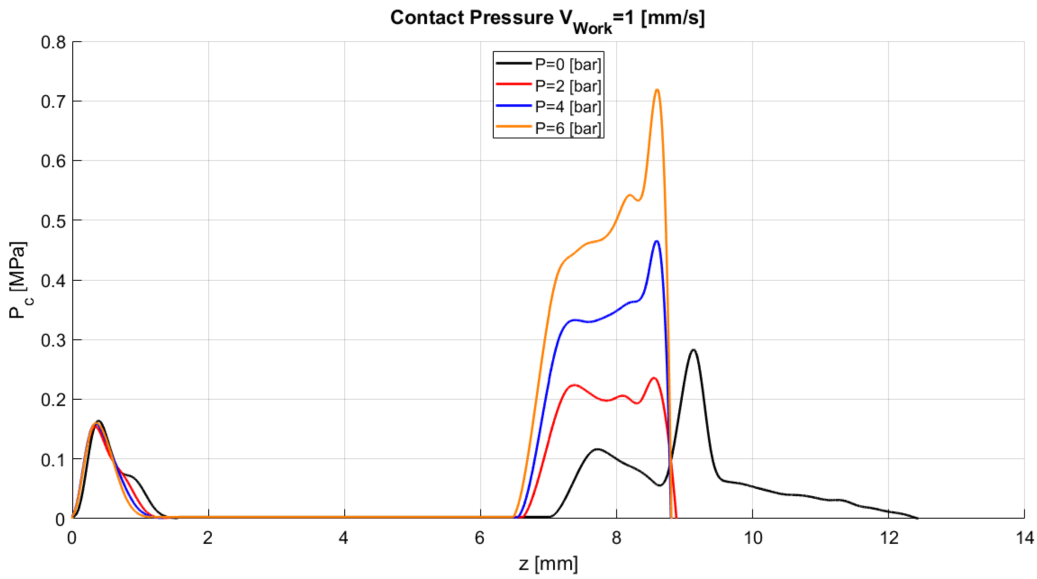


Figure 6.40: $P_{feed} = 6[bar]$ Varying the Seal Velocity additional test

6.3 Graphics Comparison

They will be taken three aleatory tests and plotted them in a single graphic.

6.3.1 P=2[bar] V=1[mm/s]

6.3.1.1 Polynomial-fit

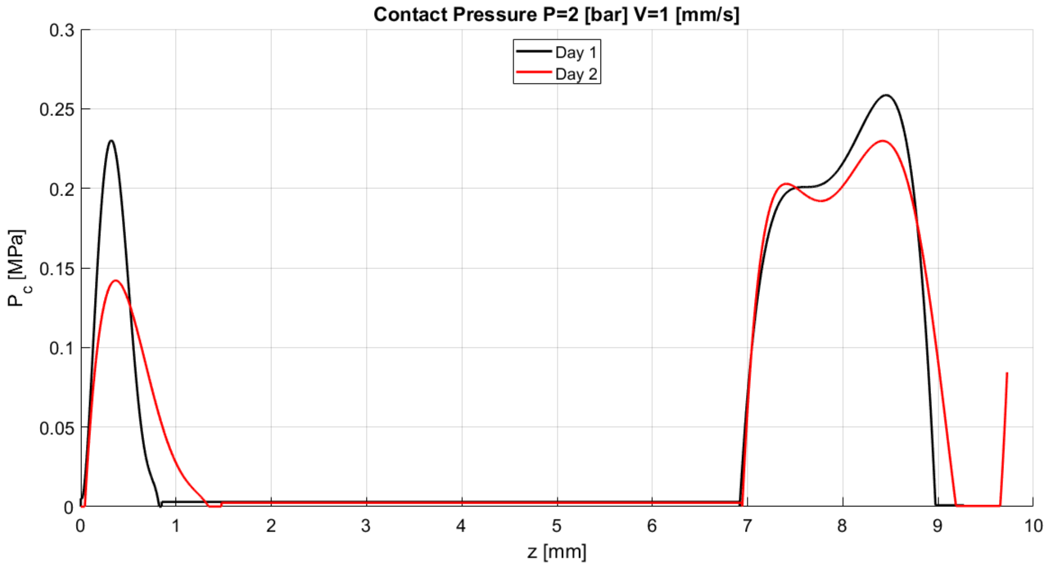


Figure 6.41: Comparison between the same test but that was done in a different days polynomial fitted

6.3.1.2 Spline-fit

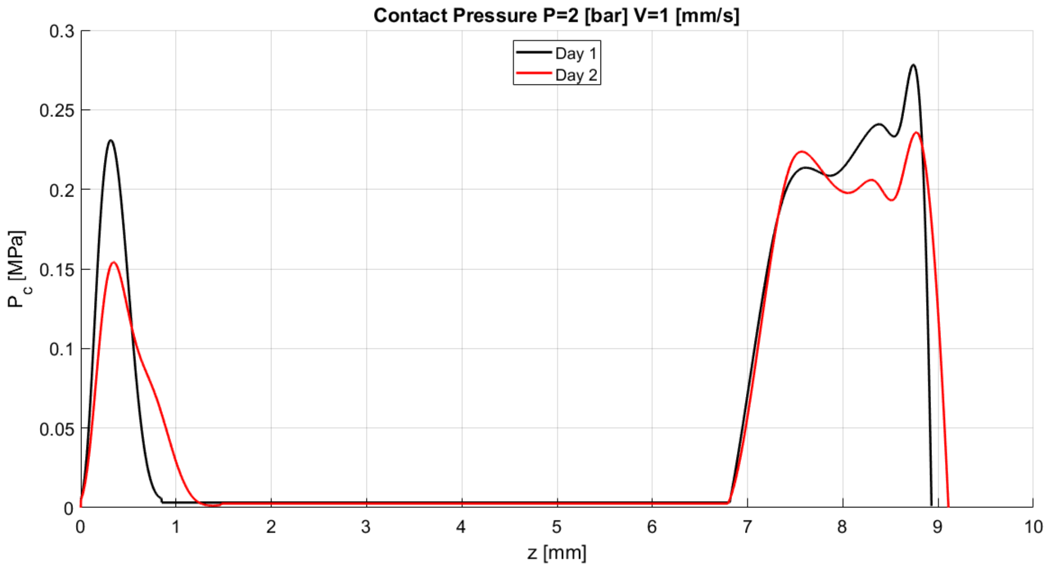


Figure 6.42: Comparison between the same test but that was done in a different days, Spline fitted

6.3.2 P=6[bar] V=1[mm/s]

6.3.2.1 Polynomial-fit

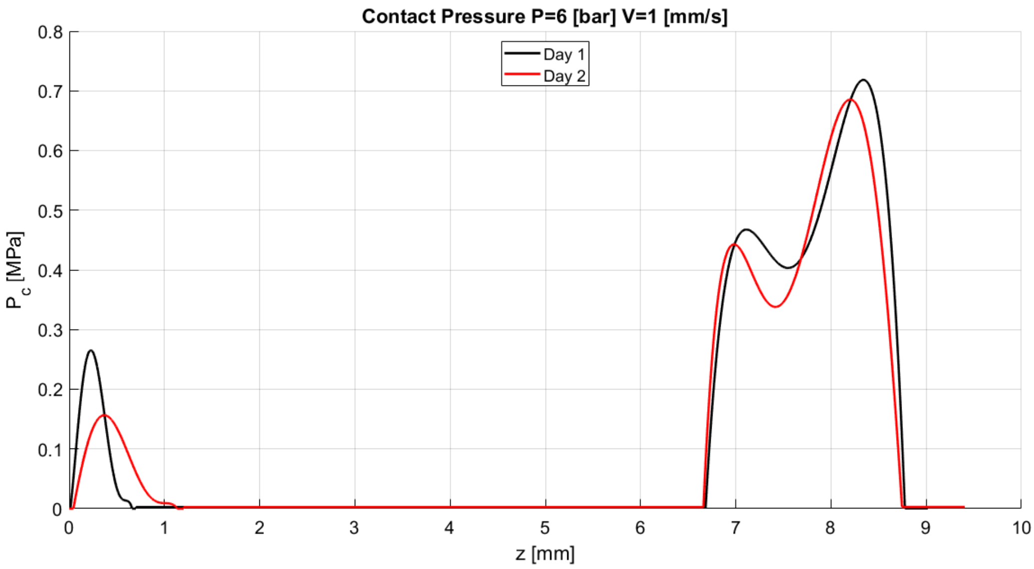


Figure 6.43: Comparison between the same test but that was done in a different days polynomial fitted

6.3.2.2 Spline-fit

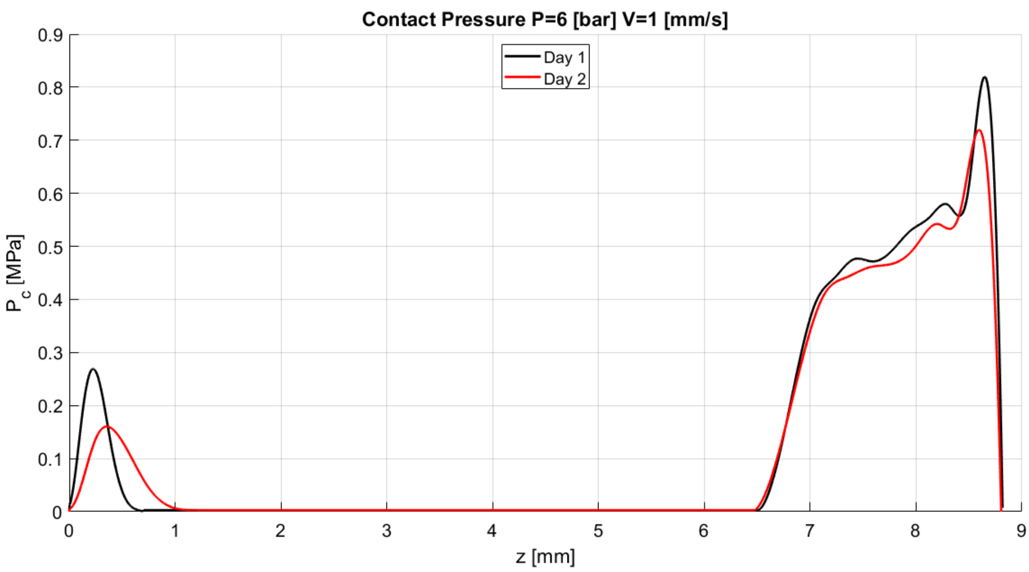


Figure 6.44: Comparison between the same test but that was done in a different days, Spline fitted

6.3.3 P=6[bar] V=50[mm/s]

6.3.3.1 Polynomial-fit

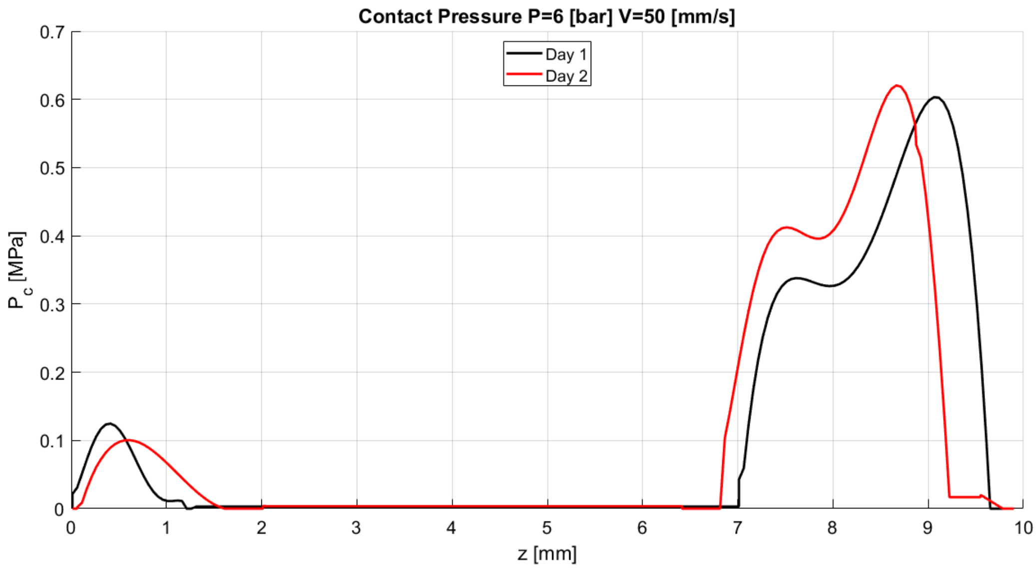


Figure 6.45: Comparison between the same test but that was done in a different days polynomial fitted

6.3.3.2 Spline-fit

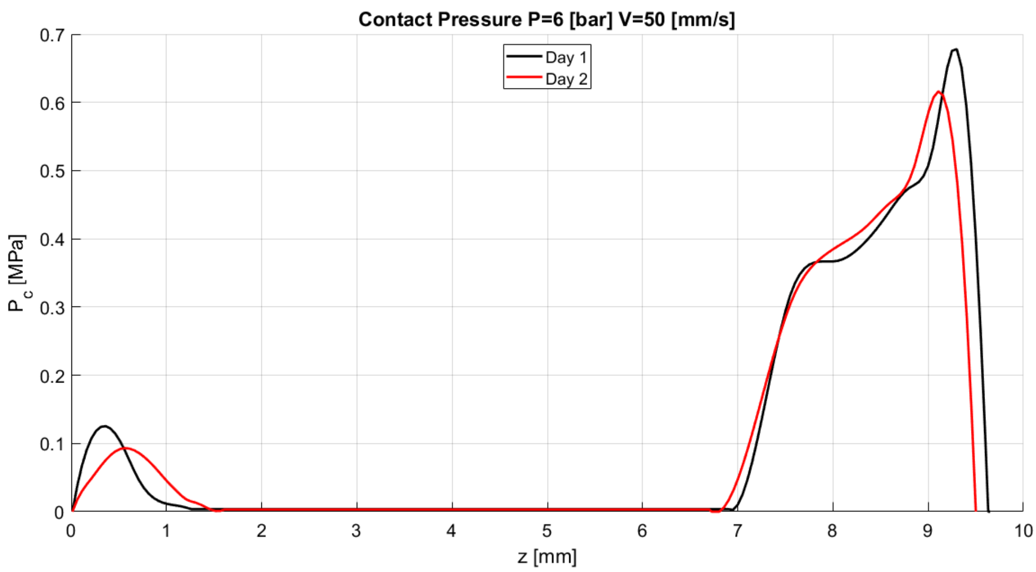


Figure 6.46: Comparison between the same test but that was done in a different days, Spline fitted

Chapter 7

Analysis of the Results

Observing the graphs of the chapter 6, it is highlighted that the feeding pressure and the Seal's velocity are influence parameter in the calculus of the contact pressure [Mpa] along the seal z [mm].

Taking in consideration that the double lips seal was worked dividing it into three main parts, and it will be analyzed as such, and how does it vary according to the method used to fit the signal?

7.1 Constant Velocity and Varying the Pressure

7.1.1 first Part

Seeing the figure 6.33 is presented different fitted signals by polynomial-fit, being studied the first part of the seal in where it highlight that at velocity $V_{work} = 1mm/s$ the contact pressure is highest of all and reached in a smaller portion of the seal. The smallest contact pressure reached on the seal for a velocity $V_{work} = 100mm/s$, but is developed in a greater portion of the seal.

At the same time, it is highlighted that this seal behaviour varies from low to high depending on the speed.

7.1.2 second part

In the second part is obtained that the contact pressure is constant along the certain seal portion that can varies depending of the velocity. The smallest is highlighted for the velocity $V_{work} = 100mm/s$ but there is not a tendency by the others tests about this feature.

7.1.3 Third part

It is outstanding the third part because the highest contact pressure is achieved by the lowest velocity in the system. Also is notated that the speeds $V_{work} = 10mm/s$ and $V_{work} = 50mm/s$ in where the green one achieves the maximum value in a minor portion of the seal but if it is increased the speed, the maximum value is minor and achieved in a greater portion of the seal, see the blue signal.

In general terms there is not a tend when it was studied the seal, varying the speed, seeing the red signal that is the lowest in comparison by the others. This one is done with a working speed 5 mm/s, it was expected that had the second highest value of contact pressure in the system instead it was the lowest value.

7.2 Constant Pressure and Varying Velocity

In the figures 6.35 and 6.36 are presented how it change the signal varying the feeing pressure with a constant velocity of 1 mm/s.

7.2.1 first Part

In the first part of the seal is observed that a pressure $P_{feed} = 0[bar]$ and the $P_{feed} = 2[bar]$ are overlapped having practically the same slope and the same maximum developed in the same portion of the seal.

It is repeating the same behaviour, but by the values of $P_{feed} = 4[bar]$ and the $P_{feed} = 6[bar]$ arriving approximately to a value 0,28 MPa, but this value is reached in a minor portion of the first lips of the seal.

7.2.2 Second part

The second part of the seal is remaining near to zero and there is a feature about this because the pressure feed is minor the second part is shifted to right and while the feed pressure increase the second part is shifted to the left. But approximately it can be seen in the figure that is equal length by the 4 test.

7.2.3 Third part

In the third one is highlighted that the pressure of the 6 bar is the highest contact pressure value and decrease as the feeding pressure decrease. The portion of the second lip to achieved the maximum value is shifted while the pressure feed is diminished but the length of the seal in where the contact pressure is evolving it seems to be the same

7.3 Polynomial fit and the spline fit comparison

Comparing the two figures 6.33 and **??** the first part of the seal remain equal there are not different between the two methods keeping the tend. The second part also remain equal.

The third part made with the spline method keep the same increase with the polynomial fitted, the only thing that have changed between them is how it achieved the maximum pressure contact value, because in the spline signal it could see the tends to always increase until the maximum value to after decrease speedily, instead by the polynomial fit there is specie of m in where there is two maximum and one minimum. But these different is directly related to the math that was calculated the polynomial signal. Another feature of these methods is that Poly-fit method generate functions more smooth than the spline method. Other feature between these methods is the error in the all test of 0,1 MPa in the third part of the lip. But these problematic is related by the mathematics with work the Polynomial-fit.

7.4 Another test

In the section 5.2 of the last chapter also is attached Graphs that were made in a different days emulating the same conditions to start the test. The result were plotted with reference 6.39 and 6.40.

Analysing the figures it can be notated that the first part of the sela have the same tends but it has a variant and it is for the speeds $V_{work} = 5mm/s$ and $V_{work} = 10mm/s$ in where the last one is more higher than the $V_{work} = 5mm/s$. Breaking the tend in comparison by the main test.

The second part has the same tend by the all tests. The third one, does not follow any trend with respect to the main graphs.

With respect to the figure from where the main parameter is the pressure, an equal trend is noted for graphs 6-4-2 bar but that of 0 bar breaks the trend being in a very strange form and not following any tend with the main tests.

Other graphics are also posted where, in equal conditions, the difference between them is the day in where those were made. Seeing in the figure from 6.42 until 6.45

Observing that there are certain changes with respect to maximum values achieved, but the slope of the graphs are equal both in the first part but according to the graphs the pressure contact is different and is developed in more portion of the seal. In the second part there is a certain parallelism between the signals but reaching different values. In the Third part of the seal also there are the same slope but did not achieve the same value of contact pressure but is approximately parallel.

Chapter 8

Conclusions and Discussion

The results of the radial force calculated in indirectly way, through the test bench modified were presented in this thesis had some features that will be discussed.

The radial force that is exerted on a seal depends on many parameters, which depending on how much they are respected can cause the form of the contact to vary considerably, having higher or smaller peaks. But in general lines the radiating force is between [0-23] [N] approximately, where it depends on the test conditions. The forms of contact pressure have in turn a sense with the physics of the problem. The filter is a parameter that influence the form of the signal, in this thesis was not had a criteria to chose a filter, a trial and error method was applied. Using a five order Besself Filter with a pass band of 20 rad/s, the result are good but with a working speed in the order to the 1 mm/s maximun 5 mm/s. More than these velocities the filter starts to interpret that the first part and the second part are disturbance of the signal and it is passed from 0 directly to the maximum value ($\approx 23N$). In order to fix this problem, it was modified the pass band of the filter increase it, and watching the behaviour of the signal. When the filter could respect the behaviour of the signal is taken, after this the calculus is the same for all test.

Starting from the previous point and using the polyfit and spline fit method, it is evident that the spline method is the one that loses the least information. On the other hand, poly fit is always subject to the Runge's phenomenon where the fitted signal tends to have certain waves throughout of the signal, problem that is accentuated by increasing the degree of it, also gives problem when working with lower values acquired in other words with lower points. Then it is important for this study increase the acquisition frequency of the acquisition board when is worked with high speed for this study, because gives more point then there are more points to do the fitted avoid this phenomenon. The same problem happens with the spline method since when zooming it does not have many points and it tends to be the joints of lines which are not quite smooth and you lose a bit of information.

To summarized both gives good fitted signals which are look a lot to the original fitted signal, the difference between them, it is in the poly-fit is obtained an equation for each main part but for the calculation math of the poly-fit, it is might lose some information the reader could reference to the chapter 5 and see the graphs and highlight this error between the two methods ($\simeq 0,1MPa$), instead the spline fit doesn't give an equation only gives it a smooth signal. The last one tends to reproduce the original signal and it is more accuracy than the polynomial fit but there will not be an equation and the calculus that it would want to do will be numerical.

In the Graphs **??** and 6.34 the signals were put on the same graph , it can be seen that when the speed increase the wiper tends to change its contact surface having more contact with the rod because is extended, as consequent the contact pressure is lower. At 1 mm/s the contact pressure is approximately 0.28 MPa and then at a higher speed (100 mm/s) it reaches approximately 0.09 MPa. In conclusion at higher speed the wiper is deformed and took more part of the rod.

The second part is near to zero and have sense because because in this part it is in the convex part of the seal in where there is not contact with the rod.

When the sealing lip is in contact with the special rod the signals don't have tends between them and it is complex to predict the seal behaviour. But it is possible to see that velocities 1 mm/s, 10 mm/s and 50 mm/s there were a tends between them and as it increases the velocities the contact pressure tend to decrease and it is developed in more contact surface in other words the seal was deformed. The speeds 5 mm/s and 100 mm/s don't follow any trend, about the highest speed the problematic was the acquisition board that worked only with 2000 MHz as acquisition frequency and there were not sufficient points to have more information about the phenomenon, then a solution it would be to acquire another acquisition board. But there is not any conclusion about the velocity 5 mm/s. To conclude at high speed the velocity, the seal is deformed and tend to flat.

Observing the graphs 6.35 and 6.36 are more predictable their behaviour when is varied the pressure feeding and maintaining the speed in a constant value 1 mm/s. Seeing the graphs the first part of the seal (Wiper) can be seen that there are two width the red one and the black one are similar and tend to stay overlapped, and this may be correlated to the fact that the black one was done at 0 bar and in 2 bar respectively, the forces exerted in the seal do not be sufficient to deform the wiper, and the contact pressure is approximately 0,22 MPa. For the blue one and the orange one (4 bar and 6 bar respectively) the pressure in the sealing lip (Third part) is able to deforms the wiper side, decreasing the contact surface and increasing the contact pressure in those conditions. Seeing the third part it can be conclude what was said before has sense, the seal is rotated and deformed and working with high pressure the seal is crushed, giving the impression of being translated to the left. The radial force is directly proportional to the supply pressure, so while it is, the contact pressure is greater.

An important point to take in consideration, is the lubrication process. It is had a seal in the sliding bearing Holder in order to insurance a close volume that will be pressurized, but this seal does not work without lubrication, it was observed in the laboratory if this is no respected the seal tended to come out of its holder.

But there is no right criterion by which these results can be compared, so it is not possible to give a just conclusion for this experimental calculation. Compared with the old results, the forms tend to be equal and these results at least it can be said that the result are corrects.

8.1 Future work

Analysing the last Chapter, it is necessary has another source to do the comparison in where it could observe the main influences parameters but and also the different parameter such as the temperature and the rod lubrication.

Modelling with Finite Elements
A modelling with finite elements is necessary to be able to have at least the response of the seal by varying the speed and feeding pressure and thus analyse the trend of the same and compare it with the graphs obtained in the laboratory.

Modify the test Bench
Modify the spacer to have a closed control volume in which the seal that, it is in the sliding bearing holder can be removed, since this necessarily has to be lubricated to work and limits the tests. Then verify that it changes when the contact is dry between the seal and the rod.

work with acquisition board with higher sampling frequency This guarantees more points in a shorter interval of time, that is, more accuracy when looking for polynomials fitted, and don't loss important information.