POLITECNICO DI TORINO

Master's Degree in
Mechatronic Engineering

Master Thesis

Control of an active air bearing: simulation and experimental tests

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Contents

List of Figures

Part I

Introduction

Chapter 1

Introduction

This thesis focuses on the study and development of an active air bearing whose working principle is based on a proportional pneumatic valve that regulates the air flow under the device in order to keep its lift from the basement constant. The final goal of the work is to realize a model able to describe the active bearing used and to deploy a control action that allows to make the bearing reach the desired elevation, no matter the possible external disturbances.

Nowadays, two typologies of air bearing exist [1]:

- the Aerostatic bearings, that are fed with pressurized air and they can provide lifting effect even without relative motion.
- the Aerodynamic bearings, whose working principle is based on the relative motion between the bearing and the structure to generate a pressurized air film.

Moreover, the type of air bearing mostly used are [1]:

- Linear-motion bearings, which allow translations in one or two directions;
- Journal bearings, supporting rotations;
- Thrust bearing, used to avoid axial translations of rotating shafts.

The air bearing analysed are the Aerostatic ones, of the linear-motion type, which exploit the pressurized air to generate vertical forces, able to lift even huge weights. The air under pressure is introduced in the upper part of the bearing and it is released in the lower part, throughout a shaped groove. The air creates a air-cushion between the static basement and the lower part of the bearing and generates a pressure. Then, the pressure exerts a force under the bearing surface which opposes to the weight loaded on the upper part.

As reported in [1], the way the air is delivered to the gap makes a further subdivision in the aerostatic bearings.

- Porous Surface: it is based on a porous material which allow the pressured air to enter the air film from the pores. In this way, it is possible to obtain a very good pressure distribution, with a high level of uniformity under the bearing. The drawback is that the porous material used may release some particles during operation.

- Partial Porous Surface: are similar to the previous but only a part of the surface is porous. The advantage is a higher damping effect in dynamic conditions.

- Discrete Orifice Feeding: they have one or more orifices that allow having small variability between different bearings. The tilting effect can be lower than 0.1 µm with the possibility of a very small particles emission. The pressure distribution depends on the positioning and the number of orifices present and they have a relative low cost, due to the manufacturing simplicity.

- Slot feeding: they provide the air from a rectangular slot, instead of having holes. They are used more for cylindrical Journal air bearing. The good point is their stiffness, but they result in having higher costs, due to the low production globally required.

- Groove Feeding: consist of multiple small groves manufactured axially into the bearing surface. They are used in cylindrical journal bearings and they have a very high stiffness but with a higher cost.

Each type of air delivery system brings to a different air pressure distribution under the bearing. For this reason, it is important to consider the determination of the correct bearing suitable for the application required, but also in the determination of the bearing model, in order to well describe the pressure distribution of the air gap.

The most important characteristic of the air bearing is the huge reduction of friction between surfaces. This effect is due to the absence of direct contact between mechanical elements, which could bring to friction energy dissipation but also to wear, generation of particulates and heat. The static friction is removed and the dynamic one is reduced at a minimum level. These characteristics can bring the air bearing to be a key element where high precision in positioning and the lack of backlash is required [1]. Moreover, the air bearings are very useful in high relative speed applications.

Being free from stick-slip and hysteresis, the air bearings are particularly suitable in machines that need high accuracy and repeatability, such as the "ultra-precision machine tools", like optical grindings. Moreover, they are used in the metrological field for very accurate measuring machines. Another important characteristic is the capability of averaging the imperfection of the surface over which it moves, due to the absence of contact and thanks to the presence of the air cushion [2].

As reported in [1] and [3], the air bearing are also used for space craft simulators, for satellite attitude determination and control hardware verification. Thus, the application fields of this kind of technology are quite big.

The main point of the use of the air bearing is the problem of the stabilization of the air film under them, thus to have a constant lifting. Usually, the used air bearings are of the passive type. This means that there is not any control about the thickness of the air gap under the bearing. Since the external factors that can influence the air film height are many, lots of investigations were performed to keep the bearing lift as much constant as possible. One possible solution is to use the passive bearing in the area where the characteristic of the Load/Gap-height curve (F/h) has the maximum slope. In this way, even if the load is modified, the air film height has a very small change, obtaining the maximum stiffness of the bearing.

On the other hand, to regulate the air gap, it is possible to use a control action, thus, an active air bearing. In past thesis works, it was used a digital valve to regulate the flow according to the bearing elevation. Some stability problems were experienced, thus, it was decided to use a proportional pneumatic valve (thesis [4] and [5]). With the introduction of a control, the aim is to reduce the air film variations and obtain a virtually infinite stiffness, where the lift variations are almost null, despite the change of external force.

The goal of this thesis is to deepen the previous works on the active control of a bearing which uses a proportional valve ([4] and [5]), in particular by improving the model of the active bearing system and the control action algorithm. Moreover, this thesis aims at characterizing a test bench (Step bench) based on a different working principle with respect to the one used previously (Mager bench). Furthermore, during this thesis work, an analysis of the different components of the bearing system will be performed. After that, the model of the device will be produced and a control action will be deployed and tested in the laboratory.

Part II

Components

Chapter 2

Mager test bench

For the initial experiments, the Mager test bench was used. This bench is basically a press, built on a massive granite basement, which must ensure a minimum level of vibrations or deformations. The block is lapped to have as few impurities as possible. Then, on the basement, a structure carries the device used for applying the desired force over the bearing. The force is generated by a vertical screw which is rotated by a rotating wheel on top of the structure. The rotation moves the screw upwards or downwards, pushing or releasing what is positioned below. The bearing is positioned over the basement, on an aluminium plate which is lapped to reduce at minimum the roughness and make the bearing work at best. In fact, the airflow under the bearing must be uniform, due to the very thin gap dimensions involved (few µm). On the screw a HBM U9C load-cell is mounted to measure the actual force exerted on the bearing. A very stiff spring system is mounted under the rotating wheel, to ensure a decoupling between the vertical motion of the screw and the force exerted. Under the load cell, there is a housing for a steel ball. This is useful to avoid incorrect loading of the bearing, ensuring that the force is transmitted perpendicularly to the bearing, even if the bench screw is slightly inclined.

On the bench plate, a structure is mounted as support for the capacitive sensors. Those sensors are fixed to the support which is screwed on the plate. This means that, during the experiments, the sensors stay still and they can measure the distance variation between the bearing and the sensors themselves. This measurement is related to the variation of the air film height, even though it is not a direct measure of the distance between the plate and the bearing. As described in the following pages, the measured values from the sensors must be set to zero at the beginning because they evaluate a distance variation and not the absolute bearing lift.

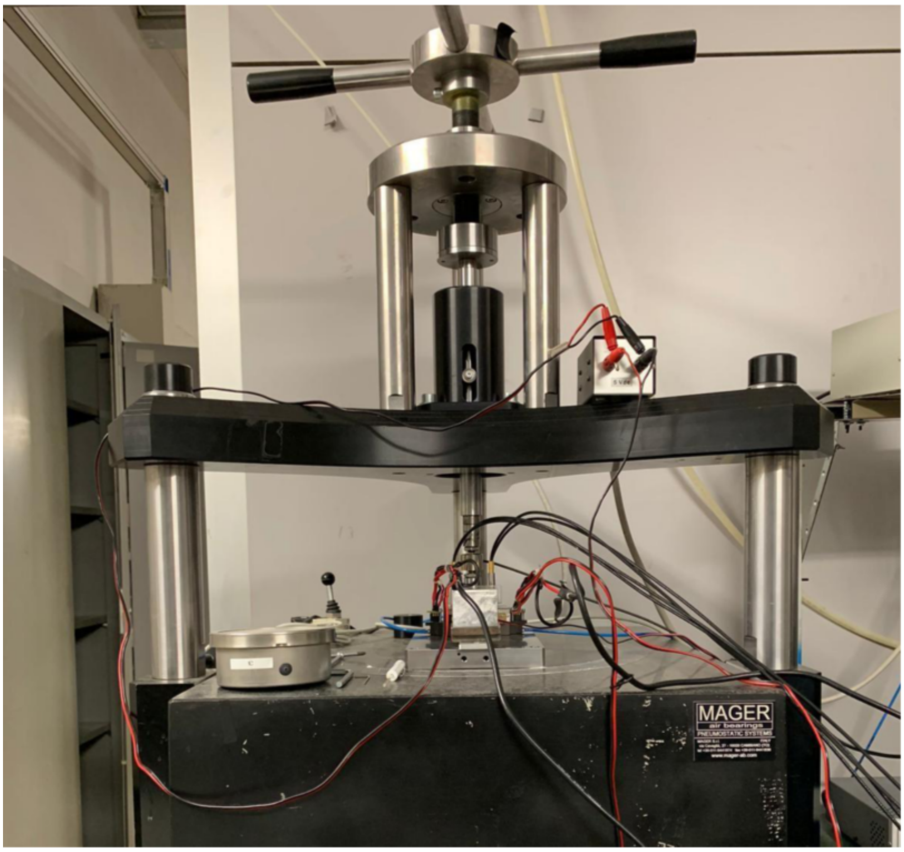


Figure 2.1. Mager test-bench

Chapter 3

Step test-bench

After the tests performed by the previous thesis experiences on the Mager test bench, it was decided to move to another bench, which was considered to better fit the real working condition of the bearing. In fact, the bearing is a device that leans against a surface and is loaded by a weight and the new bench (called "Step") is designed to allow to put on top of the bearing some weights, better reflecting the real working conditions of the device.

The Step bench is composed by a huge metal plate, working as the base structure. On top of it, another metal plate is positioned. This plate is machined to have a very smooth surface, with a very low roughness. This is important to allow the air flowing under the bearing without obstacles that can compromise a uniform pressure distribution under the plate. Moreover, the air cushion created has a very small height (order of µm), making the small imperfection of the base more and more influent on the behaviour of the system.

The bearing lies on the machined surface and it is pushed down by a structure, designed to carry and guide the load. The structure is composed by two vertical metal pivots, which are guided by two passive air bushings. The bushings are fed by compressed air, which creates a layer between the moving pivots and the static part of the bushing and the friction is brought almost to zero. The two pivots are connected by a horizontal metal beam. The system guides along the vertical direction the weights put on the structure. In this way, the forces that oppose to the vertical motion of the load are very small and can be neglected. Between the bearing and the structure, a metal ball is positioned, in order to compensate for any possible misalignment between the two and ensure the applied force to be vertical.

The pivots cross the base, which is raised from the floor, and are connected in the lower part by another beam. This configuration allows, not only to carry load on the upper part of the structure but also to attach some weights on the lower part,

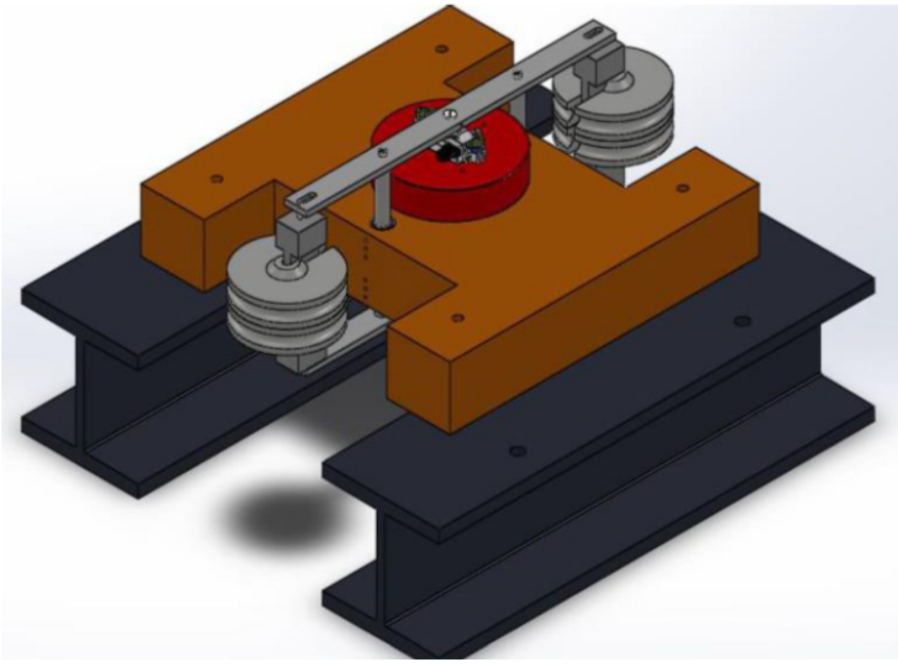


Figure 3.1. Graphical representation of the Step test-bench [5]

for example with a small rope. In this way, it is possible to apply a sudden change of loading on the bearing, by cutting the rope and simulating a step variation.

The weights used during the experiments are different disks, with a mass of about 5 kg each and they are placed over the structure. Since the supporting plate was not so big, it was decided not to overcome the number of 9 stacked weights.

To know exactly the entity of load which is carried by the bearing, it is necessary to evaluate the mass of the supporting structure that holds the weights. To do so, it is used a scale, which is positioned on the lower part of the bench, under the base. The scale is raised using some wooden blocks in order to make the moving structure lay on the weighing plate. The compressed air of the pneumatic bushings is activated and the measuring is performed. In figure 3.2 it is possible to see the followed procedure. The structure weight is about 6,120 kg.

The rising effect of the bearing air-cushion must rise the weights, the structure supporting them and the bearing itself, thus it is worth to add to the structure also the bearing weight. In this way, the structure with the bearing reachs a value of 6,480 kg.

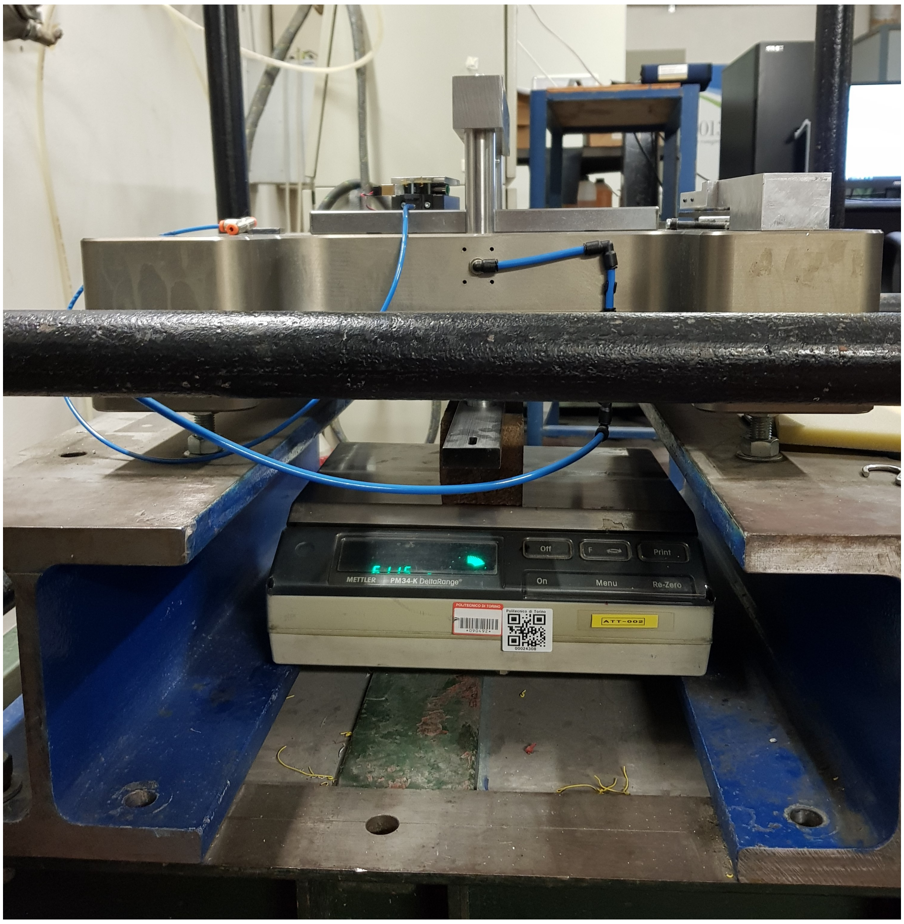


Figure 3.2. Weighing of the support structure over the bearing.

It is worth to remember that the Mager bench is structured in order to apply a force over the bearing by means of a wheel and a screw, not using real weights. The difference is that the Step bench allows an almost free vertical motion of the bearing with a constant load, while the Mager bench relates the vertical motion to the modification of the force applied on the bearing, because the screw, even if it has a non-infinite stiffness, limits the vertical motion. Due to this characteristic, the Step test-bench seems to better reflect a real working condition.

To measure how much the bearing detaches from the base, some capacitive sensors are used. Those sensors are positioned on the upper part of the bearing, detecting the motion of the metal plate which covers the bearing. To have a correct measure, it is necessary to fix the sensors on the base of the bench, overhanging them over the bearing using a dedicated structure. The same approach was used with the other bench, but, in this case, the holes on the base did not fit the old capacitive sensors support. Thus, moving from the Mager bench to the Step bench, it was necessary to manufacture another support. To do so, the size of the bearing and the bench were taken and a SolidWorks model was created.

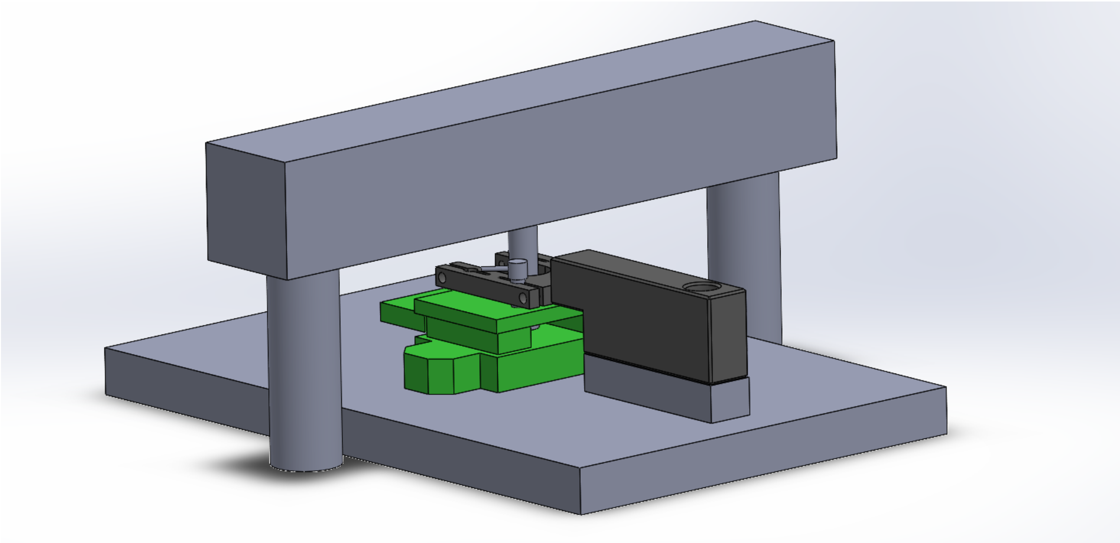


Figure 3.3. SolidWorks model of the Step test-bench.

Using the model, the new support was designed. It was taken care of fitting the existing holes present in the new bench base and putting the capacitive sensors as far as possible from each other, in order to have a measure on the bearing corners and better notice any possible tilting of it. The resulting support is shown in figure 3.4. Then, the support technical drawing is sent to a mechanical shopfloor for the realization. The drawing is reported in Annex 3.

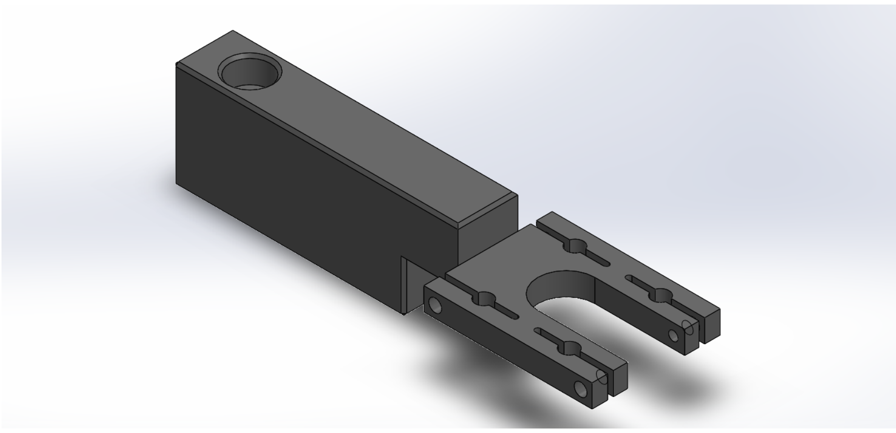


Figure 3.4. SolidWorks model of the support for the capacitive sensors.

Chapter 4

Acquisition system setup

4.1 Step test-bench

In the experimental phase, it is necessary to acquire data from the tested system to store and analyse them. Since the test-bench used is different from the one used by the previous thesis experiments, a different acquisition computer was used. The computer next to the new bench was unable to directly read data from the acquisition module, thus it was necessary to read the values from another device which had the correct interface (the module NI PXIe-6341) to accommodate the acquisition board. The device used was the NI PXIe–1071, from the National Instruments, which was connected to internet so that it was possible to communicate with the main computer, next to the bench.

The acquisition board BNC-2110, by National Instruments, was used to collect the data coming from the different sensors. This board has many possible inputs but in the case of this thesis, those one used are the 8 BNC Analog Inputs. The acquisition device is then connected to the PXIe by means of a specific cable. The board is represented in figure 4.1.

On both the main computer and the PXIe, the software LabView was used. The main computer was used to arrange an acquisition setup, managing all the parameters and the real-time graphs of the read values. However, the actual acquisition program part was running directly on the PXIe, recording the data coming from the board. Also, the file with all the measurements created during the acquisition was stored on the PXIe and it was necessary an FTP connection between the two computers to get those values, as it will be deepened later on.

Figure 4.3 and figure 4.4 show how the LabView program was organized, the structure and the windows showing the collected data in real-time. In the block

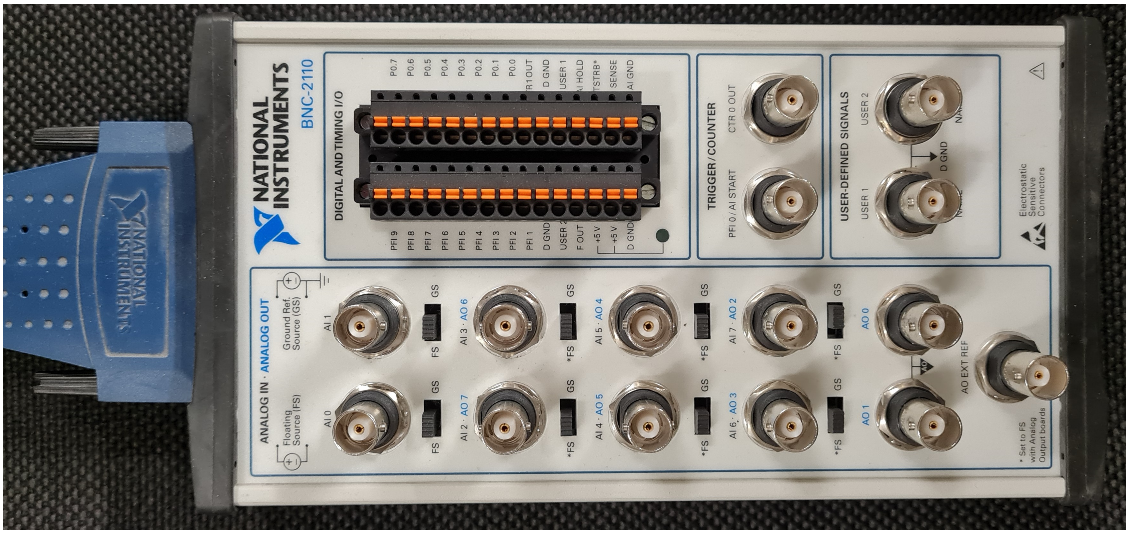


Figure 4.1. Acquisition board: BNC-2110 by National Instruments

diagram, there is the DAQ Assistant, which has the role of acquiring the data from the acquisition board. For each channel of the board, it is possible to define the minimum and maximum working range, the unit of measure and define a conversion scale to pass from the electrical signal to a unit of measure, if needed. A configuration example of the capacitive sensors is reported in figure 4.2. The output signal coming from this block is spitted by using a "Select Signal" block, which defines the channel to use in that branch. Then, the signal is sent to the different graphs. For the capacitive channels, the signal is set to zero by means of the subtraction of a constant. With the blocks in the lower part, the data are written in a ".txt" file. The grey box around the structure indicates the acquisition is performed in loop until the "stop" button is pressed. The project is organized to have some graphs which update in real time during the measurements and a system which record the collected values on a ".txt" file. This file is continuously written during the test, until the measuring session is stopped. The file is organized in columns, each one of them corresponding to a different sensor or a different acquisition board channel.

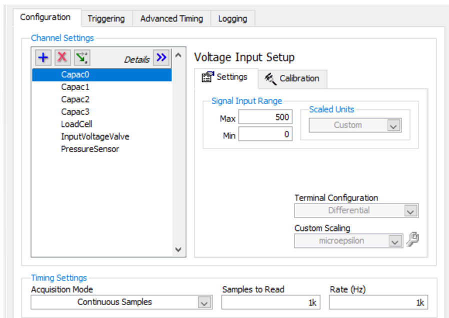


Figure 4.2. LabView DAQ Assistant configuration example.

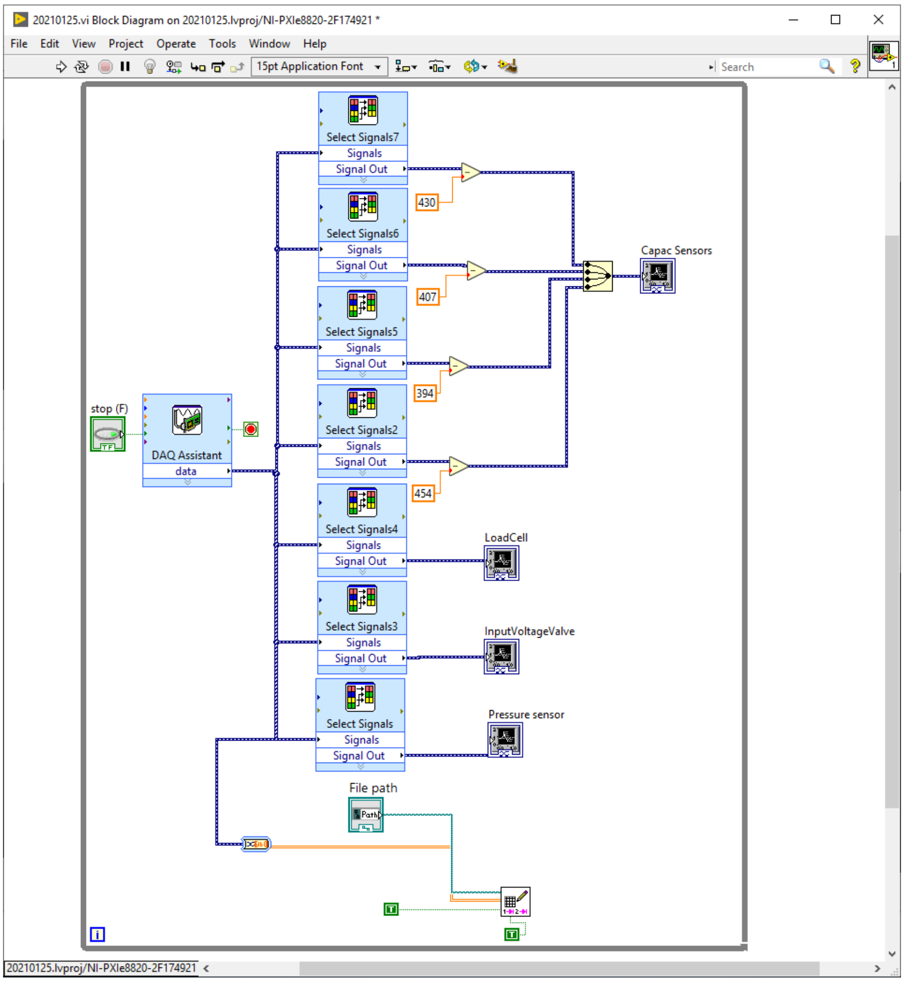


Figure 4.3. LabView block diagram.

It was not very easy to make the main computer and the PXIe communicate, because the LabView release numbers didn't match at the beginning and the PXIe was not fully updated. It was necessary to use the software NiMax to update the PXIe and install all the libraries to have a good communication between the LabView software installed on the two computers.

In figure 4.5 the scheme of the LabView project is reported. As it is possible to see, the project includes the PXIe device in it. The ".vi" file, which is the file with all the parameters and configurations for the acquisition, is positioned inside the device itself. This means that the cell is running on the PXIe and not on the main computer.

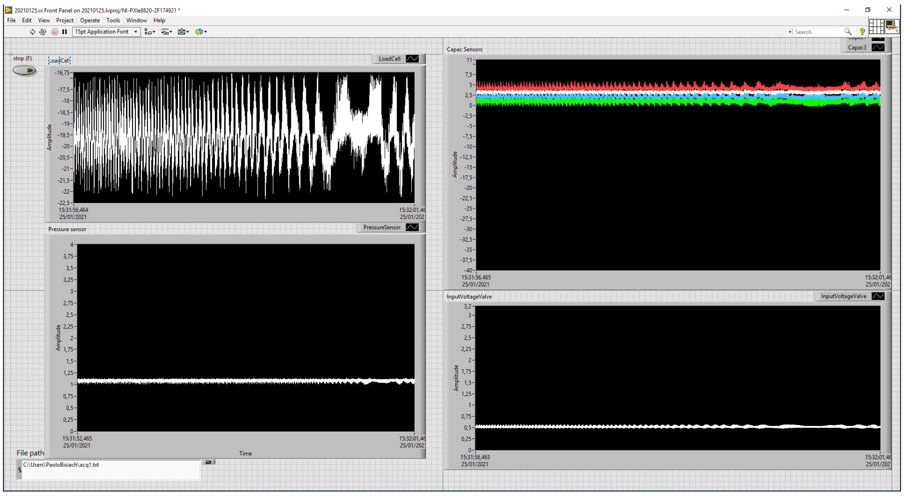


Figure 4.4. LabView real-time graphical representation of the acquired data.

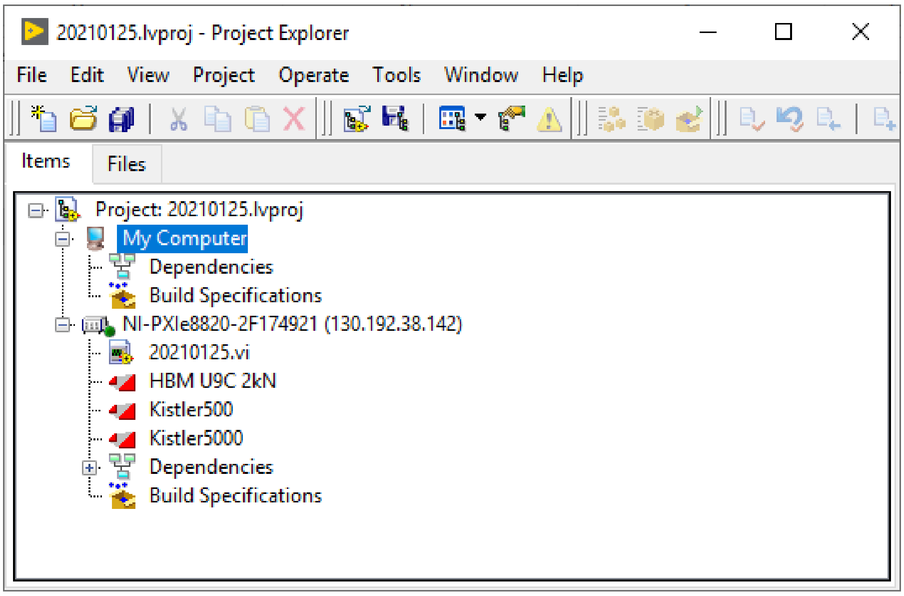


Figure 4.5. LabView program hierarchy representation.

To download the recorded values on the main pc, the FTP connection was used. To allow this connection, it was necessary to use the NiMax software, right clicking on the PXIe device to select the "file Transfer" icon. Since the acquisition was performed on the PXIe, the file was stored in its memory. The graphical interface of this device was very minimalistic and it wasn't very clear which was the correct file path to follow. After some attempts, it was found that, similarly to windows devices, the main hard disk was labelled with the "C" letter, therefore the file path to use in the LabView project cell was of the kind: "C://Users/... .../filename.txt". Instead, from the main pc it was possible to reach the saved file from the file manager at the address: "ftp://*PXIe_ip_address*/Users/... .../filename.txt". Then, it was necessary to download the file on the computer to open it and, eventually, modify it.

During the experiments, different values are collected by the acquisition board. Those are:

- the 4 capacitive sensors values, measuring how much the bearing rises;
- the load cell value, to measure the load on the bearing;
- the valve control signal voltage, sent by the control board to the proportional valve;
- the back-pressure sensor voltage;

For more clarity, a scheme relating the acquisition board channel and the recorded signals is reported in table 4.1

Sensor	Channel
Capacitive 1	A0
Capacitive 2	A1
Capacitive 3	A2
Capacitive 4	A3
Load cell	A4
Valve Command Singal	A5
Back-pressure	A6

Table 4.1. Correspondance between the board channels and the sensors connected.

The four capacitors are positioned as much on the corners of the bearing as possible. In the experiments, they are always numbered in the same way, in order to always have the same correspondence between the sensor and the bearing corner. In figure 4.6 the bearing and the enumeration of the sensors are represented. Those capacitors are connected to the acquisition module through some cables that need to have a connector which is bent of 90°, due to the presence of the structure for supporting the weights over the bearing that obstructs the cable passage.

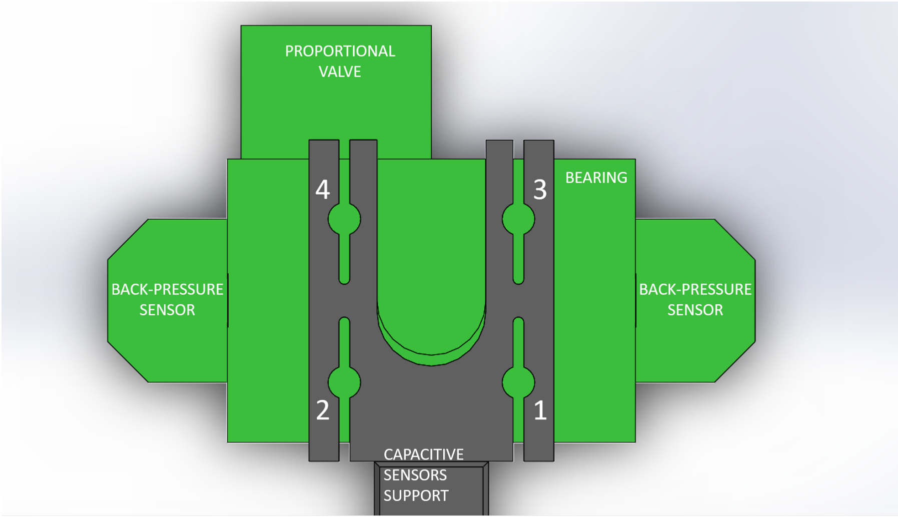


Figure 4.6. Bearing scheme, top view representation.

The voltage sent by the control board is read by the acquisition module to check the control action performed and to be able to make a time correspondence with the other recorded values. In this way, at every data collection, it is possible to know which is the exact control action performed by the controller. To be able to collect this vale, the control board is asked to send the output signal on two digital output ports: one port is then connected to the proportional valve and the other is connected to the acquisition board.

For what concerns the back-pressure sensors, their output signal is sent to the acquisition board first, to be recorded by the LabView software and then, with a "T" BNC connector, the signal is sent to the control board, to be read and used in the control action. Figure 4.7 shows the connection performed. This choice is mainly due to two reasons. The first is related to the kind of connection present on the sensor: it was hard to have two cables coming out from the small sensor, thus, it was decided to "duplicate" the signal far from the sensor, with the "T" connector on the board. The second reason concerns the reduction of the number of cables attached to the bearing, which can induce some disturbances on its motion, such as tilting effects.

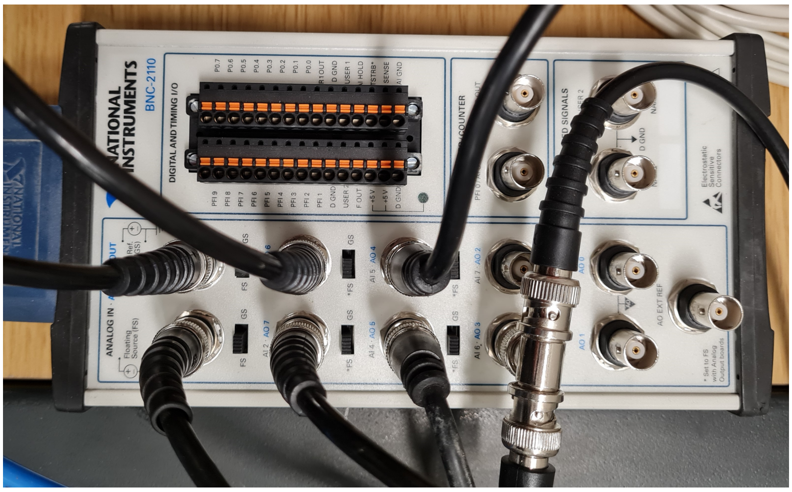


Figure 4.7. Connections on the acquisition board, in particular, the "T" connection for the back-pressure sensor.

4.2 Mager test-bench

In the Mager test-bench, the acquisition system configuration is a little bit simpler since there is no need of using a second device connected to the network and communicating with the main computer. In fact, in this bench it is possible to directly connect the acquisition board to the computer where the software LabView is running. Thus, the acquisition line is composed by:

- the main computer, where the software LabView is running;
- the acquisition board: BNC-2110 by National Instruments;
- the sensors for the data collection;

The LabView project used is very similar to the one used for the Step test bench, with only few modifications to adapt it to the load cell used. The main difference with the previous configuration is that, in this case, the LabView project is directly running on the main computer and not on another device connected to the board, thus the file with the measurements is directly stored on the main pc, without any need of downloading them form an external device. The capacitive sensors used on this bench are connected to the amplifier through cables with a straight plug. In this case, in fact, over the capacitive sensors there is enough space for the cables to pass freely.

Chapter 5

Air bearing

5.1 Bearings in general

An air bearing is a device which exploits the pressured air to create an air film under its structure to reduce the friction with the surface below and generate lifting forces. The air is introduced from the top of the bearing and is exhausted through the groove positioned under the plate. The air under the bearing generates a pressure and a force which lifts the bearing itself. Two principal parameters are involved on the lifting effect:

- the pressure of the cushion air under the bearing;
- the load applied over the bearing;

In general, the air film thickness is around 5-20 µm.

5.2 Bearing used in the experiments

The air bearing used is produced by Mager company and it is represented in figure 5.1. It's composed by an aluminium alloy, with a base of 50 mm by 75 mm. The lower surface is lapped to have a very low roughness and allow the air to flow without any impediment. The bearing has a "8" groove shape, to distribute the air under the base. The technical characteristics are shown in 5.2.

As it is possible to see, the bearing has some threaded holes (M3 size) on the shorter side, to fix the pressure sensors and some other M3 holes on the top, to fix the proportional valve. The top side of the bearing has two more holes, without any thread. Those are the holes for the air passage, which feed the groove under the bearing. In the centre, there is a housing for a sphere, which allows the bearing to be always loaded in the correct way, even if the screw of the test bench is slightly

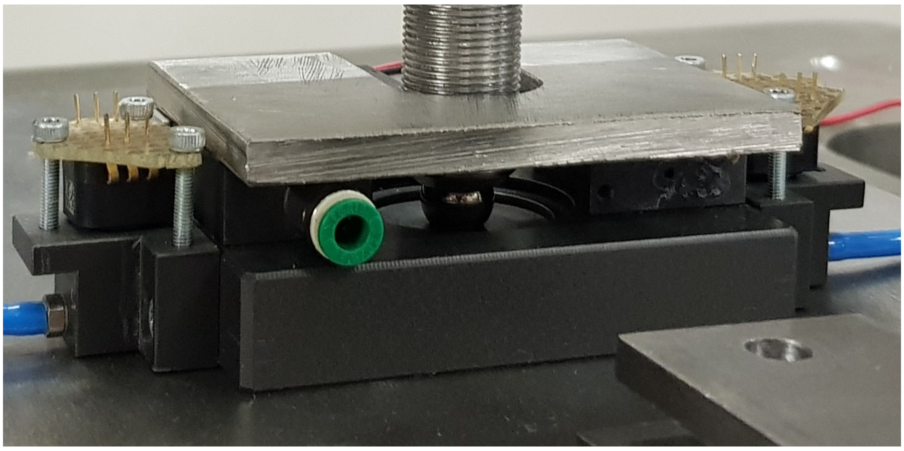


Figure 5.1. Air bearing picture.

inclined. A significant parameter to consider is the diameter of 0.25 mm of the exhaust hole under the device, because it will be useful in the development of the Simulink model. The lower part of the bearing is not perfectly flat, but it shows a slight concave curvature. This feature is particularly important when large weights are loaded on it. In fact, in this way, even if the bearing bends under the load, the

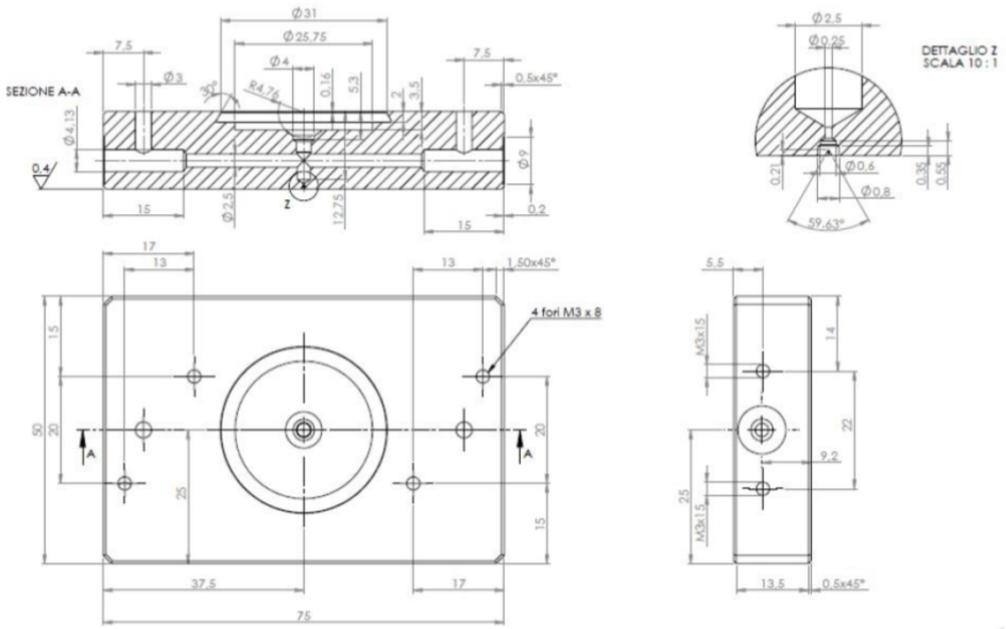


Figure 5.2. The bearing technical drawing [5].

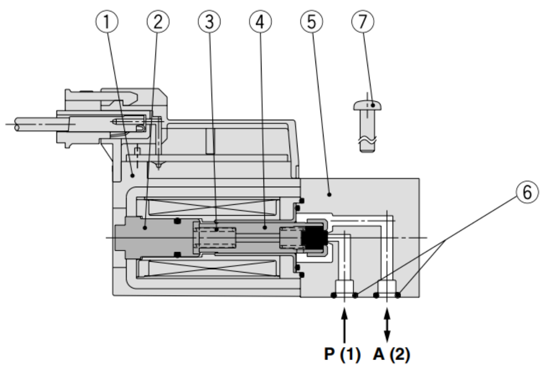
air cushion is not compromised, but it still keeps its lifting capabilities. Due to the non-infinite stiffness of the bearing, during the static characterization of the device (described in the following pages) the test is performed also without air supply, in order to evaluate the entity of the bending of the bearing when adding an increasing external load.

Over the bearing, two proportional valves are positioned to regulate the entering flow in the bearing. On the sides, the back-pressure sensors are fixed. Over the whole structure, a steel plate is positioned, to have a flat surface over the bearing where the capacitive sensors could read the distance. After some experiments, it was decided to glue this plate on the bearing structure, in other to be sure that it would not move during the working phase.

Chapter 6

Proportional valve

The valve used to regulate the flow in the bearing is a proportional valve from SMC, model PVQ13 (of the family PVQ10), with exhaust hole diameter of 0.3 mm. This valve is normally closed and works by means of a solenoid inside it, which gradually opens the valve with an input current signal. In fact, this valve is controlled with the variation of current provided. The valve must be fed with 24 V and controlled with a current range between 0 mA and 85 mA. This kind of valve is called proportional because the airflow is proportional to the inlet pressure but also to the solenoid excitation current. The big advantage is that this kind of valve is not influenced by the typical oscillations of a PWM controlled valve, which are based on a high frequency opening and closing of the duct, in order to regulate the airflow. In figure 6.1 is reported the scheme of the valve used in the laboratory.



Component Parts

No.	Description	Material	Note
1	**Solenoid coil assembly**	—	
2	**Core**	Stainless steel	
3	**Return spring**	Stainless steel	
4	**Armature assembly**	Stainless steel, Aluminum, FKM	
5	**Body**	C36	
6	**O-ring**	FKM	
7	**Round head combination screw**	Steel	M1.7 x 0.35 x 17L, 2 pcs.
8	**Sub-plate**	C36	Part no: PVQ10-15-M5

Figure 6.1. Proportional valve scheme: SMC, model PVQ13 [6].

The disadvantage of this kind of device is the reaction time which is longer than a system based on a PWM control. The valve was tested by the previous thesis analysis [5] to be sure that the airflow-current characteristic complied with the datasheet (figure 6.2).

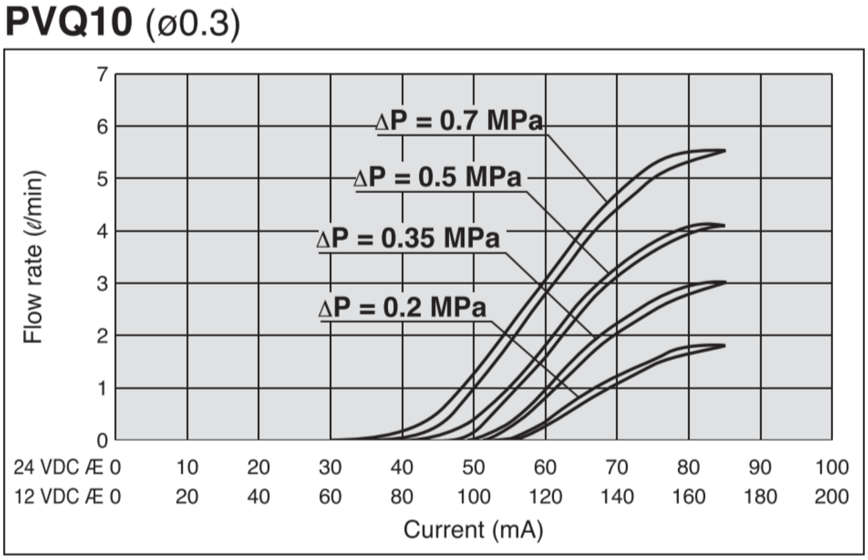


Figure 6.2. Proportional valve characteristic: Air Flow Rate [l/min] against Excitation Current [mA] [6].

From the scheme in figure 6.2, the valve shows the presence of a hysteresis phenomenon meaning that the valve has different behaviour while passing from closed to open and from open to closed. This is mainly due to the frictions inside the valve that oppose to the opening and closing. Moreover, the current value at which the valve opens depends on the inlet and outlet pressure, that contribute to help the mechanism to open the valve, making the system require a lower current to open, when the pressure difference between inlet and outlet increases.

In the previous thesis [4], the valve was tested in dynamic conditions in order to evaluate the characteristics and be able to model the valve in the correct way. In particular, the system was considered a second order one and, by varying the input frequency of a sinusoidal signal, the natural frequency was evaluated (35 Hz). The damping factor was evaluated by applying a step control signal to the valve and the obtained result was around 0,2.

Chapter 7

Voltage to current converting box

Circuit description To control the opening and closing of the valve mounted on the bearing, it is necessary to modify the current sent to the valve. The required current values range from 0 mA to 85 mA. The system used is based on a control code running on the Orange board, which is the analogous of an Arduino Due board. This kind of device has two analogue output that control the tension supplied between 0.55 V and 2.75 V. For this reason, it is necessary to convert the voltage signal coming from the board in a current signal to control the valve. A converting box was developed and used for this purpose.

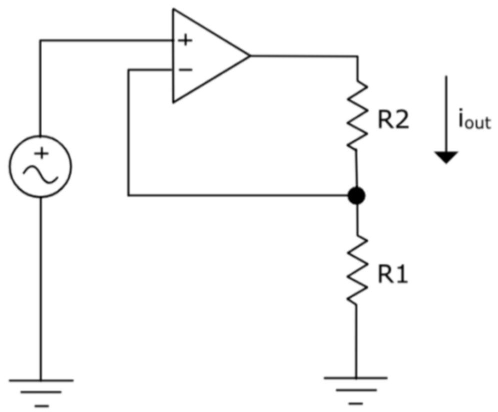


Figure 7.1. Scheme of the theoretical circuit at the base of the box converting the voltage signal into current signal [5].

The circuit is based on a simple working principle: the Trans-Admittance amplifier reported in figure 7.1. This device is based on an operational amplifier and connected to a series of two resistors. The non-inverting port is connected to the voltage signal and the inverting port to the connection between the two resistors.

Since, for the theoretical approach in the analysis of the operational amplifier, the current in the inverting and non-inverting ports is null, the current flowing in the two resistors is the same (i_{out}). For another property of the operational amplifiers, the tension level on the two inputs is the same, thus the tension across R1 is V_{in}. This means that the following equation applies.

$$I_{R1} = I_{R2} = I_{out} = \frac{V_{in}}{R1} \tag{7.1}$$

The R2 is considered the load and does not influence the amount of current flowing, which only depends on R1 and V_{in}. This scheme refers to ideal conditions and for a load which is considerable as a resistance. In this case the valve is controlled by a solenoid, thus a more complex converting circuit is necessary. Moreover, it was necessary to have a protection for the valve, to preserve it from damages due to overvoltage.

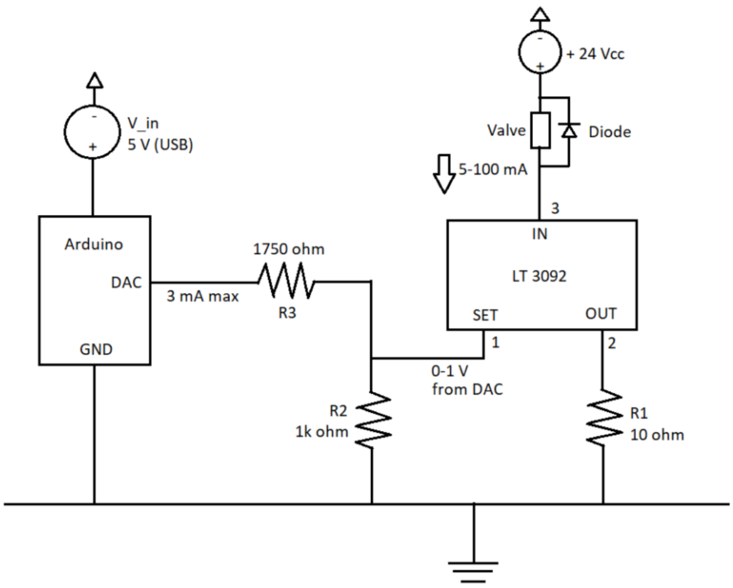


Figure 7.2. Scheme of the circuit used to convert the voltage signal coming from the Arduino-like board into a current signal [5].

The circuit 7.2 was developed by the previous thesis work [5]. It consists of a control part and a power part. The control works with tension of the order of 5 V and it is directly connected to the board, while the power is fed by 24 V and provides the current to the valve. The converting module is the LT3092, which is a commercial circuit with the purpose of converting the input voltage to output current. The two resistors R2 and R3 are useful for reducing the current entering

Figure 7.3. Converting box, external view.

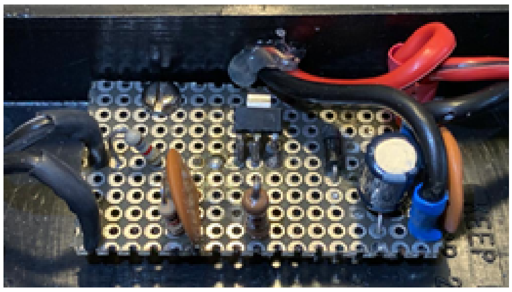


Figure 7.4. Converting box, internal view [5].

the LT3092 circuit to about 1 V. Then, as a protection for the valve, a flyback diode is positioned in parallel to the valve to protect it from tension peaks. Figure 7.3 and 7.4 represent the box from the outside and from the inside.

Circuit testing and characterization The obtained circuit is tested to be sure the behaviour and the theoretical working principles are satisfied. The circuit is tested with a supply voltage of 24 V and directly connected to the valve on the bearing. In this way the real working conditions are investigated. The control board is connected to the converting box and an ammeter is put in series with the valve in order to measure the actual current flowing. Figure 7.5 represents the connection performed. With the Simulink software, a program was developed in order to make the control board generate different values of voltage signal. The scheme is reported in figure 7.6.

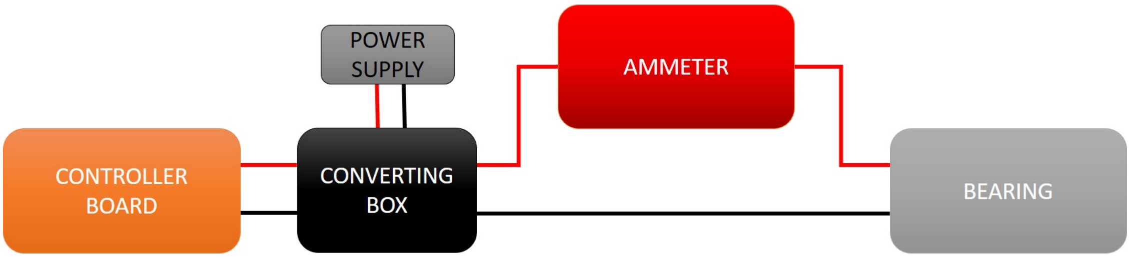


Figure 7.5. Converting box characterization: connection scheme.

As it is possible to see form figure 7.6, the signal generated is a stair with an increase of about 0.1 V each step and it has a duration of 5 seconds for each voltage value. In this way, it is possible to see on the ammeter screen the values corresponding to each step and to annotate them. Once collected, they are associated to the corresponding voltage input generated by the board. The values are plotted in figure 7.7 and the curve is linearly interpolated to know its law. The

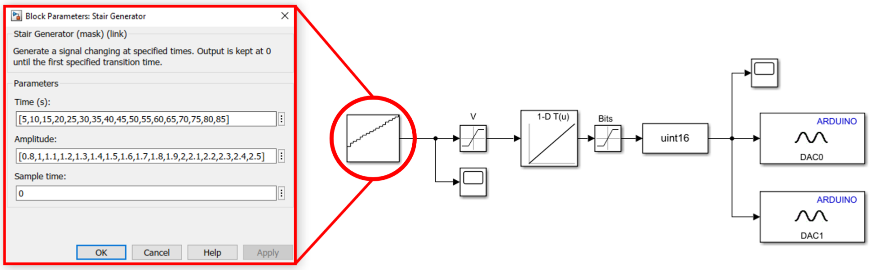


Figure 7.6. Converting box characterization: Simulink program for generating steps for different valve opening.

graph represents the output current against the input voltage. As it is possible to see, the behaviour is linear and the interpolation perfectly fits the curve. Since this test was performed also in the previous thesis analysis, a comparison is performed. The difference is that the previous characterization was performed using a 280 ω resistor as a load, while the test performed uses the valve itself.

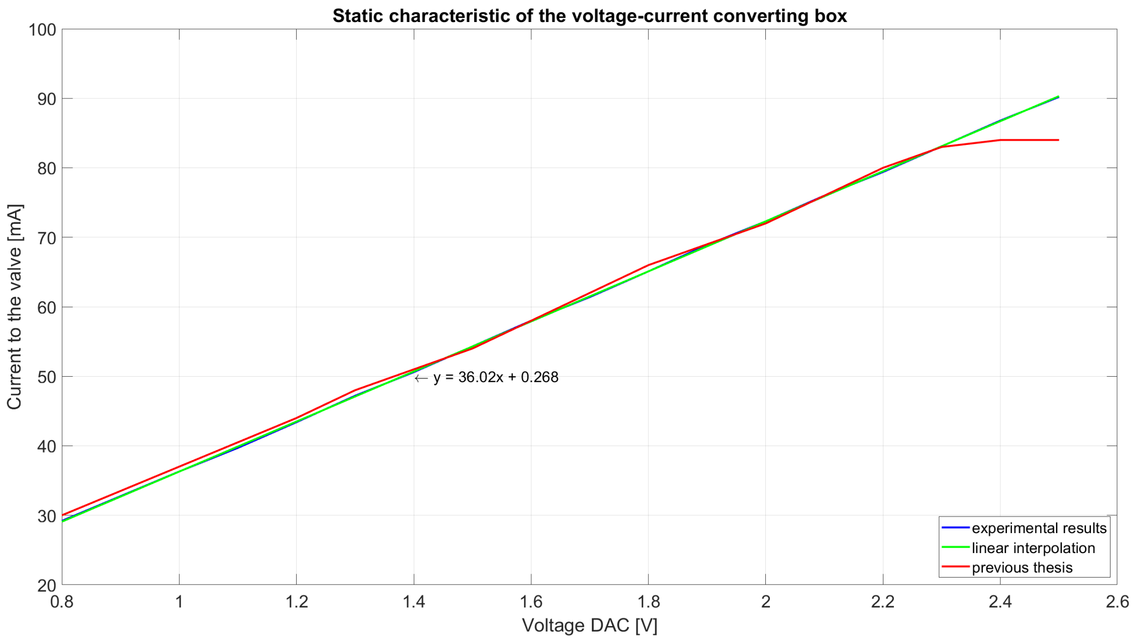


Figure 7.7. Converting box characterization: output current against input voltage.

The two characterization are very similar and they are superimposable, except for high voltage values, where the curve obtained is still linear, while the curve from the previous thesis shows a saturation effect.

Chapter 8

Capacitive sensors

Four capacitive sensors are used to measure the vertical motion of the bearing. They are positioned on the upper part of the bearing, as much on the four corners of the bearing as possible. The aim is to evaluate the elevation in point which are far from each other, in order to check how the bearing rises and every possible tilting. The sensors are the CS02 of the Micro-epsilon brand. Those sensors have the dimensions of 6 mm diameter and 12 mm height. They are very small, and this is useful in the case of the Step test-bench because the space under the structure which supports the weights is very little. Due to the limited space, the cables connected to the sensors must have a 90° connector, to avoid interferences with the structure. The dynamic resolution of the sensors is 4 nm [7].

The used capacitive sensors have a range between 0 and 200 µm with a static resolution of 0,15 nm and a dynamic resolution of 4 nm. It is useful to know what the correspondence between the voltage signal sent to the acquisition board and the distance variation is. In this case, the voltage range sent is between 0 and 10 V, thus the sensitivity is 20 µm/V.

The capacitive sensors exploit the electric characteristic called capacity. This property is typical of two conductive elements with some non-conductive material between them and represents how they respond to a variation of potential applied to them. This characteristic depends on the distance between the conductors, their dimension and the property of the material between them. By inverting the tension on the two conductors, an alternate current is generated between them and this current depends on the capacity, while the capacity depends on the configuration of the system. Since the dimension of the conductors and the type of material between is considered to be constant, the only variable element is the gap between the conductors. In this way, by evaluating the variable capacity of the system composed by sensor and target, it is possible to determine the effective distance between them. For this reason, it is important to have a conductor material positioned where the capacitive sensor is located. Therefore, a metal plate is glued on top of the bearing, working as a target conductor for the sensor.

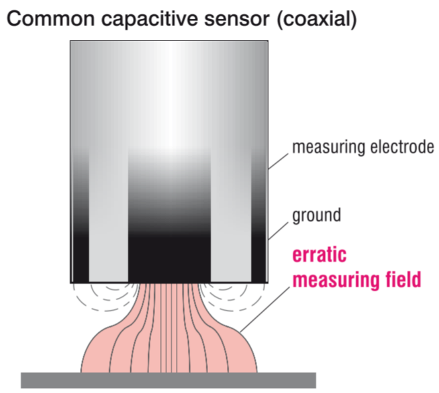


Figure 8.1. Representation of a coaxial capacitive sensor working principle.

The sensors are fixed with respect to the bench basement. To keep them in the right position, hanging over the bearing, a metal support was designed (see chapter 3). The sensors are accommodated in four holes which can be tighten by using a screw. It is important to be able to adjust the distance from the bearing for the initial calibration and then to be able to block them to avoid any movement. The support was 3D modelled with the SolidWorks software and then machined. Considering the sensors working principle, they need to be positioned over the bearing. In this way, though, it is not directly measured the gap under the bearing, but the motion of the upper part of it. This is an indirect measure, that supposes that the bearing thickness is constant and any possible deformation is not considered. Since the measurement is not absolute, but it is the distance variation which is detected, an elaboration of the collected data must be done after the acquisition. The measurements are set to zero by subtracting the mean value obtained when the bearing is not raised and touches the basement. This operation is performed for each capacitive sensor, separately. Moreover, the sensors measure a value that reduces as long as the meatus height increases, because, while lifting, the bearing gets closer to the sensors. Thus, it is necessary to invert the sign of the results, to have a clearer representation of the behaviour.

By means of the cable described before, the sensors are connected to an acquisition module, which is mainly in charge of giving power to the sensors, receive the signals and amplify them. The box is represented in figure 8.2 and is the model DT6220 with four expansions DL6220. It is able to manage four capacitive sensors. The device is fed by a 24 V power supply and has four input pins to receive the capacitive sensor signals and four ports to send the read signal to the acquisition board, by means of BNC cables.

The box has also some LEDs, labelled with “range” which are useful for the initial calibration and positioning of the sensors and some other which inform the user if some filters are enabled. The mounting of the sensors at the correct distance from

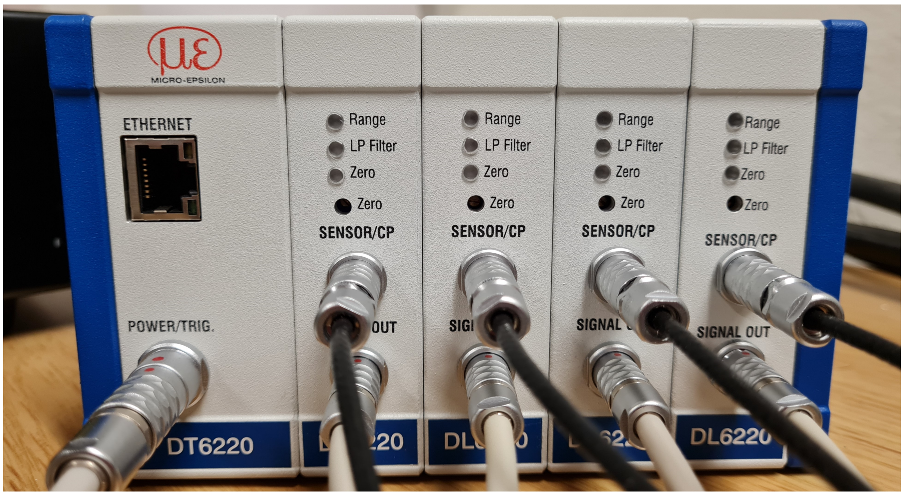


Figure 8.2. Capacitive sensors acquisition device.

the bearing is essential, because otherwise the measure cannot be performed. In fact, those sensors can only read distance variation between 0 and 200 µm, thus, at the beginning of any experiment, it is necessary to check that the distance between sensor and bearing falls inside the working range. To do so, it is sufficient to check that the "range" light is green. If it is not, it is sufficient to move upwards or downwards the sensor to adjust the gap between itself and the bearing. When this operation is performed, it is necessary to pay attention that the sensor does not touch the metal plate, to be sure the bearing can move freely. This is important because the "range" lights are green also for very small or null distance values between the sensor and the plate, thus, it is convenient to check by looking that a gap is still present by using, for example, a paper sheet which must be able to pass under the sensor.

During the experiments performed, the four capacitive sensors were always acquired following the same ordering: each sensor in a specific position is always numbered in the same way, in order to be able to better compare the different results. The numeration is the one reported in chapter 4 in figure 4.6.

Chapter 9

Load Cells

In the performed experiments, two kind of test-benches were used: the Mager bench and the Step bench. Due to laboratory organization, it was preferred not to move the load cells mounted on the different benches. Moreover, not all the used cells were compatible on both the benches, due to different connection interfaces and dimensions. For this reasons, the load cells used were two:

- HBM U9C
- KISTLER 9313AA1

Cell on the Mager test-bench The HBM cell is mounted on the Mager bench and can reach a load of 20 kN. It is connected to an amplifier produced by HBM of model AE101. It has the role of making the very small signal coming from the cell readable by the acquisition system. Then, the amplifier is powered by a 24V generator and directly connected to the acquisition board. In this case, the load cell is an absolute cell, that, once calibrated, returns a voltage value which corresponds to the actual force loaded on it, differently from the load cell of the Step test-bench, which provides a variation of force, not the absolute one, as it will be described in the following paragraphs. For this reason, there is no need of any software running on the main pc to enable or disable the cell, even if it requires an initial calibration, anyway.

Cell on the Step test-bench The KISTLER cell is mounted on the Step test-bench and it is connected to the KISTLER amplifier type 5073. This amplifier can accommodate three load cells, but in this case, only one slot is used. The amplifier is connected to the acquisition board through a BNC cable and it is also necessary to connect it to the main pc, in order to activate the load cell measurement by means of a software. This kind of cell, in fact, is not an absolute cell, measuring the actual force loaded on it, but it measures the load differences. This means that, before the measuring starts, the cell must be set to zero and, during the experiment, it will record the positive or negative load differences. Then, in the recorded data elaboration, it is necessary to add the value of the weight loaded on the cell in the moment at which the cell was set to zero. In this way it is possible to visualize the actual load on the bearing.

As said before, the amplifier is connected to the computer through a D-SUB 9 PINS connector. The software ManuWare, running on the main pc, allows to set the cell parameters, such as the sensitivity and the range. Figure 9.1 reports the configuration used. In this case, two possible ranges were created, one of 5000N and one of 500N. Before starting the laboratory activity, it is important to select the most appropriate range to use, in order to have the best sensitivity during the acquisition. Once the range is set, it is necessary to start the measure session of the cell every time a new experiment is performed and then put the cell in pause mode again. During the acquisition, the green led on the amplifier must be solid, while, during the pause mode, the green light flashes.

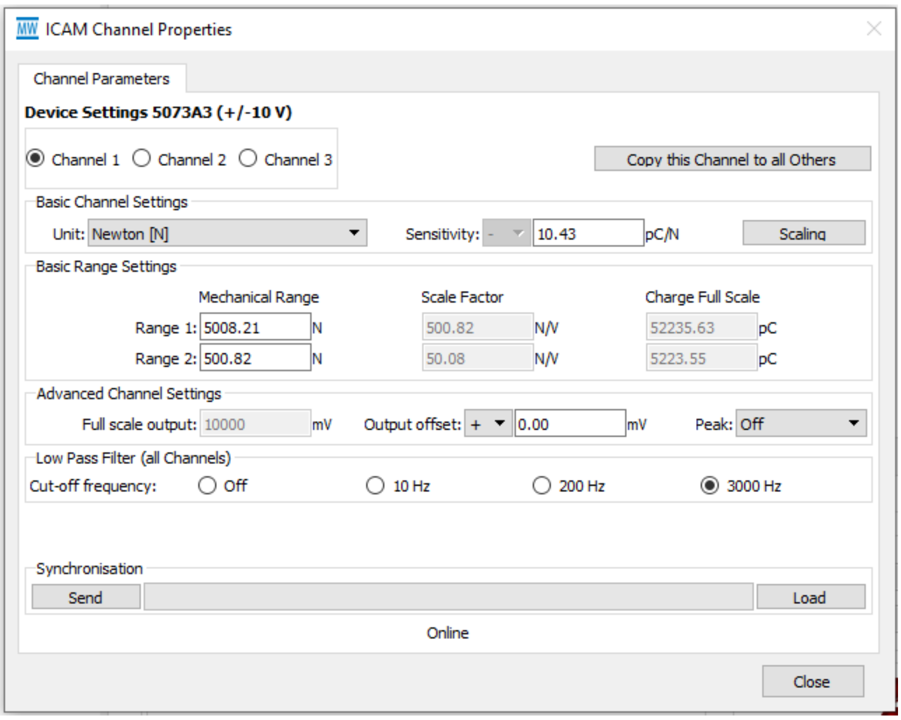


Figure 9.1. Configuration of the Kistler load cell in ManuWare software.

Chapter 10

Board

In this thesis, it is necessary to have a control unit board with the role of performing all the calculations, useful for the generation of the control action. Moreover, the board is not only used for the closed loop phase, but also to control the opening level of the valve, during the executed experiments.

Since the valve is a proportional one, it is necessary to have an analog signal exiting from the board, thus a digital to analog converter (DAC) integrated in the board. In fact, the operations inside the controller are performed in a digital way, while the signal needed is analog. The chosen board is the "Orange" model (figure 10.1), produced by What's next. This board is the analogous of the Arduino Due one.

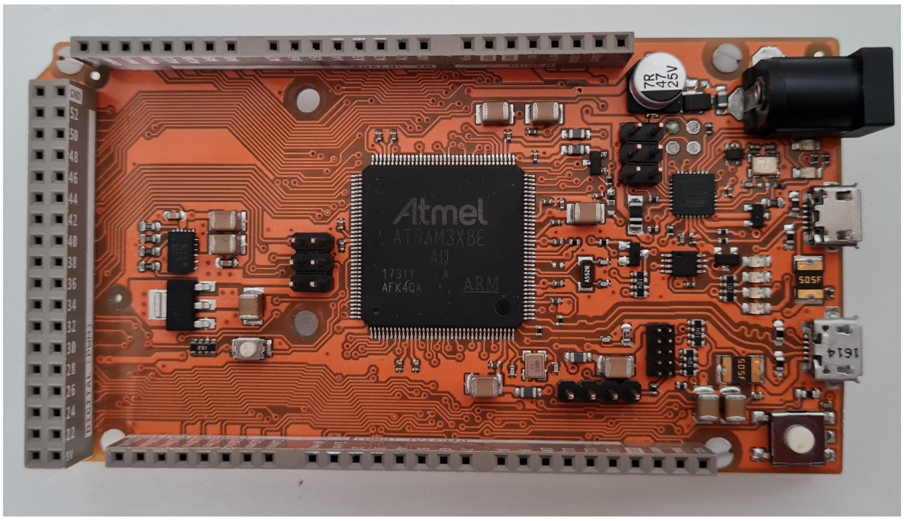


Figure 10.1. Orange control board, by What's next.

This board has two DAC pin ports with a 12-bit resolution (4096 levels), which are used for the valve opening control. It must be considered that the voltage range coming from the DAC pins is between 0.55 V and 2.75 V. The board can be powered through a 5 V micro usb port (the one in the centre of the board, closer to the black plug, in the figure), which can be also used for programming it. The processor clock is 84 MHz.

At first, the aim was to write the program through the Arduino Ide software, using the Arduino programming language, but there was no compatibility with this board. The chosen alternative is to use the Simulink software, which allows to recognize and use the “Orange” board. The generated program is based on different connected blocks and then compiled and sent to the board. To be able to use Simulink to program the board, it is necessary to install the specific Matlab toolbox for the Arduino programming.

Chapter 11

Back-pressure Sensors

For the evaluation of the bearing lifting, two back-pressure sensors are fixed on the two shortest sides of the bearing. Due to the space needed to accommodate those sensors, only two of them were used and not four, like it was chosen for the capacitive sensors.

The back-pressure sensors are composed by an inlet hole, a chamber, an exhaust hole and a membrane of the pressure sensor, as represented in figure 11.1. From the inlet hole, the pressurized air is sent into the chamber, while the exhaust hole is positioned on the lower part of the system and continuously discharges the chamber. The air passage through this second hole is partially obstructed by the presence of the basement, where the bearing lays, therefore, the resistance opposed to the air flow depends on the distance "h" between the bearing and the floor. Depending on the amount of air exiting from the chamber, the pressure inside the sensor varies, deforming the membrane. On the base on the membrane deformation, a voltage signal is sent to the control board. In this way, the pressured air is exploited to evaluate the distance between the bearing and the floor. The voltage value produced by the device is read by the control board, as a feedback for the closed loop control.

The transducer membrane used in the back-pressure sensors is the Honeywell 40PC150G. They are feed with 5 VDC and can detect pressures ranging between 0 and 10 relative bar and an output signal between 0.5 V and 4.5V. It is important to connect the device in the right way, in order to both have a good measure and avoid damages of the structure. In figure 11.2 it is represented the wiring scheme to follow.

As said before (chapter 8), the lifting of the bearing is evaluated by means of the capacitive sensors, fixed on a structure and measuring the distance between them and a metal plate located on the bearing. The choice to introduce a second measuring system to evaluate the lifting of the bearing is due to the complexity of

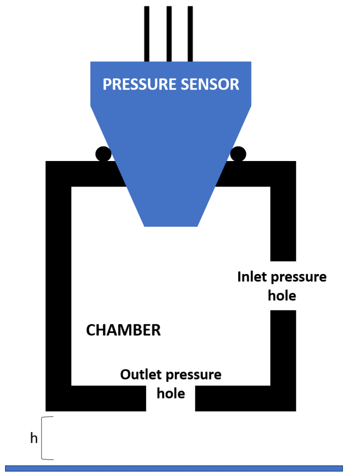


Figure 11.1. Back-pressure sensor scheme.

in the acquisition process of the capacitive sensors. First of all, the back-pressure sensors don't need a specific surface to work with, like the capacitive ones, that need a specific metal surface. Then, the sensors used directly provide a signal which is readable by the control board, without any kind of amplifier or acquisition module. Moreover, the back-pressure sensors are relatively compact and versatile. This makes the whole system easier to develop and requires less space on the hypothetical future final and commercial bearing. Another great advantage is that they work with 5 V tension, like the board itself.

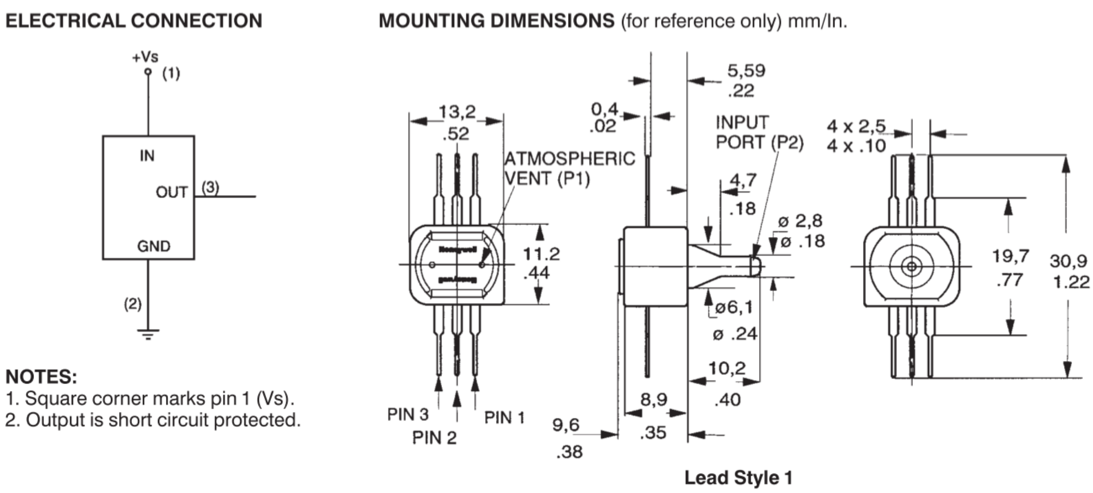


Figure 11.2. Back-pressure sensor wiring scheme.

Part III

Experimental Tests

Chapter 12

Matlab scripts

After each experiment performed, a very big number of data is collected in a ".txt" file. The Matlab software is used to elaborate and graphically represent those values. In this paragraph, the general approach to these files is described, in order to have a clearer understanding of the Matlab scripts, collected in Annex 1. Depending on the scope of each experiment and the graph that is aimed to obtain, some passages could be avoided.

The general approach in the scripts is the following:

- The desired collected data in the experiment are loaded in a program variable ("data"). (Figure 12.1)
- The moving mean is evaluated, in order to reduce the noise present it the measurements and to have a less disturbed representation. Different tests were performed and it was chosen a window of 100 elements to evaluate the moving mean. (Figure 12.2)
- The capacitive sensors are set to zero by evaluating the mean on the first 3000 capacitive data, corresponding to the first 3 seconds of acquisition. In this period, the bearing lays on the basement because the feeding air is closed. Then, this mean is subtracted to each value. At the same time, the sign is changed in order to have an increasing value as long as the bearing distance from the basement increases. (Figure 12.3)
- For each loading condition, a mean value is evaluated in order to have a single lifting value for each load. The first time, the ranges must be tuned. (Figure 12.4)
- The mean over the four capacitive sensors is performed, in order to have a single value representing the bearing height for each instant. (Figure 12.5)

```
%data acquisition
data = load('prova_statica_ciclo_completo_5bar_1_70V__1.txt');
for i = 1:4
    capac_5bar_1_70V(:,i) = data(:,i);
end
loadCell_5bar_1_70V = data(:,5)+(45+m_support)*g;
```

Figure 12.1. Data loading in the program variables.

```
% % % move mean
for i = 1:4
    capac_5bar_1_70V(:,i) = movmean(capac_5bar_1_70V(:,i),100);
end
loadCell_5bar_1_70V = movmean(loadCell_5bar_1_70V,100);
```

Figure 12.2. Moving mean evaluation.

```
for i = 1:4
    base_mean_capac_5bar_1_70V(i) = mean(capac_5bar_1_70V((1:3000),i));
end
for i = 1:4
    capac_5bar_1_70V(:,i) = -1*(capac_5bar_1_70V(:,i) - base_mean_capac_5bar_1_70V(1,i));
end
```

Figure 12.3. Setting to zero and sign changing of the capacitive sensors.

```
for i = 1:4
    single_values_5bar_1_70V(1,i) = mean(capac_5bar_1_70V((1:3000),i));
    single_values_5bar_1_70V(2,i) = mean(capac_5bar_1_70V((5500:7000),i));
    single_values_5bar_1_70V(3,i) = mean(capac_5bar_1_70V((8500:11000),i));
    single_values_5bar_1_70V(4,i) = mean(capac_5bar_1_70V((12900:14800),i));
    single_values_5bar_1_70V(5,i) = mean(capac_5bar_1_70V((16500:18500),i));
    single_values_5bar_1_70V(6,i) = mean(capac_5bar_1_70V((20500:23000),i));
    single_values_5bar_1_70V(7,i) = mean(capac_5bar_1_70V((26000:end),i));
end
```

Figure 12.4. Evaluation of one value for each loading condition.

```
for i = 1:length(capac_5bar_1_70V(:,1))
    capac_5bar_1_70V_mean(i) = mean(capac_5bar_1_70V(i,:));
end
```

Figure 12.5. Evaluation of the mean among the four capacitive sensors.

Chapter 13

Bearing characterization

13.1 Static curve with inlet air always opened

First approach in characterization The bearing is a device that exploits the pressure below itself to generate a vertical force and rise a weight which is loaded on it. The more the pressure is high under the bearing, the more the vertical force generated is huge. On the other hand, the more the bearing rises from the base, the more the pressured air can flow away in the room and the less the pressure under the bearing is. This means that there is a correspondence between the pressure generated, the height of the bearing and the weight put over the device. It is useful to understand which is the relationship between those factors, to be able to predict, at least in a rough way, the behaviour of the bearing. Moreover, in this way it is possible to choose the ranges to make the bearing work in the best way.

The characterization of the bearing is performed as follows:

- the bearing is loaded with the maximum load available: four weights of 5 kg each;
- the inlet air is closed, thus the bearing lays on the basement;
- the measurement session is started: the load cell and the LabView are activated;
- the inlet air is opened;
- the weights are removed one at a time;
- the inlet air is closed;
- the measurement session is stopped;

The measured values are collected in a ".txt" file where each column refers to a different sensor. In this case, the considered values are the first four columns, referring to the four capacitive sensors and the fifth one, corresponding to the load cell.

The experiment is performed many times, modifying the inlet pressure feeding the bearing and the opening of the valve. The tested pressures are 4, 5 and 6 bar relative. To have different opening levels of the valve, it is used the controller board with a Simulink program loaded on it (figure 13.1) that provided different voltage levels to the output pin controlling the valve. The chosen levels are 1.20V, 1.30V, 1.40V, 1.50V, 1.62V, 1.70V, 2.00V, 2.30V and 2.75V, where 1.20V corresponds to an almost closed valve and 2.75V corresponds to fully opened valve. Some other tests with lower tension values were performed but the valve opened so little that no lifting effect was experienced.

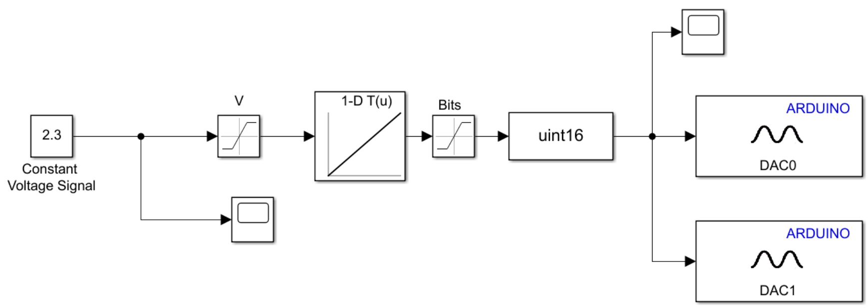


Figure 13.1. Simulink model for the valve opening control.

In the reported Simulink, the voltage signal is defined in a constant value block. Then, a saturation is placed to keep the signal between 0.55 V and 2.75 V, to avoid any damage. The other blocks are useful for the signal conditioning, in order to pass the information to the analog pin of the control board.

The data are processed with the software Matlab, following the procedure described in chapter 12. The representation of the values recorded by the capacitive sensors along the time is reported in figure 13.2. For each valve opening, the four capacitive sensors are represented.

Each step of the previous graphs represents the meatus variation in correspondence of the reduction of number of loaded weights: removing a 5 kg mass, the meatus under the bearing increases, as expected. From the figure 13.2, it is encountered a tilting phenomenon, in fact, the four curves related to the four capacitive

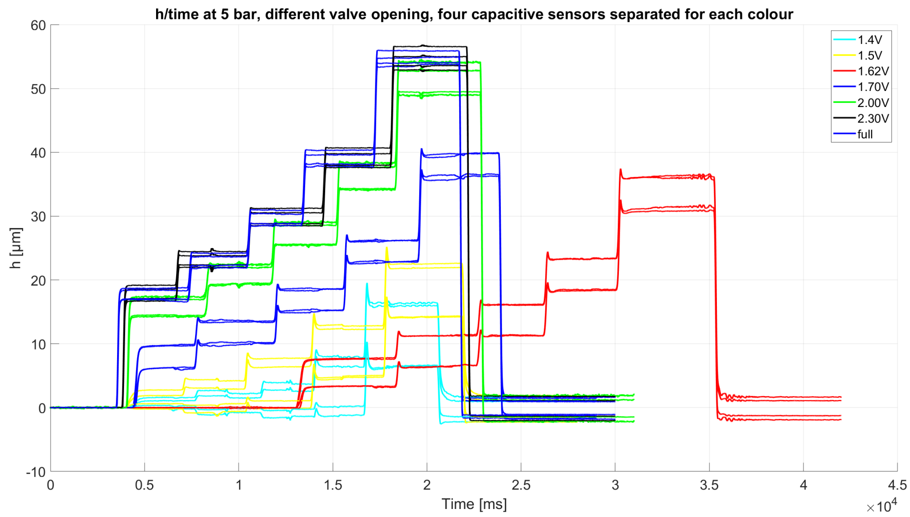


Figure 13.2. Capacitive sensors representation over the time, for different valve opening, during the static characterization.

sensors are not overlapped, meaning that some corner of the bearing lifted more than others, thus the bearing didn't move parallel to the ground. This effect is further analysed in chapter 15, dedicated to the bearing tilting. Another interesting point is that the capacitive sensors at the end, when the air is removed again, do not return to a value of zero, like at the beginning. This is due to the deformations that occur on the bearing and on the test-bench when the load is applied. Since the capacitive sensors are set to zero when the maximum load tested is applied, the value at the end, without weights, results to be different from the one at the beginning.

Then, for each weight loaded on the bearing, the mean of the capacitive values is taken in the lapse of time in which that weight is present. In this way, a vector of meatus values for each load was obtained and plotted against the corresponding force exerted on the bearing, expressed on Newton. In figures 13.3, 13.4 and 13.5, each plot refers to a different inlet pressure and for each pressure, the different curves represent the various valve opening, expressed in volt.

The meatus height is represented on the abscissa axis, while on the ordinate axis there is the force applied. For very small valve openings, the bearing remains almost always on the basement, without lifting.

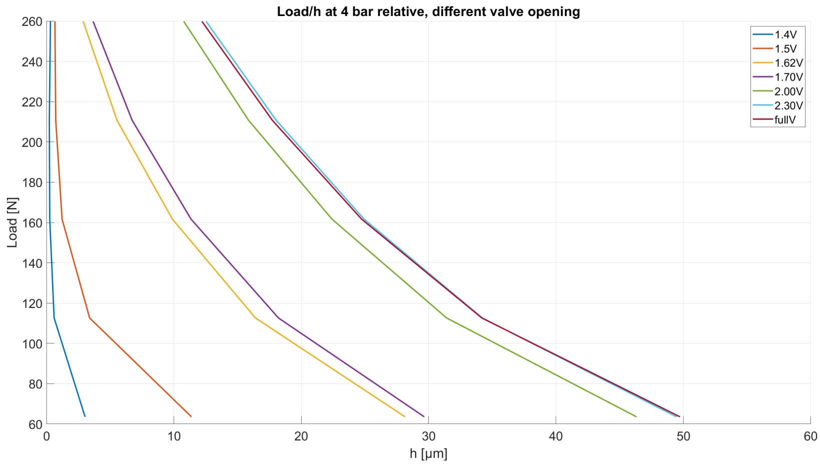


Figure 13.3. Static characterization with inlet air always opened (inlet pressure: 4 bar relative).

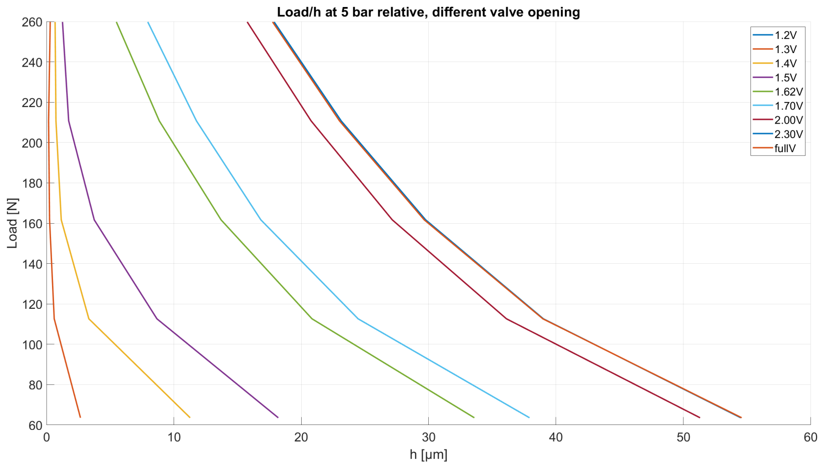


Figure 13.4. Static characterization with inlet air always opened (inlet pressure: 5 bar relative).

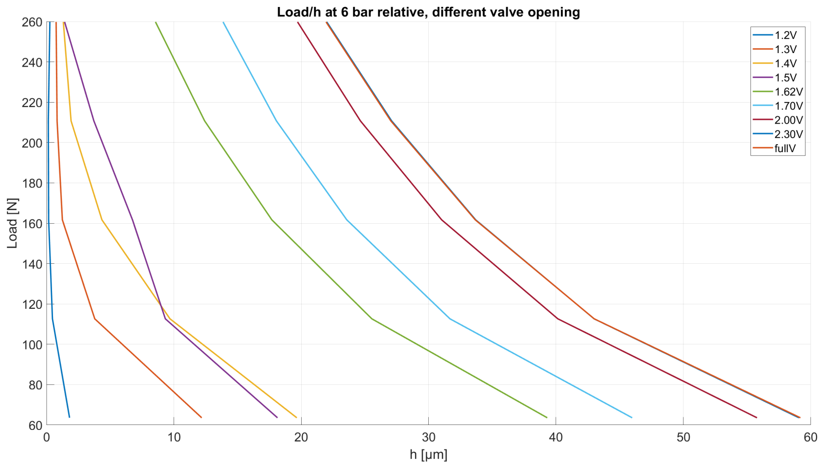


Figure 13.5. Static characterization with inlet air always opened (inlet pressure: 6 bar relative).

13.2 Complete cycle static curve

Improvement in the characterization After the first approach in the characterization, a more accurate one was performed. It was decided to increase the amount of maximum weight to load on the bearing arriving to 45 kg: nine weights of 5 kg each. It is also decided to test the stiffness of the bench, by performing slightly different sequence in the characterization of the bearing. As before, the test starts without inlet pressured air and the bearing fully loaded. Then the air is opened and the weights are removed one by one. After that, the air is removed again and the weights are loaded again on the bearing, which is laying on the basement.

In figure 13.6, 13.7 and 13.8 the plots of the force against the meatus are reported and they represent the complete measuring cycle performed. Each graph represents a different inlet pressure value and each curve is relative to a different opening of the valve. They must be read in clockwise, starting from the top left corner, where no air and maximum load are represented. The bearing lifts when the air is provided and the meatus is increasing as long as the weight is reduced, as expected. Once reached the bottom right corner, the air is removed, making the meatus go to almost zero. Then, the weights are loaded again, pushing down the bearing on the basement and coming back to the initial condition. The curve is not smooth, due to the small transitory effects generated by the removal or positioning of the weights during the experiment session.

From the graphs it is possible to see that, when the load is removed and the inlet pressured air is closed, the bearing doesn't go back to meatus equal to zero. Only by applying all the weights again, it is possible to see the bearing reaches the initial null lift value. This is ascribable to the non-infinite stiffness of the bench and a possible bending of the bearing. In fact, the set to zero is performed at the beginning, with a full load. When the load is removed, the bearing is not pushed down with the same force and, from the point of view of the capacitive sensors, it seems to be a little bit lifted. Only by applying the full load again, the bearing and the bench are pressed and the capacitive sensors detect a null meatus. It must be noticed that this deformation is of the order of 2 µm, thus, not so big. To have a better representation of the bearing behaviour, according to the loaded weight, it would be better to subtract the curve obtained without air to the curve obtained when the inlet pressured air was activated. In this way, the bending effect of the bearing and the bench is reduced as much as possible.

From the graph of the force against the meatus is possible to extract a portion, corresponding to the possible utilization range of the bearing. A good working windows is between 5 µm and 20 µm. In figure 13.9, it is represented the portion of interest, for an input pressure of 5 bar relative.

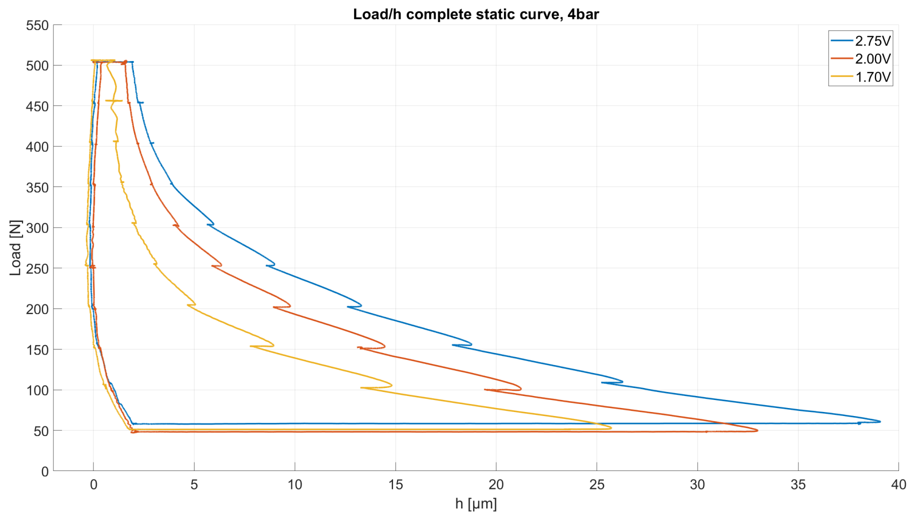


Figure 13.6. Complete static curve at 4 bar relative inlet pressure.

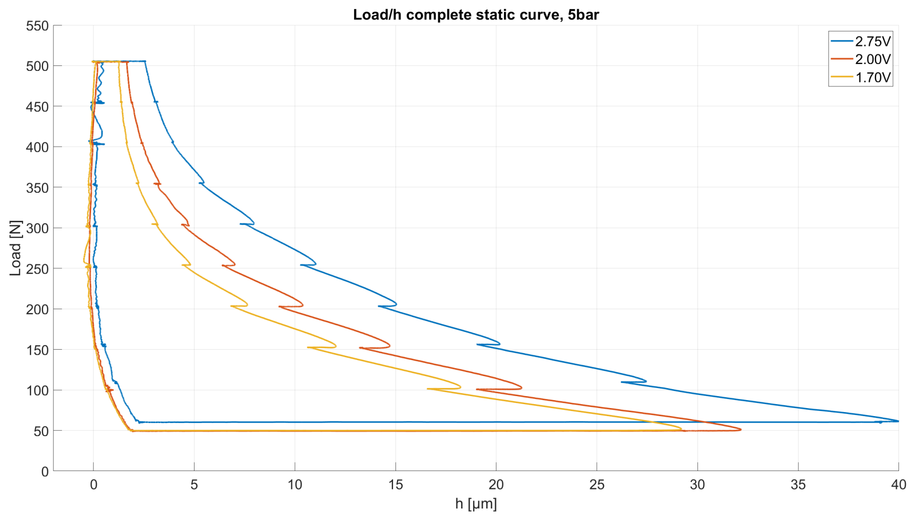


Figure 13.7. Complete static curve at 5 bar relative inlet pressure.

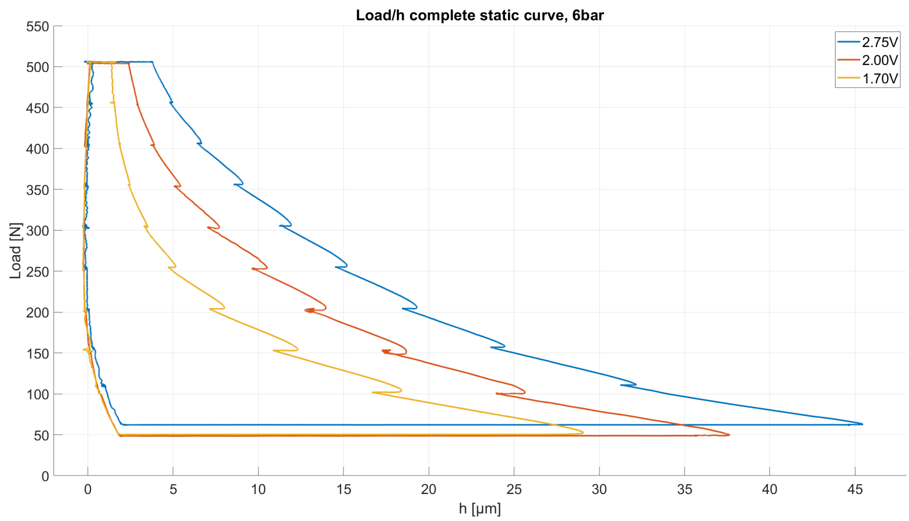


Figure 13.8. Complete static curve at 6 bar relative inlet pressure.

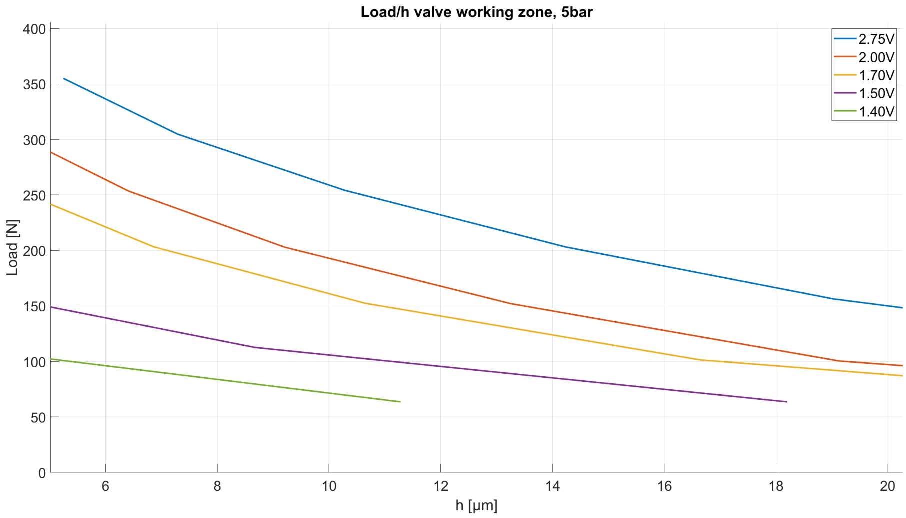


Figure 13.9. Bearing working zone at 5 bar relative inlet pressure.

From the graph it appears that with a required meatus of 10 μm, the possible load which is applicable is about 250 N, using 5 bar as inlet pressure. It is possible to increase the inlet pressure to have greater lifting capabilities. In figure 13.10, the pressure is 6 bar relative and the maximum weight, with a meatus of 10 μm, is greater than 320N.

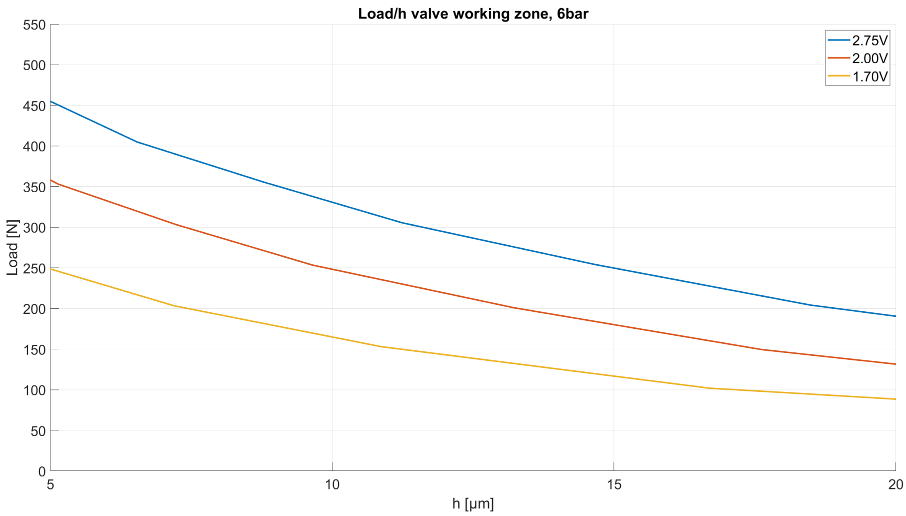


Figure 13.10. Bearing working zone at 6 bar relative inlet pressure.

Chapter 14

Proportional valve characterization

The valve used in this thesis was already tested in the previous thesis analysis, to prove the matching with the datasheet and determine some parameters. However, this characterization was based on the correspondence between the current input and the airflow passing through the valve. In the control loop, the board controls the valve with a voltage signal, the signal is converted into a current signal and the valve is opened or closed accordingly. This causes the bearing to increase or decrease the lift, which is the final goal of the system. For this reason, it was considered important to make some tests about the relationship between the voltage coming from the control board and the lift of the bearing.

The system is mainly influenced by two parameters:

- the voltage output of the control board;
- the weight loaded on the bearing;

Of course, there are also other elements influencing the device, such as the inlet air pressure to the valve, but in this case, they are kept constant, thus they are not considered as an influencing element. The experiment is performed keeping constant one of the two variable and modifying the other one. The Arduino board was programmed with a Simulink model, in order to generate a triangular output voltage signal to send to the converting box of the valve. The triangular signal ranges from 0.55 V to 2.75 V and it has a very low frequency to avoid dynamic transitory effects. During the experiment the four capacitors signals are collected, together with the real measurement of the signal generated by the board. This test is performed many times, varying the load on the bearing: about 64 N, 113 N, 162 N, 211 N, 260 N. The chosen values come from the weight of the structure over the bearing with the addition of different masses of 5 kg each, transformed in force pushing down the bearing. Figure 14.1 shows how the experiment is performed, representing the input voltage from the board on top and the measured lift from the capacitive sensors over the time on bottom.

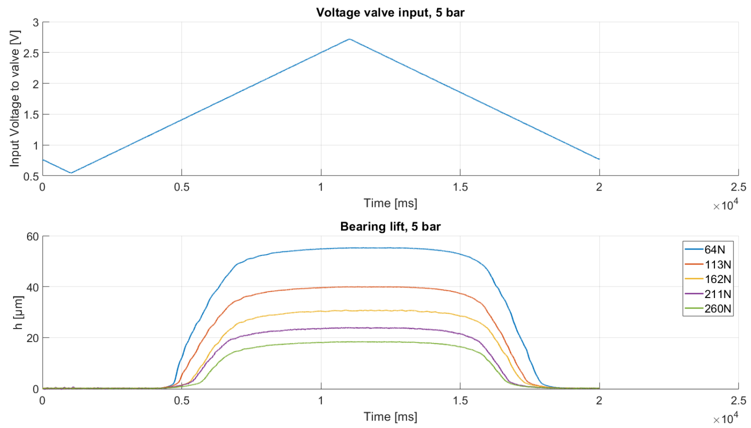


Figure 14.1. Voltage signal sent to the valve (top) and bearing elevation (bottom) during the valve characterization.

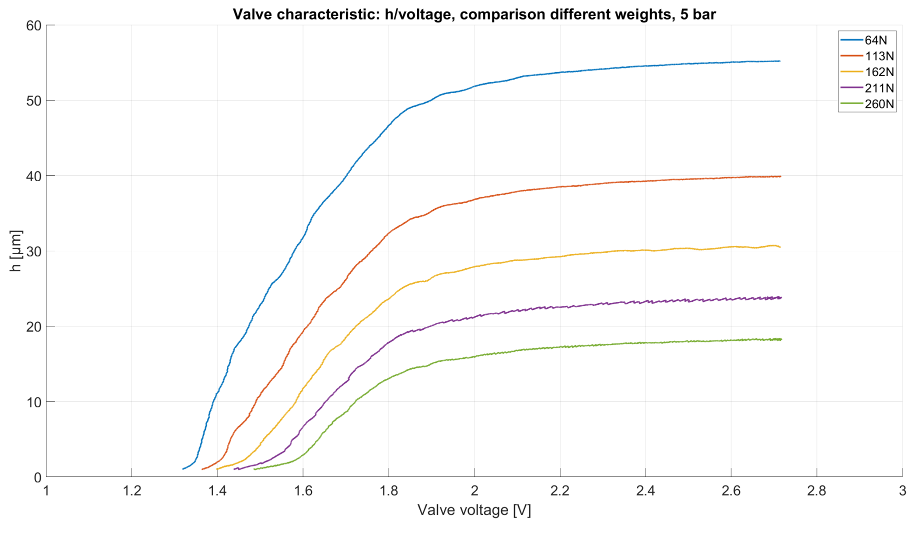


Figure 14.2. Meatus height against voltage sent to the valve for different bearing loads.

The result is a series of meatus height against input voltage graphs. They are shown in figure 14.2, where the abscissa represents the voltage input to the system, while the ordinate is the elevation of the bearing, expressed in µm. Each curve is relative to a different load. As expected, with lower loads the bearing rises more than with higher ones. These curves show a kind of saturation when the voltage increases over a certain point, making the bearing rise very little despite the voltage increase. Considering the portion of curve which is of our interest (between 5 µm and 15 µm) the curves are almost linear. Those curves are useful as a starting point for the creation of the control algorithm because they give the idea of the behaviour of the bearing, according to the variation of the voltage signal generated. Since the valve is not used by itself, but it is mounted on the bearing, several external factors contribute to modify the theoretical behaviour, reported in the datasheet. For this reason, it was decided to understand which was the voltage level at which the bearing actually started to lift, for the different loads. From the collected data, it was found the point where the bearing overcome the height of 1 µm and it was taken note of the corresponding voltage sent to the valve. The results are collected in table 14.1. The reported values depend on the weight loaded but they are around 1.4 V. Again, those values were used for the developing of the control action.

Loading conditions [N]	Valve voltage signal [V]
64	1.32
113	1.36
162	1.40
211	1.44
260	1.48

Table 14.1. Valve voltage signal at which corresponds a bearing lift of 1 µm for different loading conditions at 5 bar relative inlet pressure. The load includes the masses and the structure to carry them.

Chapter 15

Bearing tilting

By looking at figure 13.2, in the bearing characterization in chapter 13, where the data collected by the capacitive sensors are plotted against the time, it can be noticed that the four capacitive sensors are not overlapped. For this reason, a possible tilting of the bearing was considered and investigated by performing new tests.

The followed approach is quite simple. The bearing is loaded with masses of 15 kg, the measurement is started and the inlet air is opened and closed a couple of times. The results are shown in figures 15.1 and 15.2.

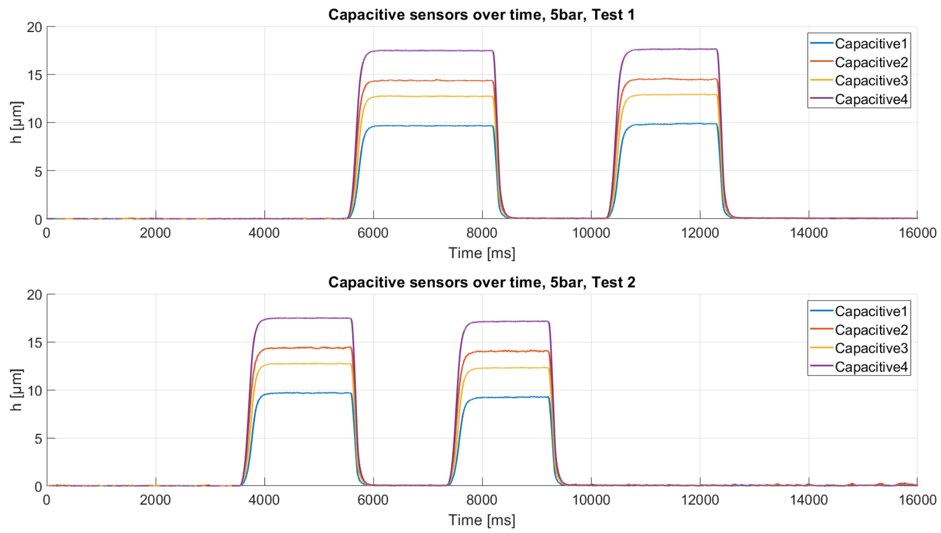


Figure 15.1. Tilting tests 1 and 2: capacitive sensors along the time.

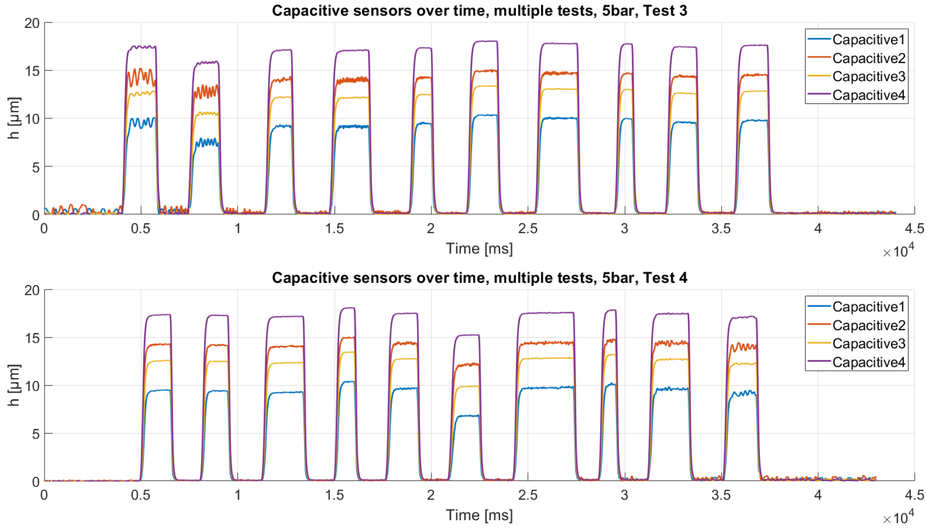


Figure 15.2. Tilting tests 3 and 4: capacitive sensors along the time.

In the graphs, the capacitive values are represented along the time. The point where the air was closed are well visible, in fact, the bearing lays on the basement and the sensors measure a null lift. When the air is opened, the bearing rises and each capacitive sensor record a different value. Figure 4.6 in the capacitive sensors chapter 4 reports the top view scheme of the bearing, with the position of the capacitive sensors (1, 2, 3,and 4) and of the back-pressure sensors, to better understand their location.

From the graphs, it is possible to se that a tilting of the bearing occurs, because the capacitive sensor report different final height, even thought they start from the same level zero. Reasoning on the sensor position, the tilting occurs more or less along an axis passing through sensors 2 and 3, and the sensor 4 rises more than the sensor 1. The lifting difference between 1 and 4 is almost 8 µm, which is a quite relevant value.

The tilting effect can be ascribed to the meatus height, that can be too big for this kind of bearing. In fact, sensor 4 reaches the value of about 17 µm, but the bearing working point is around 10 µm. Even if the bearing does not rise perfectly parallel to the ground, it is important that, once it is loaded, the lower surface of the device does not touch the ground. If this happens, the tilting problem can be neglected.

The measurement is repeated more than one time to check the repeatability of this behaviour. It is also evaluated the variance of each capacitive sensor along the different repetitions. The results are reported in table 15.1. The obtained variance is very little, showing that the bearing behaviour is quite repeatable.

Capacitive sensor	Mean	Variance
1	9.46	0.63
2	14.20	0.39
3	12.48	0.63
4	17.29	0.39

Table 15.1. For each capacitive sensor, the mean of the peaks obtained during the repetitions and the variance of those peaks is reported.

Another possible cause of the tilting can be addressed to the presence of pipes and cables connected to the device. Those elements can exert tilting forces on the bearing, making it incline. To avoid this effect, it was tried to put some tape to fix the pipes and the cables to the structure, in order to avoid as much as possible their interference. Figure 15.3 represents the bearing in three conditions: without any tape, with the tape on the electrical cables and with the tape on the electrical and pneumatic cables.

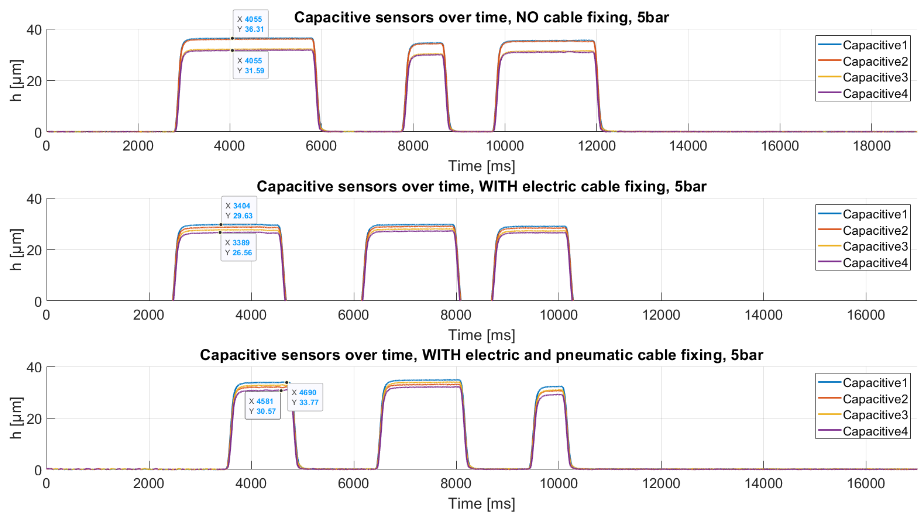


Figure 15.3. Bearing lift with different conditions of tape cable fixing.

As it is possible to see, there is an improvement in the maximum difference between capacitive sensors values passing from the bearing without tape (about 5 µm) to the bearing with the tape applied to the electric cables (about 3 µm). Instead, by also fixing the pneumatic cables, the improvement is very little. For this reason, for the further experiments, it was chosen to fix only the electric cables, since fixing the pneumatic ones is not very easy and the advantages are small.

Chapter 16

Back-pressure Sensors Characterization

16.1 Mager test-bench

To use the back-pressure sensors, it is necessary to have a relation between the voltage read by the control board and the actual lift of the bearing. To do that, a characterization is needed. At first, only the pressure transducer was tested, verifying that the device in the laboratory complied with the datasheet information and ranges. This evaluation was conducted in the previous thesis, by directly connecting the pressurized air to the sensor and by modifying the pressure. In this way a voltage-to-pressure graph was obtained. The pressure was both increased and decreased, in order to identify any possible hysteresis. In figure 16.1 the results are reported, relative to the left and right sensors [4].

As it is possible to see, the characteristic is linear and there is not any evidence of an hysteresis phenomena. This is convenient because a hysteresis on the measurements would have brought to a very complex data reading and interpretation. Moreover, it is possible to see that the sensors range between 0.5 V and 4.5 V, respectively corresponding to 0 bar and 10 bar relative.

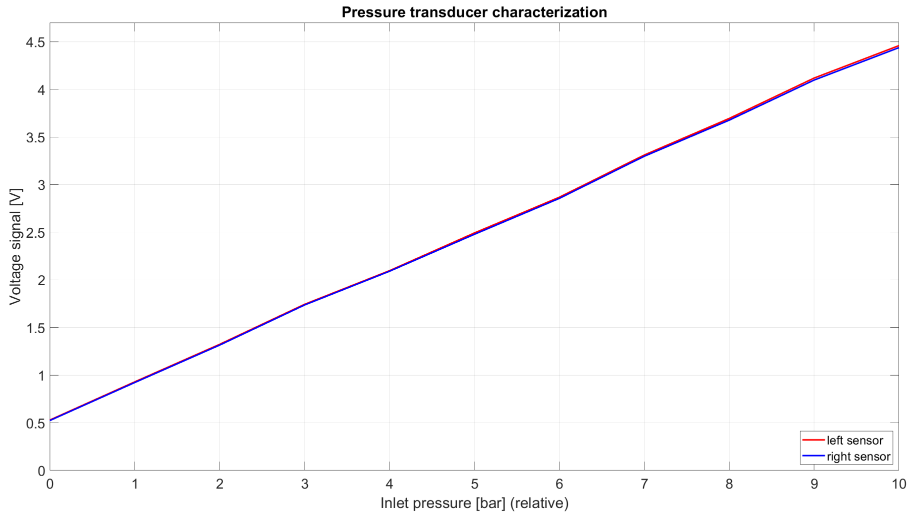


Figure 16.1. Pressure transducer characterization: voltage signal against inlet pressure [4].

16.2 Step test-bench

In order to use in the correct way the information sent to the board during the control action, it is necessary to have a characterization of the sensors, defining a correspondence between the output voltage and the bearing lift. The characterization is based on the comparison between the capacitive sensors measurements (in µm) and the voltage value read by the control board, with the aim of connecting each voltage value detected with the correspondent bearing lift.

At the beginning, the idea was to use the back-pressure sensors already installed on the bearing, but after some quick tests about the working ranges, performed with a multimeter, it was realized that the voltage range produced by both the transducer was too low. The conclusion was that the sensors were probably damaged. Therefore, another sensor was placed in its position and the calibration was performed on it. It was decided that, as a starting point, only one back-pressure sensor could be enough to perform initial closed loop tests. As a further improvement, another sensor, on the other side, could be implemented.

First of all, the aim was to evaluate the voltage ranges covered by the sensors in real operating conditions. A simple Simulink model was written and loaded on the control board, in order to make the proportional valve open and close slowly and continuously. The scheme is represented in figure 16.2. The board is asked to generate a triangular waveform signal from 0.55 V to 2.75 V, which is sent to the voltage-to-current converting box and then to the valve. In this way, the valve slowly opens and closes making the bearing rise and fall. The results are reported in figure 16.3 and it is possible to notice that, in order to cover a bearing motion of about 40 µm, the sensor ranges form 0.8 V to 1.1 V.

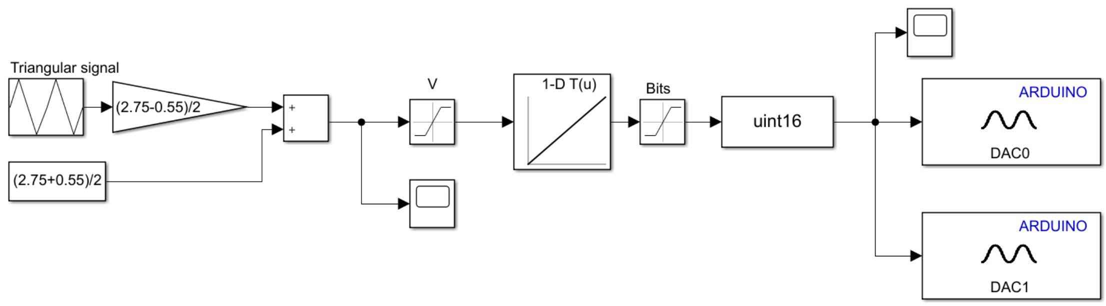


Figure 16.2. Simulink: triangular signal generation.

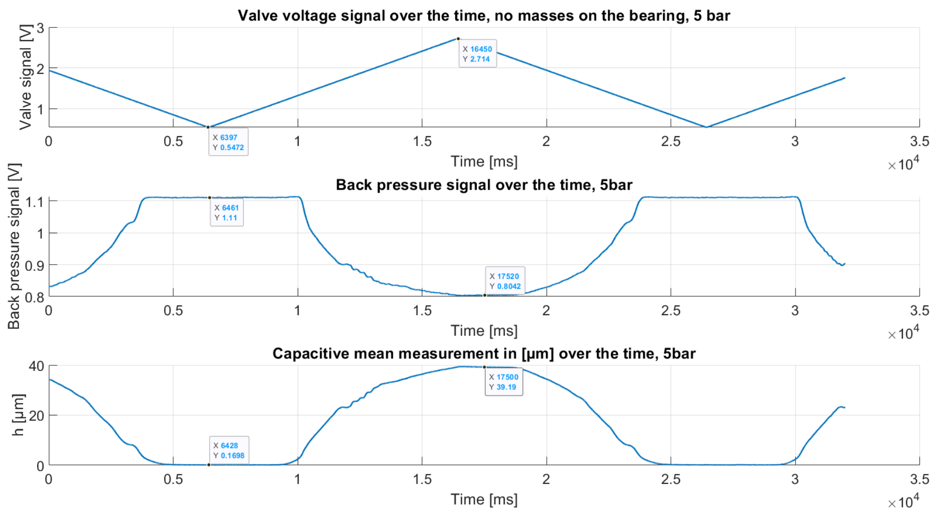


Figure 16.3. Representation of the test performed: triangular wave as input to the valve and evaluation of the signal generated by the back-pressure sensor and the bearing lift. The load on the bearing is null to have the biggest signal variation possible.

The second part of the characterization aims at relating the sensor voltage output to the actual bearing lift. The elevation (measured through the capacitive sensors) and the voltage signal coming from the back-pressure sensors are measured and recorded in a file. Then, it was possible to plot a graph representing the voltage generated by the sensors according to the bearing lift, as represented in figure 16.4. In the graph, different curves are reported, one for each different load applied to the bearing.

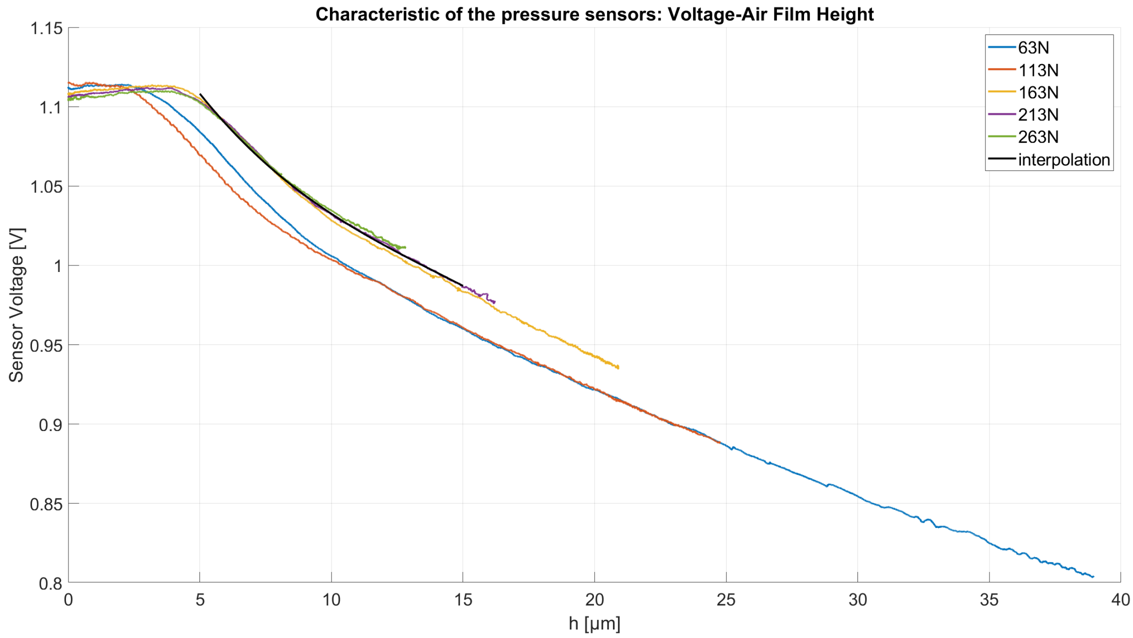


Figure 16.4. Voltage signal of the back-pressure sensor against the bearing lift.

In this case, the curves relative to different loads are not overlapped. This is not an expected result because the investigated relation is between the bearing lift and the voltage signal of the back-pressure sensors, which should not depend on the load on the bearing. The only effect of a higher weight on the bearing is that the maximum lift is reduced, but the relation between the lift and the signal was expected to be the same. A possible explanation can be the presence of a different tilting effect on the bearing when the load is increased: this can bring to have a different lift of the capacitive sensors and the back-pressure sensor, since they are not positioned exactly in the same point. Moreover, the bearing has probably a deformation when the load is applied, which brings to have different measurements for different applied loads. Instead, the expected load effect is visible in the graph where the curves corresponding to higher loads are shorter. This is because the maximum bearing lift is smaller, thus a smaller number of data is available for the plot.

To face this problem, it was decided to use the higher loads curves to make the interpolation, because they are the curves which are closer to a real working condition: the bearing will be more likely highly loaded instead of being almost unloaded.

The black line shown in the graph in figure 16.4 is the interpolation of the third order of the curves. This value is useful in the closed loop control to be able to pass from the voltage signal to the meatus height. To use the interpolation law in the control loop it is necessary to switch the input and the output, thus, another interpolation is performed obtaining the formula 16.1 as a result:

$$h = -606.8V^3 + 2275.3V^2 - 2849.9V + 1194.7 \tag{16.1}$$

To test the conversion formula of the back-pressure sensors, the static curve is represented with the curve obtained by means of the conversion. The result is reported in figure 16.5

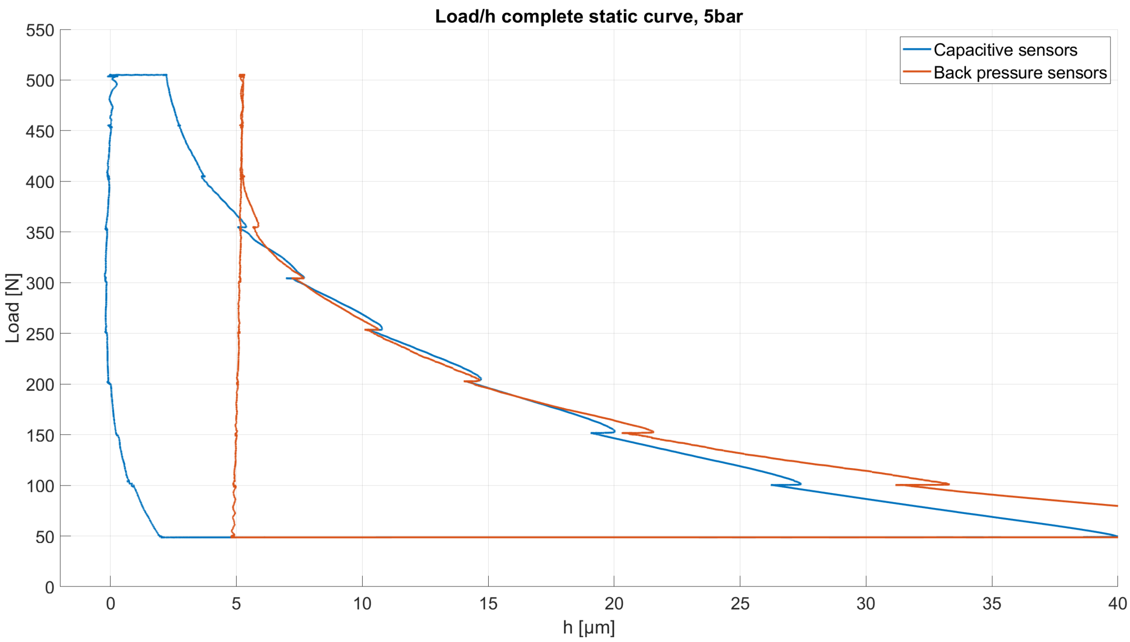


Figure 16.5. Comparison between the static curve obtained with the capacitive sensors and the curve obtained with the back-pressure sensors and the interpolating formula.

From the graph, it is visible that the correspondence between the two cycles is quite precise inside a meatus range between 5 μm and 20 μm. In other points of the cycle, the curves do not match. This is not very important because the bearing will be used in the range where the correspondence exists, thus the rest of the curve does not affect too much the bearing behaviour. From this consideration it is possible to be quite confident in the use of the conversion 16.1 in the closed loop control of the active bearing.

Moreover, from the graph in figure 16.4, it is possible to see that the curves from h = 0 to h = 5 µm are almost horizontal. This means that the sensor is not able to detect any air film variation between these two values. The effect is reflected in figure 16.5, where the representation based on the back-pressure sensor does not go under the height of about 5 µm. As said before, this is not a problem for our purposes because it is out of the bearing working range.

Chapter 17

Comparison between the Mager and the Step test-bench

In this thesis experience, two test-benches were used to perform experiments and to verify the behaviour of the pneumostatic bearing. In particular, the Mager test-bench was mainly used during the initial tests and then it was decided to pass to the Step bench to perform other experiments in other conditions.

The main curves investigated were those relative to the static behaviour of the bearing, such as those in figure 13.7 in chapter 13. These curves represent the correspondence between the force applied over the bearing and the meatus height reached, for a specific valve opening. This curve is important in order to know the behaviour of the device, thus, it was decided to make a comparison between the curve obtained on the Mager test-bench and the one obtained on the Step.

For both the benches, the same procedure was followed:

- the bearing proportional valve was fully opened;
- at the beginning, the inlet air was closed and the device was loaded with the maximum weight or the maximum force possible on the bench;
- the air was opened;
- the load was gradually decreased until the bearing was unloaded;
- the inlet air was closed;
- the load was increased again, until the maximum initial value;

The results are collected with the LabView software by means of the acquisition module. In this case, the most important parameters collected were:

- the 4 capacitive sensors values, for the bearing lift determination;
- the load measured by the load cell;

Those parameters allow to draw the static characteristic graph. The two test-benches have some little differences, such as the maximum possible load which can be put on the device. The Mager, indeed, is based on a wheel and a screw that pushes down the bearing, thus, it is possible to apply a very big load by only turning the wheel. On the other hand, the Step test-bench load is generated by adding different weights on top of the bearing. Due to the laboratory conditions, it was possible to add masses to arrive to a maximum of 45 kg, in addition to the structure to accommodate the weights themselves. For this reason, during the tests on the Mager bench, it was decided to avoid loading the bearing too much, to have comparable working conditions between the benches.

From figure 17.1 and figure 17.2, it is possible to see how the experiment was conducted for the Mager and the Step bench respectively. Looking at the load cell data, the first bench has a continuous variation, because the force is generated with the rotation of the screw, while the second has some step variations of the load, due to the removal or addition of single masses of 5 kg each. Then, collected the data, the force was plotted against the mean of the capacitive sensors. From those graphs, a tilting effect is visible in the representation of the single capacitive values set to zero. The maximum difference between the highest and the lowest value is about 15 µm for both benches.

The static characteristic of the bearing on the Mager bench was also obtained during the previous thesis experiences [5], thus the comparisons are:

- the Step bench with the Mager bench using the previous thesis experiments (figure 17.3)
- the Step bench with the Mager bench using the current thesis experiments (figure 17.4)

In general, the measurement concerns also the part where the bearing is not fed with air and the load is increased again. This part is useful to determine the stiffness of the bearing and the bench where the experiment is performed. In fact, the meatus height is not directly measured, but, with the capacitive sensors, it is evaluated the motion of the upper part of the bearing. Then, this motion is

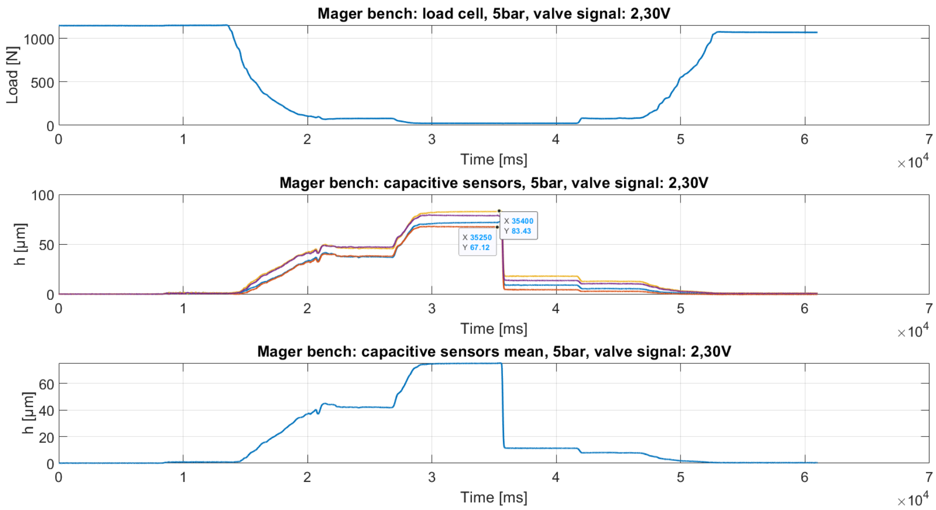


Figure 17.1. Static characterization execution on Mager test-bench.

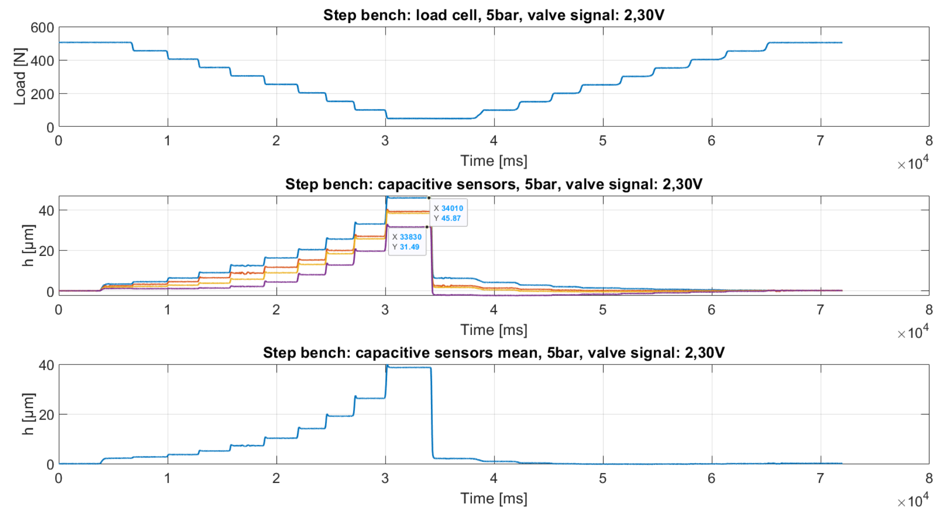


Figure 17.2. Static characterization execution on Step test-bench.

associated to the bearing lift as a rigid correspondence, but this is not exactly true. In fact, the device itself and the bench basement can have some deformations. By loading the system again, without air, it is possible to evaluate this deformation, because the height variation detected by the capacitive sensors can only be ascribed to the material bending. In this way, for each loading condition, the deformation

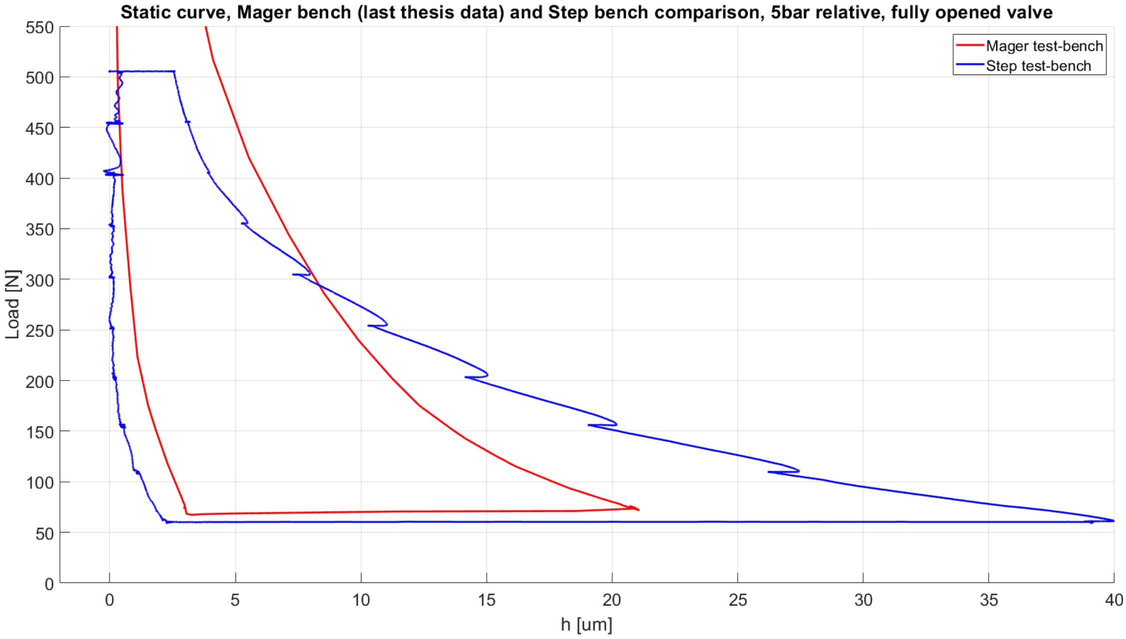


Figure 17.3. Static curve: comparison between Step bench and Mager bench (with previous thesis data).

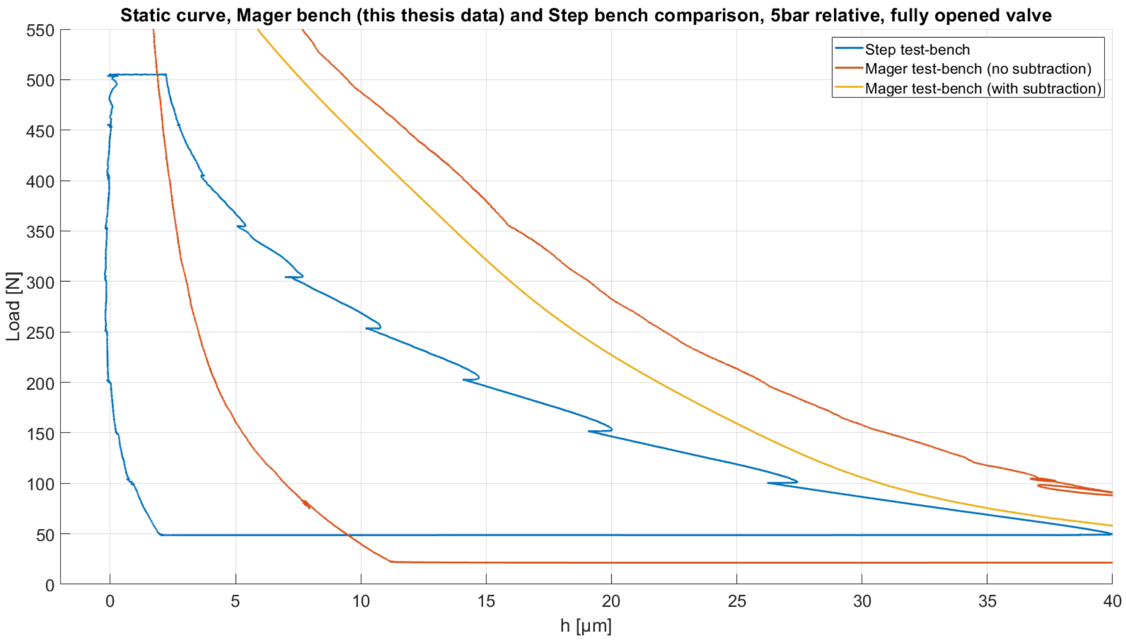


Figure 17.4. Static curve: comparison between Step bench and Mager bench (with current thesis data). The yellow curve refers to the static curve on the Mager, after the subtraction of the part obtained without inlet air.

is detected, and it can be subtracted from the curve acquired with the inlet air opened, obtaining a curve which better reflects the actual bearing lift. Figure 17.4 reports the curve detected during the experiment, in red, and the curve obtained after the subtraction of the “no-air” curve, in yellow.

By comparing the two test-benches, it is evident that the Mager bench is much less stiff than the Step one. This is because, on the curve relative to the loading without air, at the same loading, the meatus height detected is bigger on the Mager bench. Thus, with the same load, the Mager bench bends more than the Step. If the stiffness is lower, the subtraction of the curve is more important because the bending is bigger and the meatus height value is less accurate.

Analysing the graph in figure 17.3, the two curves are not very similar. The general behaviour is the same, but the curve registered on the Mager bench by the previous thesis is much steeper than the curve obtained in the Step bench. This means that with the same load variation, the measured meatus varies less on the Mager than on the Step. This behaviour is not expected, because the static characteristic is typical of the bearing itself and it should not depend on the bench where it is evaluated. Some variations can be tolerated due to the uncertainty of the measures, but in this case the difference is quite big.

In the graph in figure 17.4, the comparison is performed between the Step and the Mager benches with the data collected during this thesis experience. The general trend is quite similar, but, again, the two curves cannot be overlapped. In this case the Mager bench shows a curve which is less steep than before but still steeper than the one obtained in the Step bench. The subtraction with the curve obtained without air is performed in the yellow curve, obtaining a result closer to the Step bench characteristic. Only when the meatus height is quite high, the two curves get closer.

Calibration of the HBM load cell The comparison between the two static curves obtained in the Mager and Step test-benches showed that there was an important difference between them. For this reason, another calibration of the HBM cell was performed. The hypothesis was that the calibration used for the static curve on the Mager test-bench was not accurate and brought to wrong results. The Kistler cell does not need any further calibration because it is easy to check the cell is working well during the test, by just looking at the weights put or removed from it and comparing the value with the data collected by the cell. In the case of the HBM cell, this is not possible because the force over the bearing is generated by a screw, thus it is not easy to have an evident confirmation (during the test itself) that the cell is measuring the right force.

For the calibration, the cell must be removed from the bench, in order to fix it on a calibration jig. A metal beam is blocked on a structure by means of some grips. Then, the upper part of the cell is fixed to the jig through a screw and a nut and the lower part is placed in a hole in the metal beam. In this way, the cell is compressed while the weights are added in the lower part of the jig. To exactly know the weight loaded on the cell, the jig was weighted and it resulted to be 1,046 kg. To better understand, figure 17.5 shows the adopted setup for the calibration.

Figure 17.5. Picture of the load cell calibration procedure.

The calibration is performed by starting the measuring session on LabView and by adding known weights on the jig support (at the beginning, even the jig was removed from the cell). When all the loads were hanged, the weights were removed one by one to have a second check and detect any possible hysteresis. Every time, the voltage signal coming from the cell was collected, obtaining the graph in figure 17.6, representing the force applied on the cell against the voltage signal.

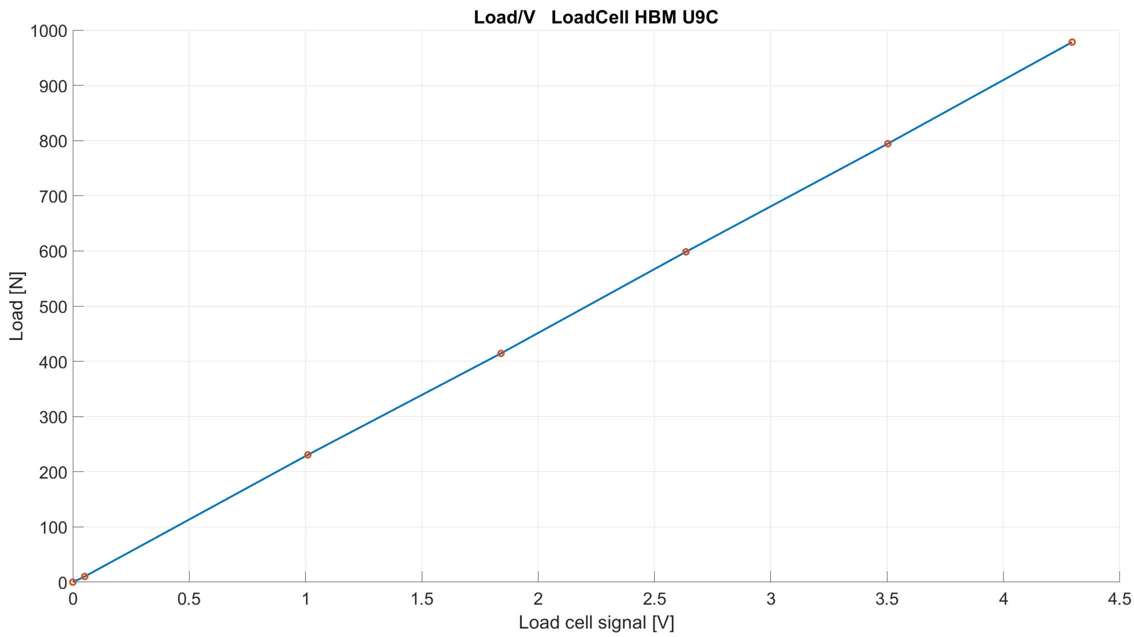


Figure 17.6. Load cell calibration graph: load against the load cell signal voltage.

Voltege signal [V]	Load [N]
0	0
0.05	10
1.01	230
1.84	414
2.64	598
3.50	794
4.30	978

Table 17.1. Data collected during the load cell characterization.

The obtained curve is linear and it is possible to evaluate the mathematical law through an interpolation. The straight line obtained is the following:

$$F = 227.5V - 1.0$$

with an inclination m = 227.5 N/V and an intercept q = -1.0N.

The obtained results comply with the values of the calibration used during the evaluation of the static curve on the Mager test-bench. This means that the calibration was accurate and cannot be the reason why the curves are different.

Conclusions The difference between the static curve obtained in the two test-benches could be ascribed to the different point where the capacitive sensors are set to zero. In fact, in the Step bench the initialization of the sensors is done at the beginning, with a load of about 500 N, while in the Mager bench it is performed with an higher load (even 1100÷1800 N). This is due to the difficulty in the control of the force applied to the bearing on this last bench, since it is generated by a rotating screw and even a small rotation generates a big force variation. With this discrepancy in the capacitive sensors setting to zero, the obtained curves can show some inconsistency, due to the different initial deformation of the bearing and the test-bench. This problem is partially solved by subtracting the curve obtained without air to the curve obtained with the inlet air opened, on the Mager. A possible further test could be the initialization of the capacitive sensors of the Mager when the load on the bearing is comparable to the one obtained on the Step.

Moreover, the differences should be analysed by considering the differences between the Step and the Mager and the differences between the two measurements on the Mager, performed in this thesis and in the previous one. The two benches are different from the point of view of the configuration and the working principles, but they can be different also in the surface roughness of the basement and the porosity of the materials. This can cause a different behaviour of the bearing air film and, consequently, of the force generated as a function of the lifting. Instead, the difference between the measurements on the Mager between the two thesis works can be due to the different moments in which the tests were performed and also due to the different operators performing the experiment. Since the bearing is based on very small holes and grooves, even the presence of a small foreign body in the system can change the behaviour of the bearing. Moreover, the two tests are performed in very distant-in-time moments, thus the configuration of the load cell or the measuring system could have been different. Another possible difference found is that the plate where the sensors measure the lifting of the bearing was glued to the bearing during this thesis work. This could have influenced the measurements.

In any case, the study is performed on devices which move in the order of µm, thus, even a very small variation can bring to have very big differences in the measurements.

Chapter 18

Closed loop

The final goal of this thesis is the development of a control program to keep the bearing air film height constant at a desired value. To do so, it is necessary to use the control board, running a control program, and to have a feedback signal to be read by the board, in order to know the meatus height. In this way, a closed loop is obtained. The name comes from the fact that the system crucial characteristics are evaluated by means of some sensors and sent back to the controller. In figure 18.1 it is possible to see a general schematics representation of the used control. Once created the code, some experimental tests are performed, in order to evaluate the behaviour and the ability of the bearing to keep a constant air film height.

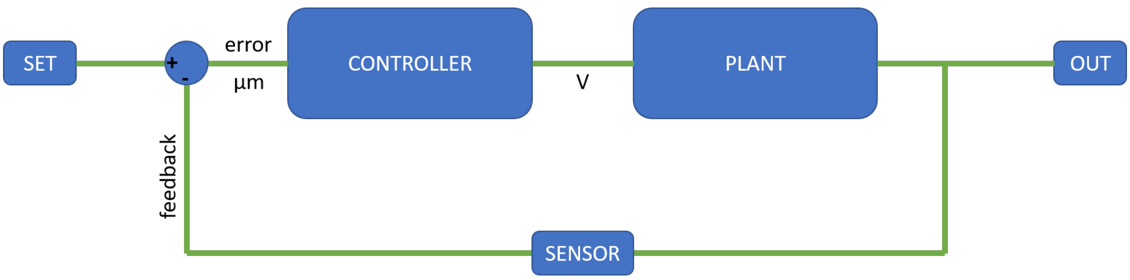


Figure 18.1. Block scheme of the controlling logic.

The closed loop is built by using all the acquired information obtained during the different previous tests performed in this thesis. Indeed, all the characterization and data collected are propaedeutic for the final goal of creating a good control action.

For the closed loop tests, the Step test-bench was used with the same configuration used for the other tests. The only difference is that, this time, the board is connected to both the back-pressure sensors, to read the feedback, and to the valve, to regulate it.

The connection is visible in figure 18.2: the back-pressure sensors are connected to the pins 2 and 3. The valve converting box is connected to the DAC0 pin, which allows to produce an analog output, to control the valve opening. The pin DAC1 is used to transmit to the acquisition board the same voltage signal generated for the valve. Thus, the Simulink model is developed in order to duplicate the signal to both the DAC pins (18.3). In this way, it is possible to acquire this signal and better understand the behaviour of the control. For each sensor or connected device, the ground cable is connected to the GND pins of the board.

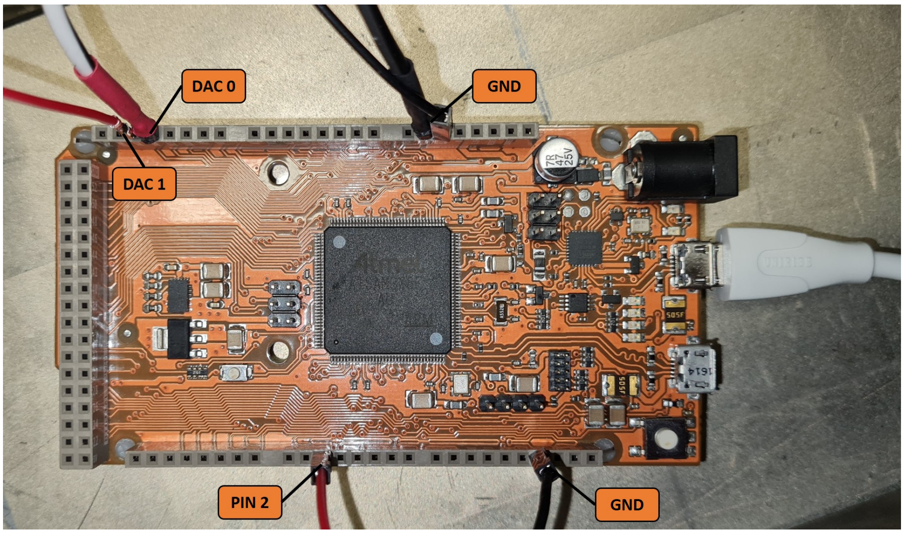


Figure 18.2. Board connections.

In the analysed case, only one back-pressure sensor is used, because the aim was to have a simpler system to manage, at the beginning. Anyway, once the second sensor is installed and connected, the idea is to perform a mean between the values obtained from both the sensors and use this value to perform the control action. Possible further improvements could be to perform a weighted mean between them, on the base of the tilting effect studied and of the performances obtained by the system.

Simulink Control The program to generate the control action is written using Simulink. The choice is due to the kind of board used: even if it is similar to an Arduino Due board, it is not possible to make it communicate with the Arduino Ide program, to upload the code. The Simulink program is not based on written code but on a series of blocks connected to each other. To control the board, it is necessary to install a specific toolbox in Matlab which allows to control different devices, such as the Orange board used (which is recognized as an Arduino Due). The complete program is reported in figure 18.3.

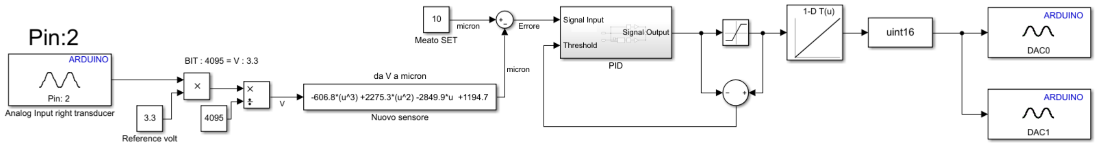


Figure 18.3. Simulink scheme of the control algorithm.

On the left hand side, there is the analog pin 2, which is used to acquire the signal coming from the back-pressure sensor. This signal is the feedback of the closed loop. The acquisition is performed in bits, thus it is necessary to convert it in the corresponding volt signal. The conversion is done with the proportion 18.1.

$$BIT : 4095 = V : 3.3 \tag{18.1}$$

Once obtained the Volt signal, it is necessary to convert it again, obtaining the height in µm of the air film measured by the back-pressure sensor. To do this, the conversion formula is obtained from the characterization of the back-pressure sensors, described in chapter 16. With this operation, the bearing lift is obtained in µm and it can be compared with the desired set value.

Once the error is evaluated, it is sent to the real control part of the program. It was chosen to use a PID controller, thus a controller which performs a control action which is the sum of a part which is proportional to the error evaluated, a part which is the integral and a part which is the derivative of the error. The part relative to the PID action is grouped in the subsystem represented in figure 18.4. As it is possible to see, the signal input is the error evaluated by the difference between the set and the feedback read. This signal is multiplied by the proportional part (K_p), it is derived and multiplied by the derivative coefficient (K_d) and it is integrated and multiplied by the integrative coefficient (K_i). The three results are summed together to generate the signal output, sent to the following blocks. Form the figure it is also visible a part called "Anti WIND-UP" switch: this part will be better described in the following paragraphs.

The signal coming from the PID subsystem is then sent to a saturation block, which has the role of avoiding that a too big signal could be sent to the valve. The

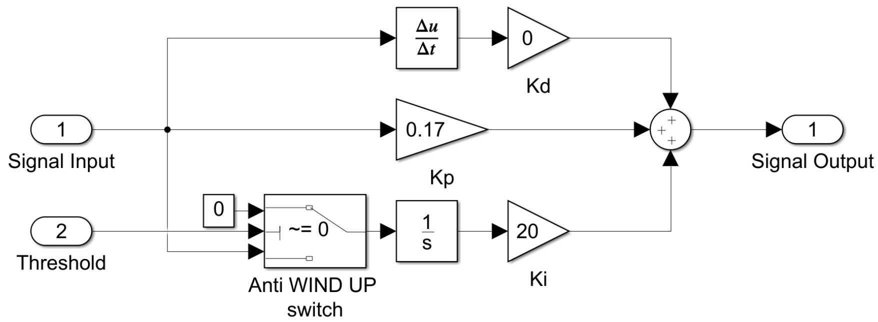


Figure 18.4. Simulink block diagram for the realization of the PID control.

signal is forced to be inside the range 0.7 – 2.75 V, which is the working range of the valve. Those values come from the previous experiments performed on the valve.

The following blocks have the role of generating a signal which is compatible with the output analog DAC pins of the board. The Analog Output block, that controls the DAC pins of the board, works on the base of a specific formula (18.2), which accepts numbers between 0 and 4095 as input. For this reason, the signal must be conditioned, in order to obtain the real voltage value on the pin. The parameter to insert in the board are specified in the Matlab support manual [8]. In the case of the used board, the reference numbers reported in table 18.1, must be considered as it was an Arduino Due board. Moreover, the Analog Output block accepts as input "unit16" values, thus a block for this conversion is needed. The present look-up table is useful to pass from the saturation block to values between 0 and 4095. With the look-up table block, the unit16 block and the Analog Output block, it is possible to replicate on the board DAC pin the value generated by the control block, with a one-to-one correspondence (this was checked using a multimeter on the board pin).

$$V_{out} = V_{ref}(\frac{input}{2^N - 1}) + V_{offset} \tag{18.2}$$

An important point in the analysis of the control program is the evaluation of the unit of measure of each passage. As described before, the comparison feedback-set is performed in µm, then, the error obtained enters the PID. Form a conventional point of view, it is necessary to define if the parameters of the PID are dimensionless or if they have a unit of measure. In fact, if the K_p,K_i and K_d have no dimension, the signal coming out from the control is in µm and it must be converted in Volt,

Variable	Arduino Due	Description
V_{ref}	2.2	Reference voltage for the DAC pin.
input	0÷4095	When using Arduino Due, input provided to the block must be between 0 and 4095. Any value higher than 4095 saturates the voltage output at the DAC pin.
N	12	Number of bits on DAC channel.
V_{offset}	0.56	Offset voltage on Arduino board.

Table 18.1. Table representing the variables to use in the equation 18.2 [8].

to be sent to the valve. On the other hand, if they have dimension (V/µm), the output is in Volt and it does not have to be converted.

As a first approach, it was considered to deploy a very simple controller. The system with the controller can be described with few blocks, representing the controller, the bearing itself (PLANT) and the sensor to obtain the feedback (18.1). Since the complete system, seen from a very high level, is a series of components whose input is the voltage signal generated by the controller (V) and the output is the elevation of the bearing from the basement (h), to have an initial idea about the controller parameters, it was decided to consider a graph reporting the trend of the air film lift as a function of the voltage signal. This representation was already obtained with the previous experiments. This graph depends on the masses loaded on the bearing, thus, after an analysis of the possible ranges allowed by the bearing, it was chosen to use the curve relative to the weight of 20 kg loaded on the bearing (chapter 14, figure 14.1). With this configuration, it is necessary to have a conversion from µm to Volt, obtained by linearizing the central part of the graph, around 10 µm (18.5). This means also that it was chosen to have non dimensional PID parameters.

The obtained block is the conversion block and it must be located after the PID controller, as represented in figure 18.6.

The logic behind this choice is that the system expects a weight of about 20 kg loaded on it and then it performs a corrective control action if the loaded mass is modified. A good result obtained is $K_p = 1$ and $K_i = 40$.

The other option is to use the PID parameters with dimensions. In this case, the signal coming out from the controller is not in µm, but it is directly in Volts, thus,

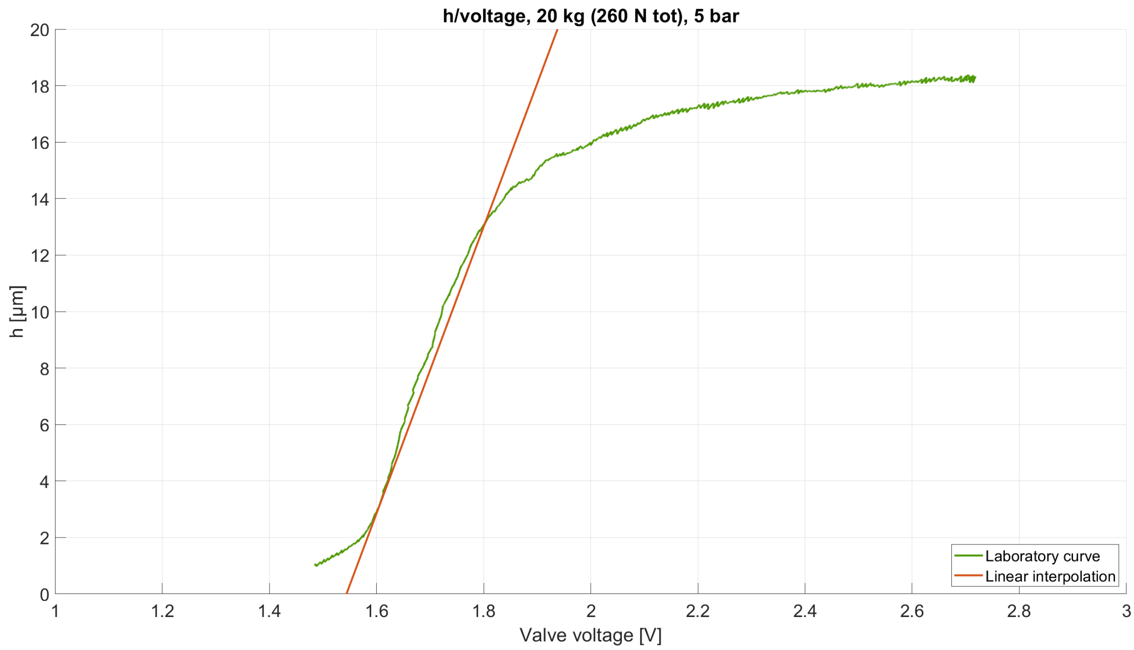


Figure 18.5. Valve characteristic with 260 N load (weights plus support structure): lift against valve voltage signal.

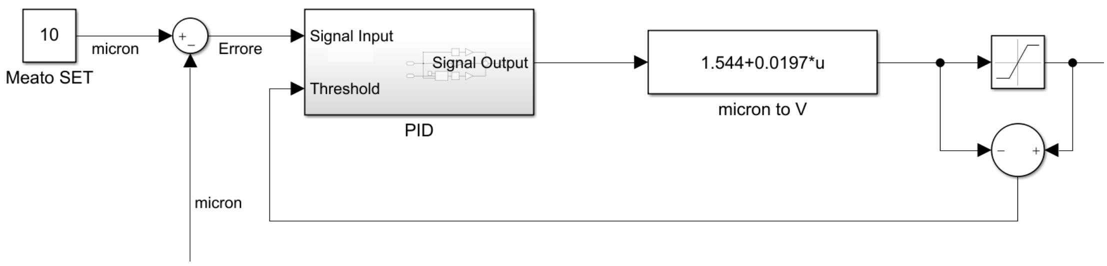


Figure 18.6. Controlling logic with the unit of measure conversion block.

it is not necessary any block between the PID and the saturation. Of course, the parameters of the PID must be regulated in a different way because they are not processed by the conversion block.

To pass from one configuration to the other, it was considered to have a similar control action at the level of the saturation block. Since in the case of the converting block, the part of the signal changing according to the error is small (equation 18.3), the K_p chosen for the control without conversion was much lower. After some tests, K_p was chosen to be 0.17, because a too small value produced very bad control action results.

$$K_p 0.0197 = 0.0197 \tag{18.3}$$

PID parameters: first choice There are different ways to choose the parameter to use for the PID controller. One of the most famous is the one developed by Ziegler and Nicholas. They invented an empirical method for the calibration of PID controllers that can be applied to closed loop systems. The first step is to set to zero the integrative and derivative components and focus on the only proportional part (K_p). This value must be gradually increased until the response to a step perturbation becomes permanently oscillatory. At this point, the value of K_p must be annotated as K_{p0} and the oscillation period T_0 must be evaluated. This value will be used, according to the table 18.2, to determine the PID parameters. The obtained results must be considered as a starting point for a finer tuning to obtain the best controlling behaviour possible.

	K_P	K_I	K_D
P	0.5 K_{P0}		
PI	0.45 K_{P0}	1.2 $\frac{K_P}{T_0}$	
PID	0.6 K_{P0}	2 $\frac{K_P}{T_0}$	0.125 K_P T_0

Table 18.2. Table relative to the Ziegler and Nicholas method to evaluate the parameters for the PID control.

The method can be applied if the system behaves in a clear way and when it is possible to clearly determine when the system starts oscillating. In this case, different tests are performed, but it was always hard to determine when the system started oscillating. In fact, the general behaviour of the air film height is never flat, but it always has some fluctuations.

Another possible approach is to start defining a possible initial value for the proportional parameter according to a defined criterion. For example, it is possible to decide to have the saturation of the controller for an error of a certain entity. For the case of the controller with the internal conversion block, the chosen error is 1 µm at which it should correspond a saturation of the generated signal (2.75 V). The obtained value of K_p is about 60. Since this value was a bit higher than the value used in the previous thesis works, some tests with lower value of K_p were performed. Then, also the value K_i was introduced in the controller. In figure 18.11 and figure 18.12 the tests are compared.

A similar approach was used for the controller without the unit of measure conversion block. It was chosen to have a saturation of the signal when an error of 1 µm was detected. In this way, the obtained starting K_p was 2,75. Some tests were performed with this parameter to check the behaviour.

Then, another criterion for the choice of K_p was experimented. Since, after some tests, the condition of $K_p = 1$ was quite good in the case of the controller with the conversion, a similar behaviour was desired. By analysing the control structure with the conversion block (18.6), it is possible to see that the variable part (thus, the one that varies according to the error entity) is very little, because the value obtained from the PID block is multiplied by 0.0197. To have a similar behaviour, the K_p in the controller without conversion block should have a $K_p = 0.02$. This value was tested but it resulted to be too small. After some other experiments, a good K_p value obtained was 0.17.

A possible further improvement in the control action could be the introduction of the derivative parameter in the PID.

Anti wind-up During the laboratory trials, a problem was faced: after a period of time where the valve was kept opened (thus whenever the controller saturated), the board had some troubles to control the system in the correct way. This condition figured out when, for example, the inlet air was closed and the controller kept trying to lift the bearing, with a full open of the valve even when the inlet air was opened again. This abnormal working is due to the wind-up effect. This problem is caused by the integrative part, that keeps increasing in the case of saturation of the output signal and then it takes some time to reduce again, maintaining the output saturated.

To avoid this problem, an anti-wind-up system is implemented. The working principle is based on the inhibition of the integrative branch of the PID when the saturation of the signal is reached. To do so, the comparison between the signal before and after the saturation is performed and whenever their difference is not zero, thus the saturation is active, the K_i contribution is stopped, avoiding its value to increase. In this way, the controller started working much better, without showing the faced trouble.

Tests and experiments performed To understand the behaviour of the control system and to tune all the parameters of the PID, different tests were performed. The starting point was the K_p value, which was chosen following the logics explained before, then, the parameters were modified to compare the different effects. The experiments were done using the controller with and without the unit of measure conversion block. Usually, a parameter between K_p or K_i is kept fixed, while the other one is varied. A table of the different tests performed is reported.

	K_p	K_i	Loaded Masses [kg]
WITH unit of measure conversion block			
Tests			
	0.8	40	30
	1	40	20-15-20-25
Fixed K_p			
	1	40-100	20-15-20-25
Fixed K_i			
	1-10-40	0	20
	1-10-40	40	20
WITHOUT unit of measure conversion block			
Tests			
	0.17	20	10
	0.17	20	20-10-20
	0.17	20	45
Fixed K_p			
	0.17	1-10-20	20
	0.8	0-1-10-50-100	20
	1.75	1-10-100	20
	2.75	1-10-100	20
Fixed K_i			
	0.5-0.8-1.2-1.75-2.75	0	20
	0.1-0.17-0.8	20	10
Other tests			
Load-Unload with 50 N steps each time			$45 \rightarrow 0 \rightarrow 45$ [kg]
Gradual inlet pressure increase			$5 \rightarrow 8$ [bar]

Experimental results Many experiments were performed to test the capabilities of the controller designed. It was decided to report the most significant in the thesis, while the others are reported in the Annex 2. The tests are subdivided between the tests performed with and without the converting block in the control algorithm. In all the tests performed, the derivative parameter K_d is always set to zero. In the interpretation of the graphs, it should be considered that the bearing lift is not parallel to the ground, due to the tilting effect described in the previous chapter. Thus, the four capacitors report four different air film heights. Since the control action refers to the back-pressure sensor installed between the capacitive number 1 and 3, to check if the bearing reaches the required height, it is convenient to look at the mean between those two capacitives. Alternatively, it is possible to consider the feedback measured by the back-pressure sensor and transform the voltage signal into µm. In some of the following graphs the mean between the capacitive 1 and 3 or the feedback signal will be represented.

Control algorithm with the unit of measure converting block. In one of the experiments, the proportional (K_p) and the integrative parameters (K_i) were kept constant and the load over the bearing was modified. In this case, it is followed a loading sequence of 20 kg, then 15, 20 and 25 kg (figure 18.7). With these parameters it seems the control action is keeping the mean of the capacitive sensors around the required height. From the third graph it is possible to check the load on the bearing, which is varied. In figure 18.8, another test is performed with the same proportional and integrative parts, because the results were good. The test is performed opening and closing the valve two times. The bearing lifts around the set and it shows a particular behaviour when the air is removed and opened again, keeping a value particularly constant.

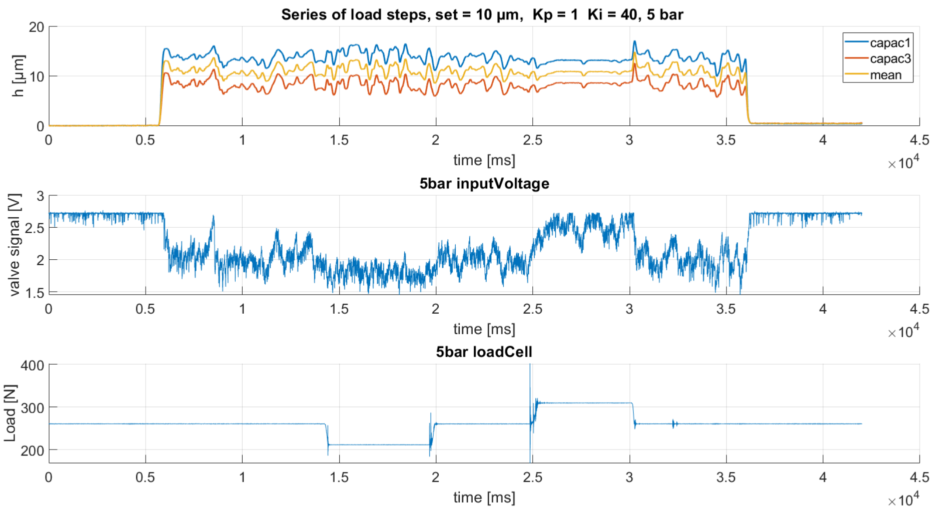


Figure 18.7. Series of load steps (masses: 20-15-20-25 kg), set=10 µm, K_p=1 K_i=100, 5 bar.

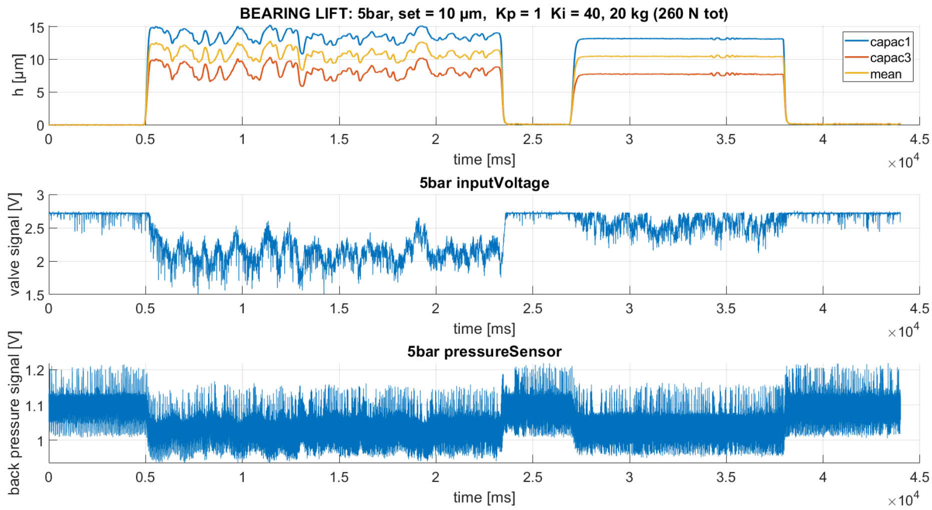


Figure 18.8. Bearing lift along the time, load: 20 kg (260 N tot), set=10 μm, K_p=1 K_i=40, 5 bar.

The test with a series of load steps is performed again, but the integrative coefficient was set to 100. In this case the set is not always followed in an accurate way (figure 18.9). Moreover, when the load decreases at around 110 N, the system is very reactive and generates vibrations.

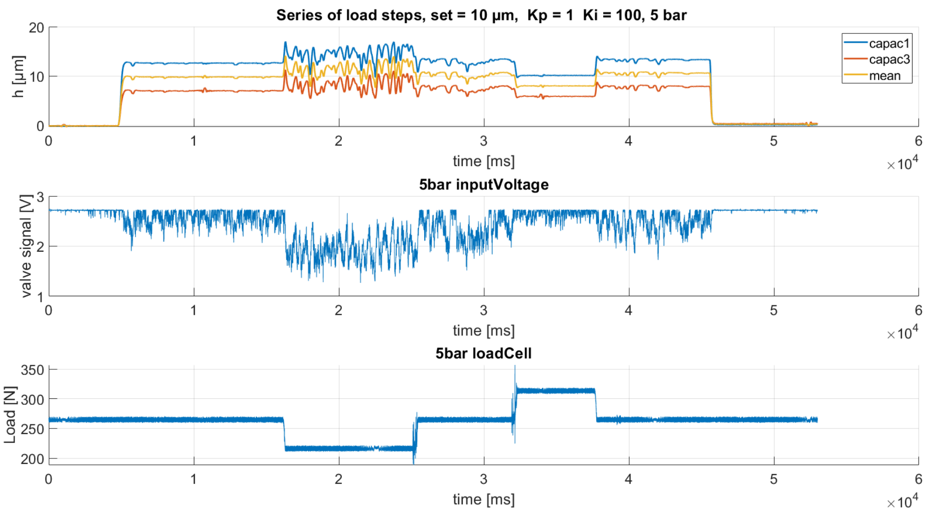


Figure 18.9. Series of load steps (masses: 20-15-20-25 kg), set=10 μm, K_p=1 K_i=100, 5 bar.

Another test is performed with a load of 358 N, thus with a mass of 30 kg over the structure of the bearing. As it is possible to see in figure 18.10, the valve is almost always opened, because the signal is almost always at 2.75 V, but the required height is not reached, keeping a mean value of about 8.8 µm. This behaviour could be expected by looking at the ranges diagram in figure 13.9.

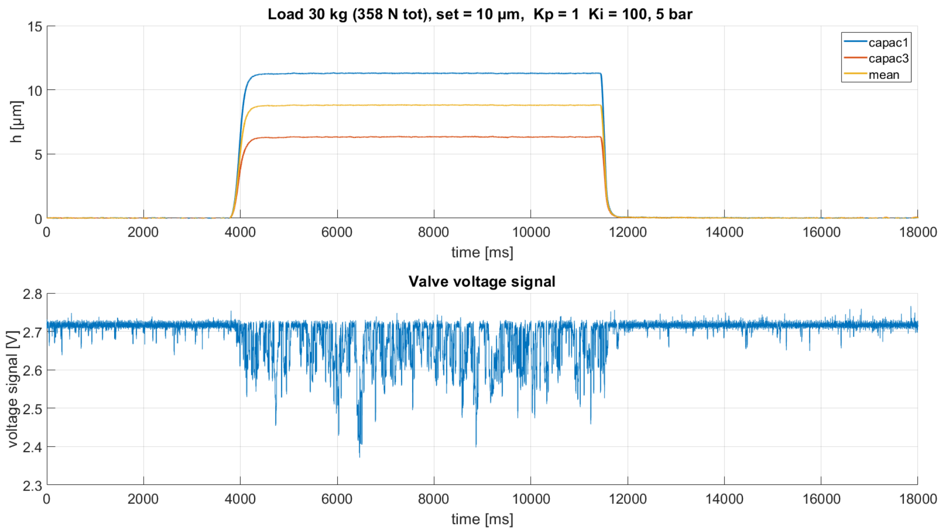


Figure 18.10. 358 N load (mass: 30 kg), set=10 µm, K_p=1 K_i=100, 5 bar.

Then, some tests were performed by keeping the K_i value constant and verify how the control behaviour changes by varying the K_p parameter (figure 18.11). The result is that, increasing the proportional value, the bearing gets closer to the required target but, at the same time, the control is more reactive.

Similar experiments were performed keeping the $K_i = 40$ and increasing the K_p (figure 18.12). The tests are performed opening and closing the inlet air valve twice. A good result could be the couple: $K_p = 1$ and $K_i = 40$.

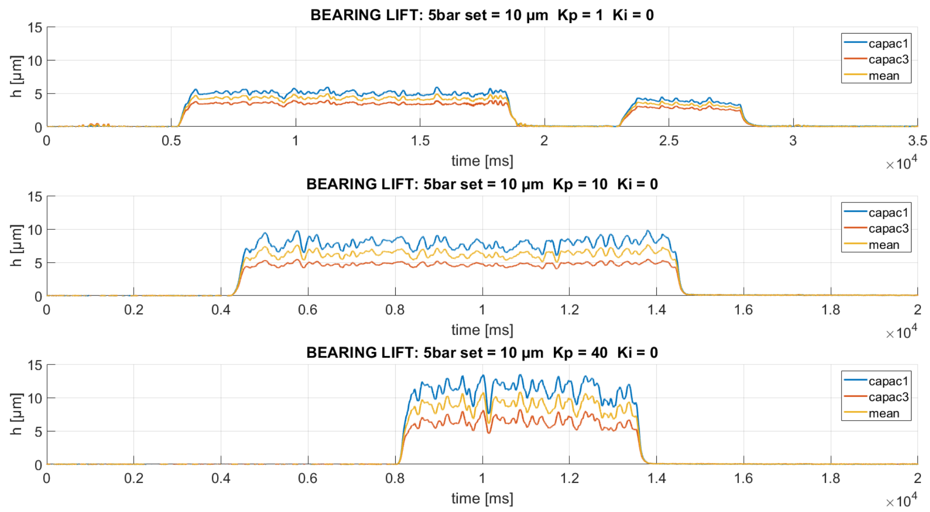


Figure 18.11. Bearing lift along the time. K_i=0 and different values of K_p. Loaded masses: 20 kg.

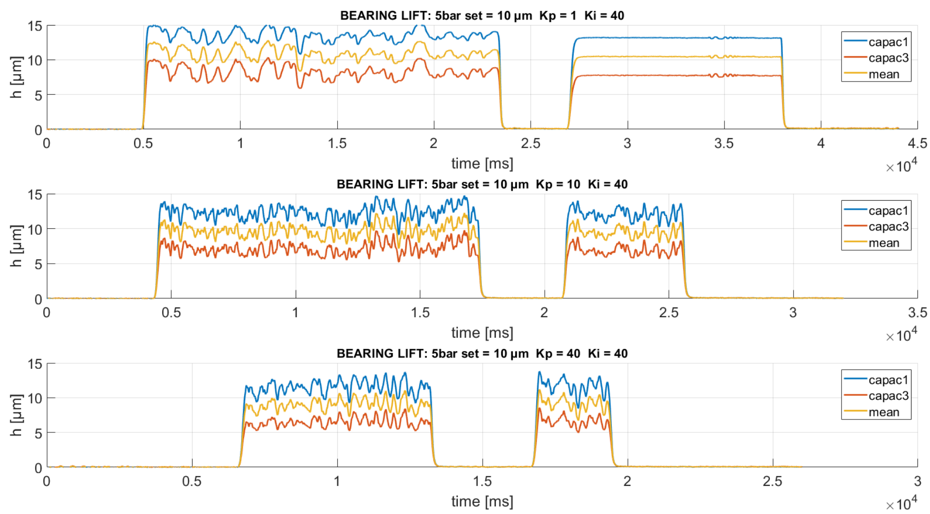


Figure 18.12. Bearing lift along the time. K_i=40 and different values of K_p. Loaded masses: 20 kg.

Control algorithm without the unit of measure converting block. In the following graphs, the control is realised without the unit of measure converting block. The graph in figure 18.13 reports a series of load steps test. The controller is not always keeping the bearing at the required lift level, in fact, it has some troubles when the load is removed and passes from 260 to 162 N, because the 10 µm required are overcome.

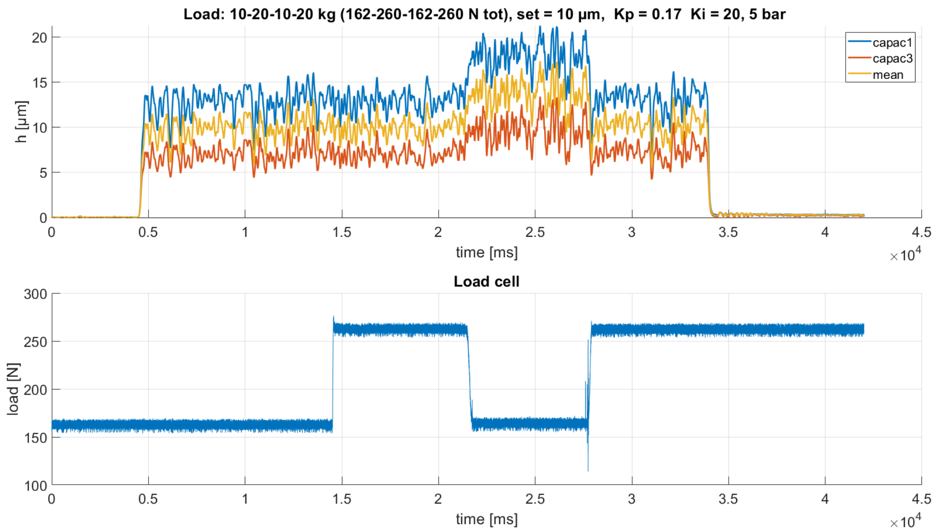


Figure 18.13. Load cycle: 10-20-10-20 kg (162-260-162-260 N tot), set=10 µm, K_p=0.17 K_i=20, 5 bar.

Another test performed is about keeping the proportional value constant and varying the integrative one. Figure 18.14 is the representation of it. It was tried to use also higher values of K_i, but the results were not good. By increasing the integrative, the control seems to be more precise and a good result reached is $K_p = 0.17$ and $K_i = 20$.

It is also tried to use an higher value of proportional (0.8), increasing the integrative, obtaining the graph in figure 18.15. In this case the feedback read from the back-pressure sensors is represented (already converted in µm). Again, by increasing the integrative part, the control is more effective and only in the last case the set is reached.

In figure 18.16 the K_p is 1.75 and the K_i varies. The bearing gets closer to the set but then, for too high integrative values, it has an anomalous behaviour. A good result is $K_p = 1.75$ and $K_i = 10$.

Then, the integrative part is set to zero and the proportional one is increased (figure 18.17). Again, with higher values of proportional, the controller reaches better results in terms of lift level, but the behaviour is more and more "nervous".

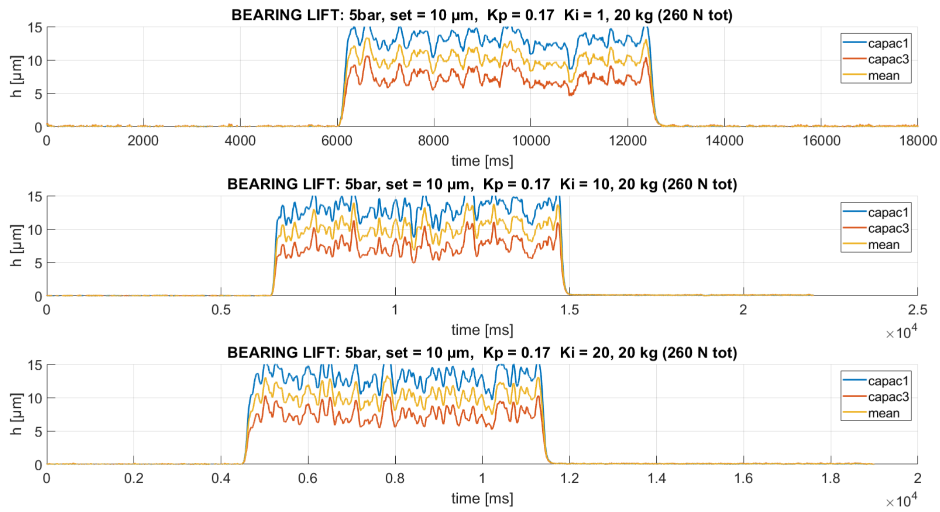


Figure 18.14. Closed loop test graph. Fixed load: 20 kg (260 N tot), K_p=0.17, K_i=1-10-20.

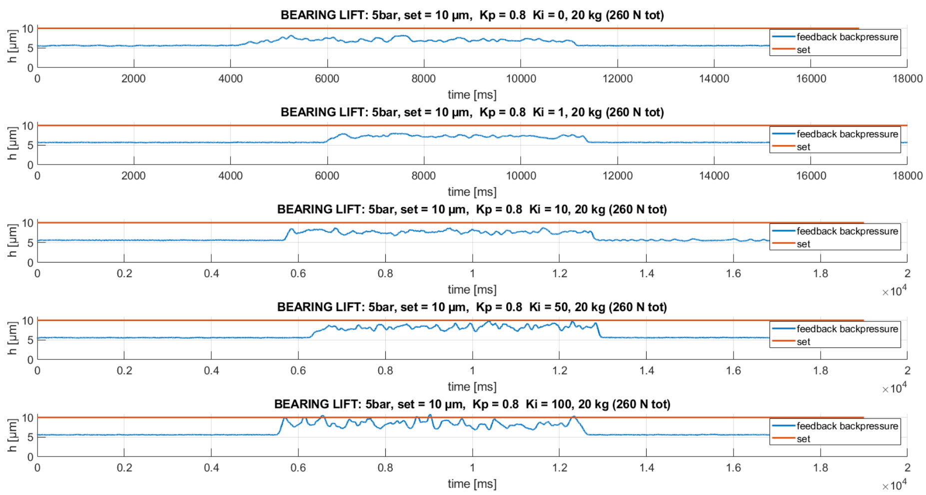


Figure 18.15. Closed loop test graph, feedback from back-pressure sensors and set required. Fixed load: 20 kg (260 N tot), K_p=0.80, K_i=0-1-10-50-100.

It was also tried to test the control with a lower value of load. In figure 18.18 the mass over the structure is 10 kg, thus, the total force over the bearing is 162 N. The controller is tried with different values of K_p and a fixed K_i of 20. The result is not really satisfying because the set is overcome in all the cases.

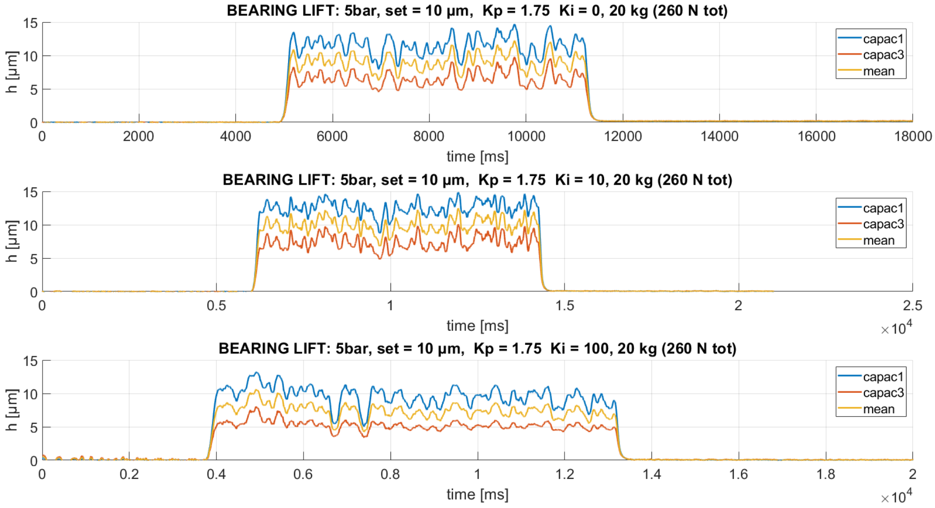


Figure 18.16. Bearing lift graph. Fixed load: 20 kg (260 N tot), K_p=1.75, K_i=0-10-100

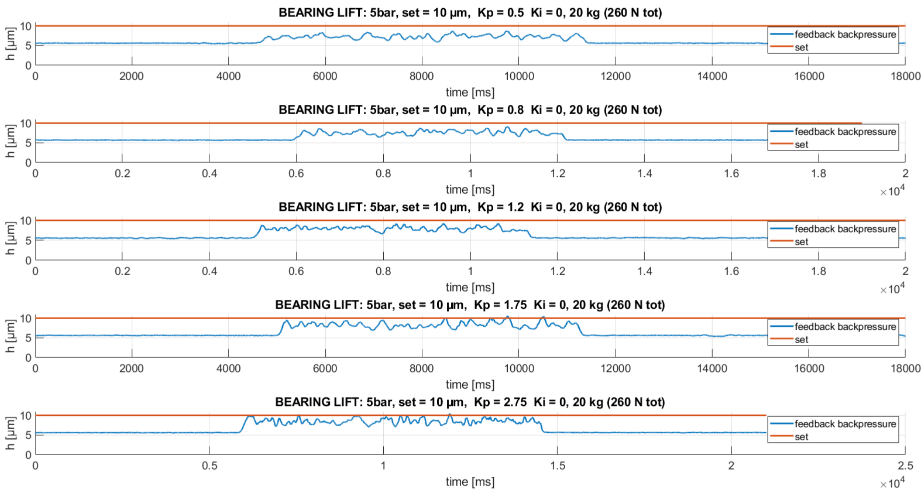


Figure 18.17. Closed loop test graph, feedback from back-pressure sensors and set required. Fixed load: 20 kg (260 N tot), K_p=0.5-0.8-1.2-1.75-2.75, K_i=0.

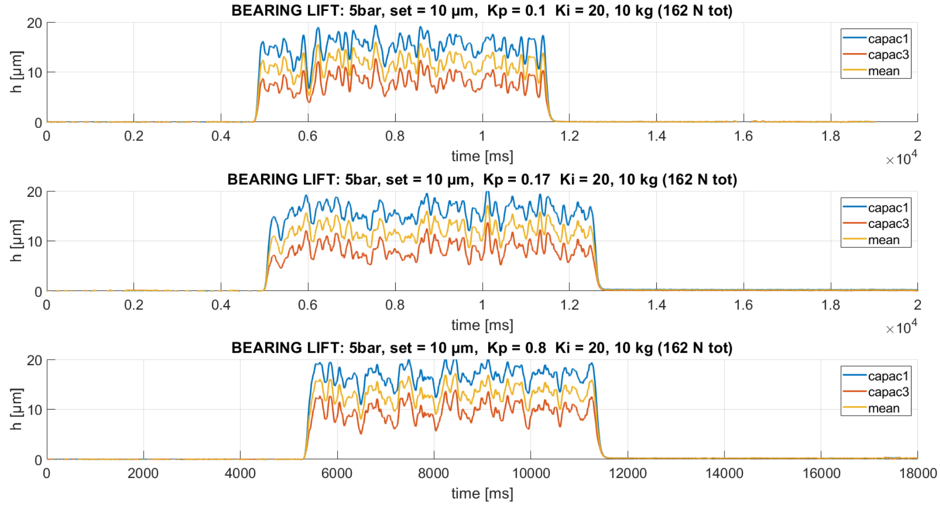


Figure 18.18. Bearing lift graph. Fixed load: 10 kg (162 N tot), K_p=0.10-0.17-0.80, K_i=20

Closed loop conclusions. In conclusion, for the development of a good control action, two approaches were followed, using two different block logic diagrams. For both cases, different tests were performed. For what concerns the control with the conversion block, a good result was obtained with the combination of a proportional parameter of 1 and an integrative of 40. Those values bring to have a quite good follow of the required air film height. It is then interesting to see that, with those parameters, letting the control work for a while and after some modifications of the external parameters (inlet air closed and opened or external weight modification) the bearing has a quite perfectly following of the set (figure 18.8). Instead, for the control without conversion block, a good result is obtained with a K_p = 0.17 and a K_i = 20 (figure 18.14). This control action grants good performances, but the set following is not always perfect, like in figure 18.13.

The performed tests show that with too high loads the bearing cannot reach the desired air lift. This behaviour was predictable by looking at the working ranges of the bearing. In fact, the obtained graph about the working ranges of the bearing reports that a lift of 10 µm is possible for the bearing with a total load of maximum about 250 N (inlet pressure: 5 bar relative). If this value is overcome, the impossibility to reach the required lifting is expected. On the other hand, sometimes the bearing has some troubles in keeping the required lift when a small load is carried on the structure, reaching too high lifting values (figure 18.13). This is a point which should be deepened in order to make the system work better. In fact, the proportional valve should be kept closed more, in order to have a lower thrust and to avoid overcoming the required bearing lift.

Other tests, reported in the Annex 2, are also performed to see how the inlet pressure influences the control and how the bearing behaves with a series of many external force disturbance steps. Those tests are just an initial approach but further investigations are needed.

During the performed tests, the obtained graphs show curves which are not very smooth, but they show some ripples and are almost never flat. This result can be ascribed both to the imperfect control action of the bearing but also to possible external disturbances on the acquisition and cables. The behaviour obtained with the conversion block and $K_p = 1$ and $K_i = 40$ (figure 18.8) is interesting because, after closing and opening again the inlet air, the bearing lift curve is flat, without ripples. This behaviour should be further analysed.

Moreover, attention must be paid when in the graphs the feedback read by the board is represented. In those cases, even if the bearing was touching the ground due to the absence of inlet pressured air, the sensors seemed to read a lifting of about 5 µm. This is due to the characteristic of the back-pressure sensors, which start evaluating the correct air film height only above 5 µm.

The control program developed has a good behaviour, but it can be improved and modified to reach better results in the achievement of the desired air film height. A possible future improvement could be the research of a proportional and integrative parameters that can give the bearing a better behaviour. Moreover, it is possible to imagine adding a derivative parameter to the PID controller, in order to increase the stability of the system. Another interesting possible improvement is the development of a feedforward component, that can make the control even more accurate. For this implementation it would be necessary to introduce a sensor to determine the entity of the force generated over the bearing, in order to be able to anticipate the control action, in case of load change.

Part IV

Models and comparison with laboratory results

Chapter 19

Open loop model

It is convenient to build a model that represents the behaviour of the bearing. In this way it is possible to study the system without performing the tests in the laboratory. The model aims to represent the behaviour of the bearing without any active control action, thus in open loop condition. Each single component of the system is modelled and then they are connected together to simulate the entire bearing behaviour. In figure 19.1 a scheme of the components is represented, in order to specify what the parameters used in the following formulas refer to. Moreover, the figure gives a better idea of the composition of the bearing. The sequence of elements reported in the scheme will be followed in the model when all the components will be linked together.

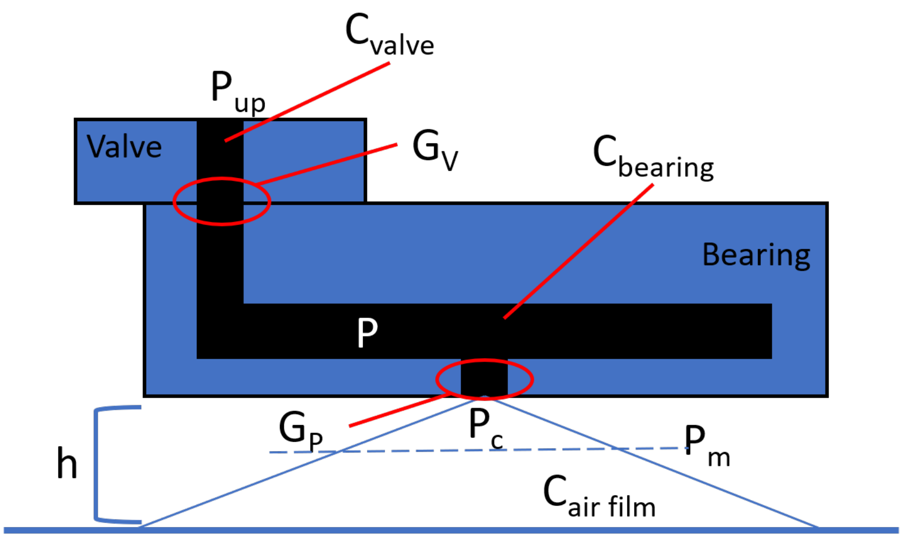


Figure 19.1. Schematic section of the bearing with the indication of the parameters used in the model.

19.1 Proportional valve model

The first element which is modelled is the proportional valve. At first, it is represented and tested by itself, then, it is introduced in the complete model of the bearing.

The valve is modelled as a hole with a variable opening. The flow motion through the hole can be sonic or subsonic, depending on the pressure conditions before and after the valve. The threshold to determine whether it is critical or not is the parameter b, which is called critical ratio and it is considered to be 0.528.

The mass flow rate, G, depends on a parameter C, called conductance. This parameter depends on the maximum flow rate possible and the supply pressure, but, since this valve is proportional, it can have different openings, which means that the duct opening can vary and so the flow. This brings to have a variation of the conductance. Since the valve is controlled in current, there exist a correlation between the current signal and the conductance. For this reason, it is convenient to find the correlation between the flow and the current with some experiments and then, from this, evaluate the relation between the conductance and the current by applying the formula 19.4. The experiments where conduced in the previous thesis at a pressure of 5 bar relative, obtaining the graph in figure 19.2.

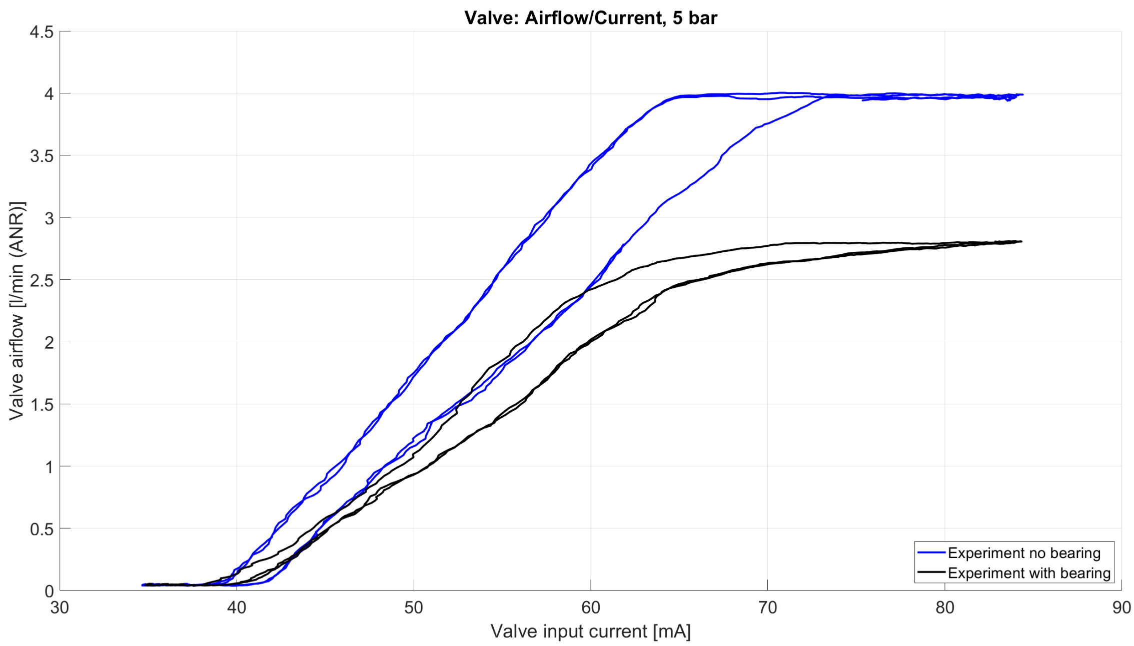


Figure 19.2. Valve tested with and without bearing attached: airflow against input current.

The valve can be studied by using a second order model, representing the valve opening area, as follows:

$$\frac{d^2 A_v}{dt^2} + 2\zeta\omega_n \frac{dA_v}{dt} + \omega_n^2 A_v = K_s \omega_n^2 I_{ref} \tag{19.1}$$

In this equation, A_v is the valve opening area, ω_n is the natural frequency, ζ is the damping factor, K_s is the static gain of the valve opening area and I_{ref} is the valve current control signal.

It is assumed that the valve opening has a linear relation with the current signal. Moreover, it is assumed that, since the conductance can be obtained from the following formula 19.2, the linear relation between the flow and the current(graph 19.2, central part), stands also for the relation of the conductance and the current. Those relations are reported in the following equations.

$$C = \frac{Q}{P_1} \tag{19.2}$$

$$A \quad \alpha \quad I_{ref} \tag{19.3}$$

$$C = K_C A_v = K_C K_s I_{ref} = K_v I_{ref} \tag{19.4}$$

It is possible to substitute the previous relations in equation 19.1 and obtain the following:

$$\frac{d^2 C}{dt^2} + 2\zeta\omega_n \frac{dC}{dt} + \omega_n^2 C = K_v \omega_n^2 I_{ref} \tag{19.5}$$

The valve model is based on this equation, where the value of K_v is obtained from the experimental results got from the graph in figure 19.2. In the model, the conductance is obtained and it is used to evaluate the mass flow rate.

The model is based on two parts. The first is the evaluation of the conductance, as explained before, while in the second part the aim is to define whether the valve is in sonic or subsonic conditions and the flow direction. The Simulink model is reported in figure 19.3. The upper part represents the determination of the conductance, through the second order model, while the lower part determines whether the upstream pressure is higher or lower than the downstream one and evaluates, according to the sonic or subsonic status, the coefficient to multiply to the conductance obtained in the upper part (according to equations 19.6 and 19.7), to get the correct flow rate as output. In the model configuration, it is convenient to set the "t_sim" value in the maximum step size box, in the solver options.

$$Sonic flow \qquad 0 < \frac{P_2}{P_1} < 0.528 \qquad G = P_1 C \quad [kg/s] \tag{19.6}$$

$$Subsonic flow \qquad 0.528 < \frac{P_2}{P_1} < 1 \qquad G = P_1 C \sqrt{1 - (\frac{\frac{P_2}{P_1} - b}{1 - b})^2} \quad [kg/s] \tag{19.7}$$

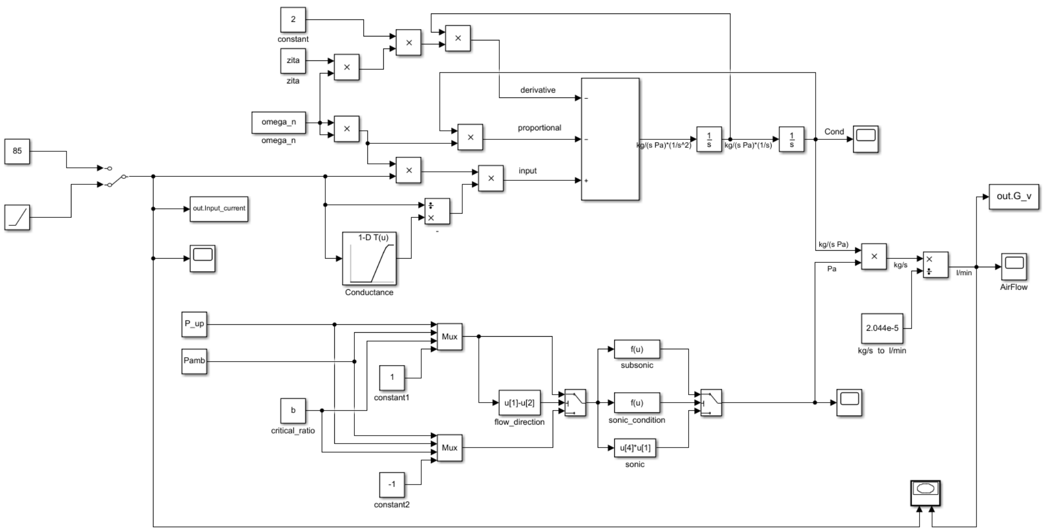


Figure 19.3. Simulink model of the valve.

In the upper part, a lookup table block is inserted which returns the conductance value, depending on the input current, according to the real experimental results. Then, this value is used for the evaluation of the coefficient K_v, as described before. The "current_values" and the "conductance_values" vectors contain the values obtained from the graph of the flow rate against current signal (figure 19.2). The conductance values are evaluated from the flow rate by adjusting the unit of measure and by dividing each time for the absolute upstream pressure value. The hysteresis that is present is not taken into account for sake of simplicity.

The model principal parameters are evaluated in previous thesis experiences, obtaining a value of $\omega_n = 35$ Hz and $\zeta = 0.2$.

A Matlab script is used to initialise all the variables used in the model, in this way, it is easier to modify the parameter if needed. A principal Matlab script is run, which in turns runs another script with the configuration desired. In this way, it is possible to have different configuration files and choose the one desired. The main script is then used to plot graphs on the basis of the simulation performed. The valve model is tested and compared with the real values obtained. A ramp current signal is generated and the output flow rate is plotted against the input current. This graph is superimposed on the experimental one and the result is reported in figure 19.4 and figure 19.5.

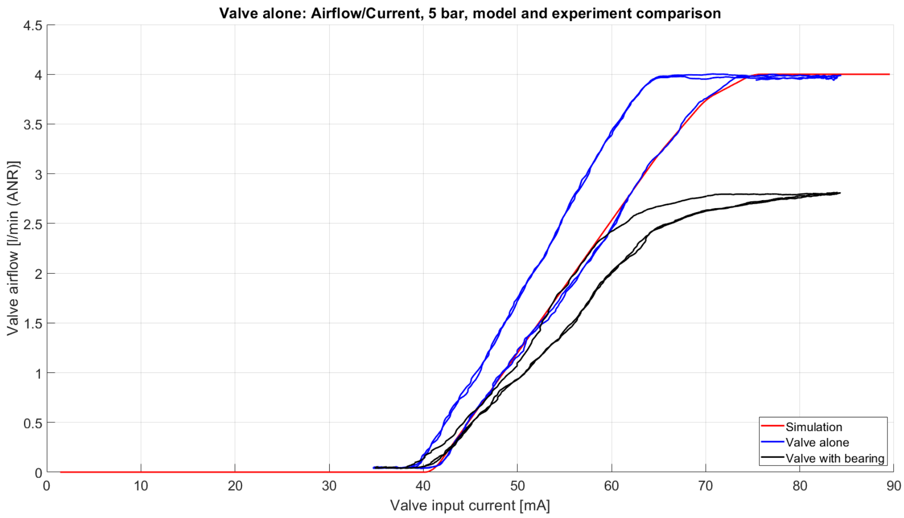


Figure 19.4. Comparison of the simulation and the laboratory results of the only valve alone, without bearing.

In the graph there are two kind of experiments: one considering only the valve by itself and one considering also the bearing connected. The simulation is about the single valve and, as it is possible to see, the curve reflects quite well the experimental one. This means that the valve model works well. It is possible to change the values of the array conductance_values, using data according to the one obtained for the valve mounted on the bearing. The superimposition with the other curve is still good.

Of course, the hysteresis is not followed by the simulation because only the part relative to the increase of command current was modelled. As a further improvement, a more precise model can be implemented by including the frictions inside the valve and the hysteresis effects.

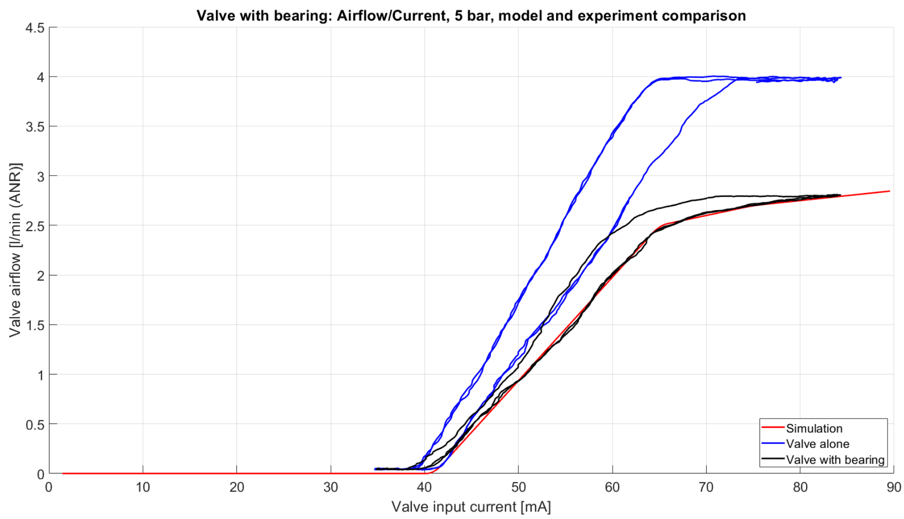


Figure 19.5. Comparison of the simulation and the laboratory results of the only valve with the bearing mounted.

19.2 Bearing model

The bearing model can be schematically represented by using two pneumatic resistances and two pneumatic capacities, as represented in figure 19.6, where:

- P_s is the inlet pressure, coming from the valve;
- G_p is the flow passing through the bearing itself;
- C_p is the pneumatic capacity of the ducts inside the bearing;
- R_f is the resistance of the exhaust hole;
- C_m is the variable pneumatic capacity of the volume under the bearing;
- R_m is the variable pneumatic resistance of the volume under the bearing;

Each one of the component is modelled in a Simulink subsystem, which are analysed in the following paragraphs and then they are connected, together with the valve model, to create the complete system.

Bearing pneumatic capacity The pneumatic capacity is relevant during the transitory of the system. It should be considered when a chamber in a pneumatic device is present. The capacity, in fact, represents the accumulation of material, in this case air, and it has a role when a flow enters a chamber which has a volume V,

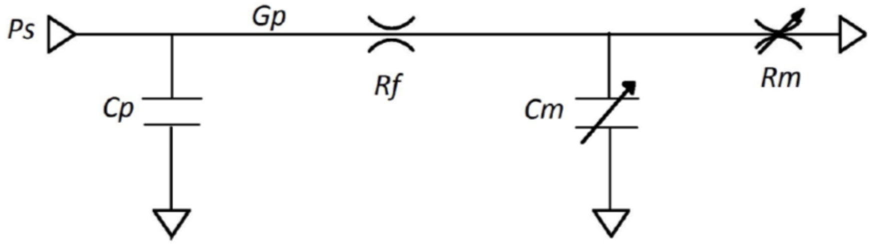


Figure 19.6. The bearing pneumatic scheme.

a pressure P and a temperature T. To obtain the model of the capacity the starting point is the mass flow rate, as reported in equation 19.9.

$$M = \rho V \tag{19.8}$$

$$G = \frac{dM}{dt} \tag{19.9}$$

$$G = \frac{d}{dt}(\rho V) = \rho\frac{dV}{dt} + V\frac{d\rho}{dt} \tag{19.10}$$

Then, the volume inside the bearing is considered to be constant, thus, the evaluation of the variation of the volume is null.

$$\frac{dV}{dt} = 0 \tag{19.11}$$

Since the volume variation is not considered anymore, the focus passes to the variation of air density. To be general, the typology of transformation considered is the polytropic one, characterized by the polytropic coefficient "n".

$$\rho = \rho_i(\frac{p}{p_i})^{\frac{1}{n}} \tag{19.12}$$

The derivative of the air density is performed and the result of the mass flow rate is represented in equation 19.13.

$$G = [\frac{\rho_i}{k_i}(\frac{p}{p_i})^{\frac{1}{n}} + \frac{V\rho_i}{np_i}(\frac{p}{p_i})^{\frac{1-n}{n}}]\frac{dp}{dt} = C\frac{dp}{dt} \tag{19.13}$$

Considering an isotropic transformation, the polytropic coefficient considered is n = 1. After some substitution, the formula for the capacity evaluation is the one in equation 19.14.

$$C = \frac{V}{RT} \tag{19.14}$$

From the equation of the flow rate, it is possible to find the variation of the pressure over the time and, based on that equation, the Simulink model reported in figure 19.7. An integrator is used to pass from the derivative of the pressure to the pressure itself.

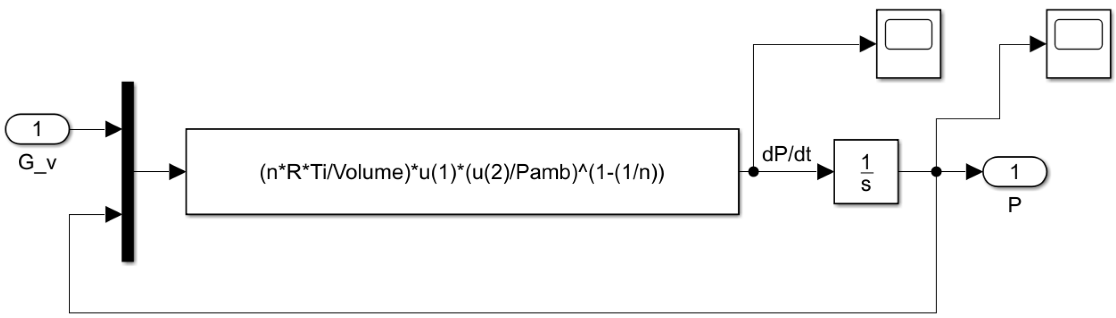


Figure 19.7. Simulink model of the bearing capacity.

Bearing exhaust hole resistance The exhaust hole under the bearing is modelled with an approach similar to the one used for the valve modelling. The hole is considered as a nozzle, thus an analysis to determine whether the condition is subsonic or sonic must be done. Depending on the system state, a different formula is applied, as follows:

$$Sonic flow \quad 0 < \frac{P_2}{P_1} < 0.528 \quad G = \frac{\pi d_s^2}{4} \Psi P_s c_d \quad [kg/s] \tag{19.15}$$

$$Subsonic flow \quad 0.528 < \frac{P_2}{P_1} < 1 \quad G = \frac{\pi d_s^2}{4} \Psi P_s c_d \sqrt{1 - (\frac{\frac{P_c}{P_s} - b}{1 - b})^2} \quad [kg/s] \tag{19.16}$$

Where:

- G is the mass flow rate passing through the hole, expressed in [kg/s];
- d_s is the diameter of the bearing exhaust hole, $d_s = 0.25$ mm;
- P_s is the inlet pressure of the air coming from the valve;
- P_c is the pressure under the bearing, thus the pressure after the hole;
- $\Psi = \frac{0.685}{\sqrt{RT}}$ with R = 287 J/kg K and T = 288 K;
- c_d is the flow coefficient coming from the formula: $c_d = 0.85(1 - (e^{-8.2\frac{h_s}{d_s}}))$ with R = 287 J/kg K and T = 288 K;

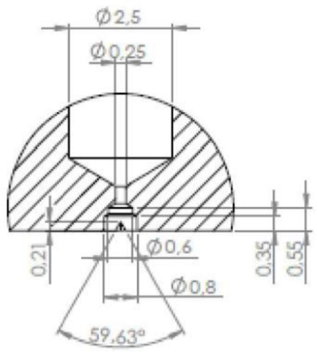


Figure 19.8. Bearing exhaust hole technical drawing [5].

The diameter of the hole is obtained from the technical drawing of the bearing (19.8). The value h_s is the distance between the hole and the basement where the bearing lays. As it is possible to see from the drawing, the distance between the hole and the base of the bearing is 0.550 mm. Since the bearing lift from the basement is about 0.020 mm, the value of h_s can be confused with the value 0.550 mm, reported in the drawing. Then, by substituting the real values in the formula of c_d, it is possible to see that the result can be approximated to 0.85 with a negligible error.

To model this resistance, the reported formulas are deployed in Simulink and the result is shown in figure 19.9. In the lower part, the flow direction is evaluated on the base of the pressure difference between the inlet and the outlet and a “1” or a “-1” is multiplied. In the upper part, the described formulas are applied to evaluate the mass flow rate coming from the bearing.

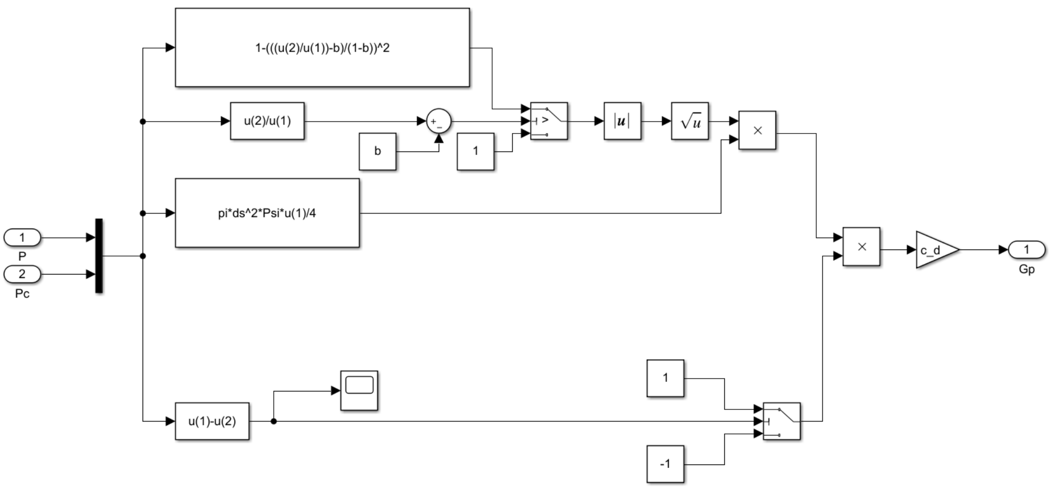


Figure 19.9. Bearing exhaust hole resistance model.

Air film capacity To determine the capacity of the air film under the bearing it is necessary to consider that the volume, in this case, is not constant, but depends on the bearing height h. As for the evaluation of the capacity of the bearing, the formula of the mass flow rate is considered (19.10). In this case, there is no simplification of the derivative of the volume because it varies in time. The first part of the formula is very similar to before, while for the second part, the volume must be derived.

$$V = L_1 L_2 h \tag{19.17}$$

$$\frac{dV}{dt} = L_1 L_2 \frac{dh}{dt} \tag{19.18}$$

In the previous formula, the value L_1 and L_2 are the length and width of the bearing, respectively 0.075 mm and 0.050 mm. The pressure value to use in the calculations is the mean pressure of the air film. To obtain this value it is possible to hypothesize a pyramidal pressure distribution under the bearing. The formula used is the 19.19, where the P_c is the maximum pressure under the bearing, which is experienced right next to the exhaust hole of the bearing, in the centre, and P_{amb} is the atmospheric pressure.

$$P_m = \frac{P_c - P_{amb}}{3} + P_{amb} \tag{19.19}$$

By performing some calculations, the equation 19.20 is obtained, representing the mass flow rate passing through the air film under the bearing.

$$G = \frac{dP_m}{dt} \left(\frac{P_m}{RT} L_1 L_2 \frac{dh}{dt} \frac{dt}{dP_m} + L_1 L_2 \frac{h}{RT}\right) \tag{19.20}$$

Then, the capacity of the air film is the following:

$$C = \frac{P_m}{RT} L_1 L_2 \frac{dh}{dt} \frac{dt}{dP} + L_1 L_2 \frac{h}{RT} \tag{19.21}$$

Since the output desired is the pressure P_m, the inverse of the formula is used:

$$\frac{dP_m}{dt} = G \frac{RT}{L_1 L_2 h} - \frac{P_m}{h} \frac{dh}{dt} \tag{19.22}$$

The implementation in Simulink is reported in figure 19.10. The saturation on the h branch is put to avoid the value to be negative, since negative heights values have no meaning.

Air film resistance The air film under the bearing has a pneumatic resistance that must be taken into account and modelled. This resistance depends on the air film height "h", thus it is not constant but it varies in time. To determine the resistance, it is needed to know the maximum pressure under the bearing, at the exhaust hole (P_c). This value can be obtained from the formula 19.19.

$$P_c = 3P_m - 2P_a \tag{19.23}$$

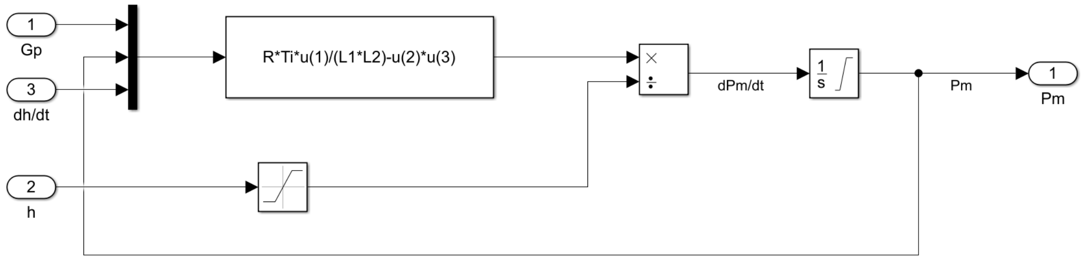


Figure 19.10. Bearing air film capacity Simulink model.

Then, the equation 19.24 is applied to determine the air flow going out from the meatus. The equation describes the air flow through a rectangular duct, on the base of the pressures upstream and downstream the duct itself (in this case respectively P_c and P_{amb}). The flow depends also on the meatus height at the third power. In the analysed case, the duct is not exactly a rectangular one, thus the coefficient c_h is introduced in order to adapt the formula and its value was defined in the previous thesis work [5].

$$G_{out} = c_h h^3 (P_c^2 - P_{amb}^2) \tag{19.24}$$

In the formula:

- G_{out} is the mass flow rate going out from the air film, expressed in [kg/s];
- c_h is the bearing coefficient, $c_h = 0.8$ [s/m^2]
- P_{amb} is the atmospheric pressure;
- P_c is the maximum pressure under the bearing, thus the pressure after the exhaust hole;
- h is the air film height

This formula is then used to develop the Simulink model, as reported in figure 19.11.

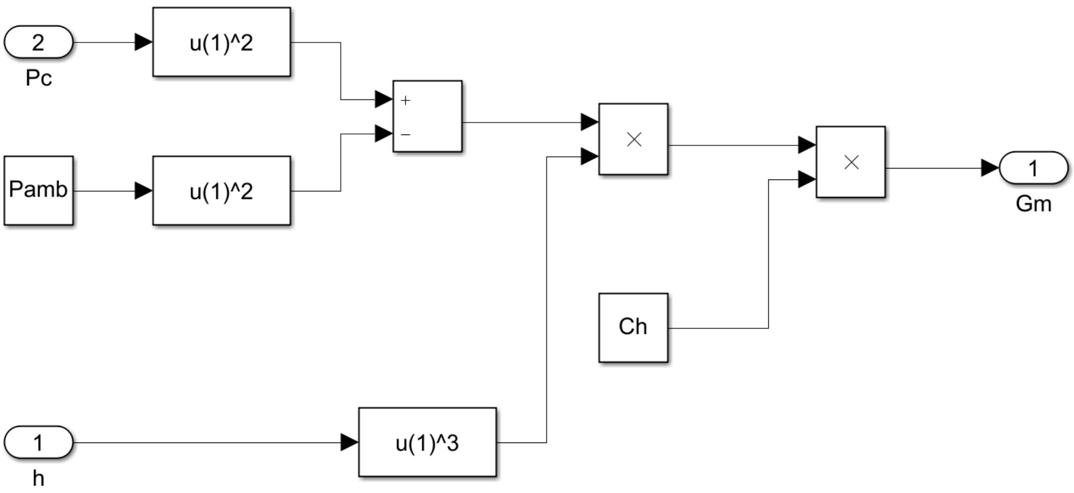


Figure 19.11. Bearing air film resistance Simulink model.

Vertical equilibrium equation The last part of the model concerns the evaluation of the vertical force equilibrium of the system, since the force generated by the pressure under the bearing must balance the force generated by the weights on the bearing and the bearing weight itself. The equilibrium is studied along the vertical direction, using the variable called "h". A scheme is reported in figure 19.12

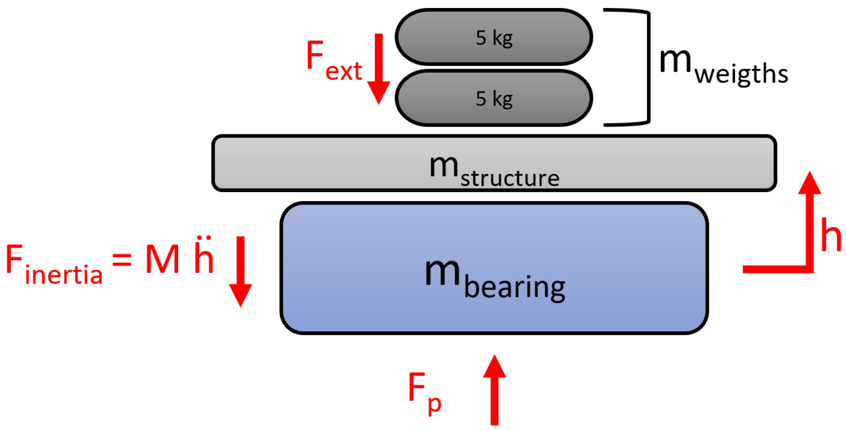


Figure 19.12. Scheme of the vertical equilibrium.

A clarification must be done for what concerns the masses:

- M is the mass of the bearing body ($m_{bearing}$ = 0.360 kg) plus the structure carrying the weights ($m_{structure}$ = 6.120 kg), thus M = 6.480 kg;
- $m_{weights}$ is the mass of the weights added on the structure. In the model, the force applied on the bearing is measured in Newton, thus, $m_{weights}$ derives from:

$$m_{weights} = F_{ext}/g \tag{19.25}$$

- the total mass applied to the bearing is:

$$M_{tot} = M + F_{ext}/g \tag{19.26}$$

  where F_{ext} is the external force applied with the weights and g is the gravity acceleration;

The vertical equation obtained is reported in equation 19.27. The dynamic forces are taken into account to have a more complete representation of the behaviour. In particular, the considered forces are the force generated by the pressure, the forces generated by the masses and the forces due to the inertia.

$$\ddot{h} = \frac{(P_c - P_a)L_1L_2}{3M_{tot}} - g \tag{19.27}$$

In the formula:

- M_{tot} is the total mass, as described before;
- P_c is the maximum pressure under the bearing;
- P_{amb} is the atmospheric pressure;
- L_1 and L_2 are the width and the length of the bearing;
- g is the gravity acceleration;
- the division by 3 is due to the pyramidal distribution of the pressure under the bearing;

The model realized in Simulink is reported in figure 19.13.

In this way, the double derivative of the vertical motion is obtained and then it is necessary to integrate two times to obtain the value of h.

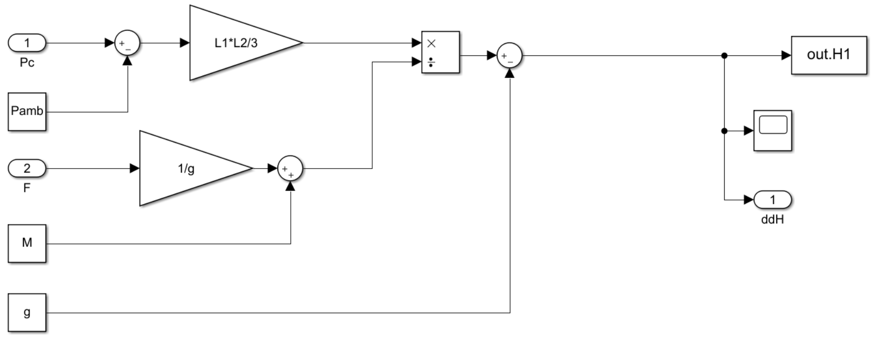


Figure 19.13. Vertical equation Simulink model.

General overview of the model The different obtained parts of the model, that compose the bearing system, are assembled in the Simulink shown in figure 19.14. The valve is driven by the voltage signal generated by the control board and then, this voltage is converted in current, simulating the action of the converting box.

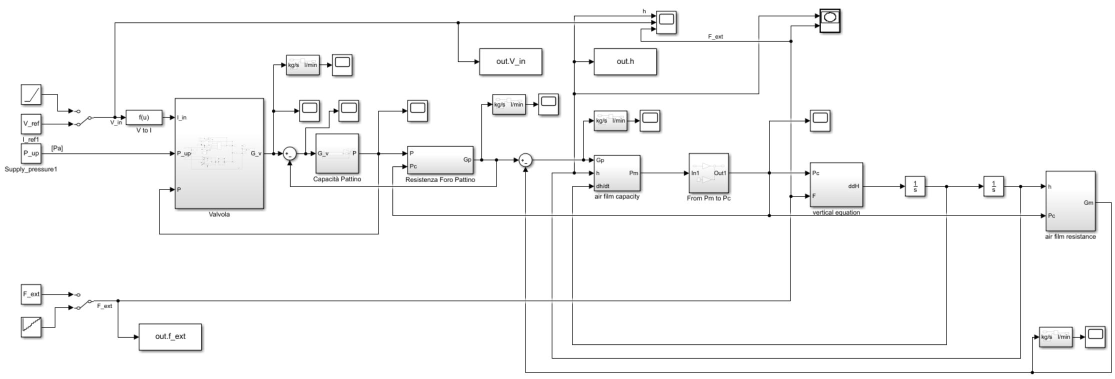


Figure 19.14. Complete Simulink model of the bearing.

Each subsystem represents an element: from left to right there are:

- the valve;
- the bearing capacity;
- the exhaust hole resistance;
- the air film capacity;

- the evaluation of the maximum pressure;
- the vertical equation;
- the air film resistance;

The system can have many inputs and outputs. For the purpose of the model, many parameters are fixed and it was decided to act on only few of them. As inputs, only the input voltage provided by the board and the force applied on the bearing are considered. The others, such as the input pressure (5 bar relative) or the atmospheric pressure (1 bar relative), are fixed. As output, the model is only focalized on the air film height “h”.

Since it is better to modify only one parameter at a time, two manual switches are inserted. The first switch allows to choose between a constant input voltage value or a ramp from 1.2 V to 2.75 V. The second switch is used to choose between a constant force or a series of steps representing the different weights loaded on the bearing during the static characterization.

Chapter 20

Comparison between simulation and laboratory results

The obtained model is run in order to verify if it could give results similar to the ones obtained in the laboratory or not. The compared curves are:

- the correspondence between the valve current excitation and the airflow flowing in the valve;
- the correspondence between valve signal tension and meatus height: Valve signal vs Air Film Height;
- the static characteristic of the bearing: Load vs Air Film Height;

The model is based on a series of components, each one of them refers to some parameters which are proper of the system, such as the dimension of the bearing, the inlet pressure, the pressure of the laboratory atmosphere etc. . .

The main parameters used in the simulation are reported in table 20.1. Each one of them can be obtained from the bearing, by measuring or by checking on the datasheet of each component. Some other parameters come from universal constant, such as the universal gas constant "R". However, during the simulations, some of the parameters are changed to try to better follow the curves obtained in the laboratory.

The first comparison is about the flow rate of the valve against the excitation current graph. For the simulation, the values used for the tuning of the valve subsystem were those relative to the conductance of the valve obtained from the flow-current curve relative to the valve alone, not mounted on the bearing (blue curve in figure 20.1). This choice is due to the independence of the conductance of the valve from the mounting typology.

Variable	Symbol	Value
Critical ratio	b	0.528
Natural frequency	ω_n	$35 \cdot 2 \cdot \pi \quad rad/s$
Damping factor	ζ	0.2
Flow coefficient	C_d	0.85
Bearing length	L_1	0.075 m
Bearing width	L_2	0.050 m
Bearing exhaust hole	d_s	$0.25 \cdot 10^{-3} m$
Internal chamber volume	V	$739.2 \cdot 10^{-}9 m^3$
Politropic exponent	n	1
Ideal gas constant	R	287 J/kgK
Room temperature	T_i	288 K
Air film temperature	T_m	293 K
Ψconstant	Ψ	$0.685/\sqrt{RT_i}$
Bearing coefficient	C_h	0.8 s/m^2
Under bearing pressures ratio	P_c/P_m	3
Gravity acceleration	g	9.81 m/s^2

Table 20.1. Table summarising all the used parameters.

During the simulation, the values of current and mass airflow are collected and plotted in the same graph, together with the curves obtained in laboratory (figure 20.1). As it is possible to see, even if the valve was initialized with the conductance value of the valve alone, the red line, representing the simulation, follows quite well the black curve, relative to the valve mounted on the bearing. This is a good result, showing that, the part relative to the valve, should work fine.

The second curve analysed is the air film height against the valve voltage signal graph, reported in figure 20.2. In this case, the correspondence between the simulation and the laboratory is not good. Only the general behaviour can have some similarities, but for what concerns the values, the difference is quite big. The problem faced is that, even if the valve signal is modified, the air film height changes very little, and this is not the real behaviour experienced in the laboratory.

The last graph considered is the one relative to the static characterization of the bearing, thus the load against bearing lift graph. The simulation covers only the part where the load is gradually incremented and the supply air is opened. The result is shown in figure 20.3, where the red line is the simulation while the blue one is the curve obtained on the Step test-bench. In this case, it is represented also the curve obtained on the Mager test-bench, in order to compare the three situations.

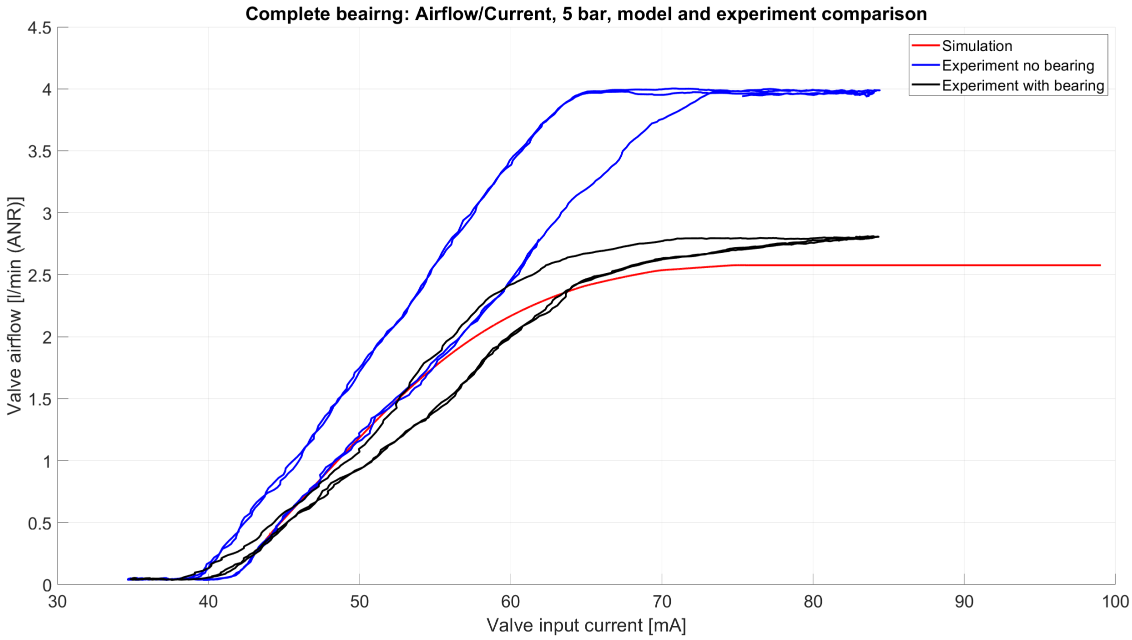


Figure 20.1. Comparison between the simulation and the laboratory results of the air-flow vs input-current graph.

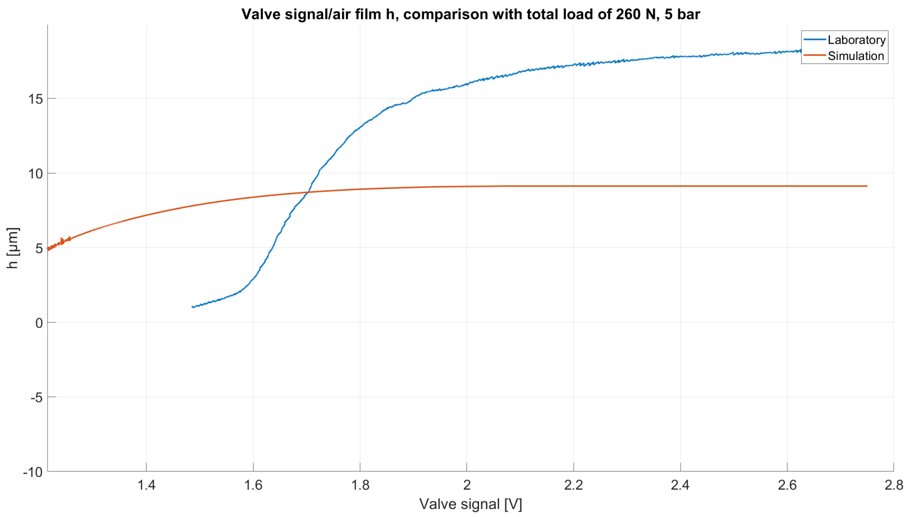


Figure 20.2. Comparison between the simulation and the laboratory results of the air-film height vs valve voltage signal graph.

As it is possible to see, the general behaviour can be considered similar, thus all the three curves represent a decreasing load as long as the "h" increases. However, the numerical correspondence among the curves is not precise.

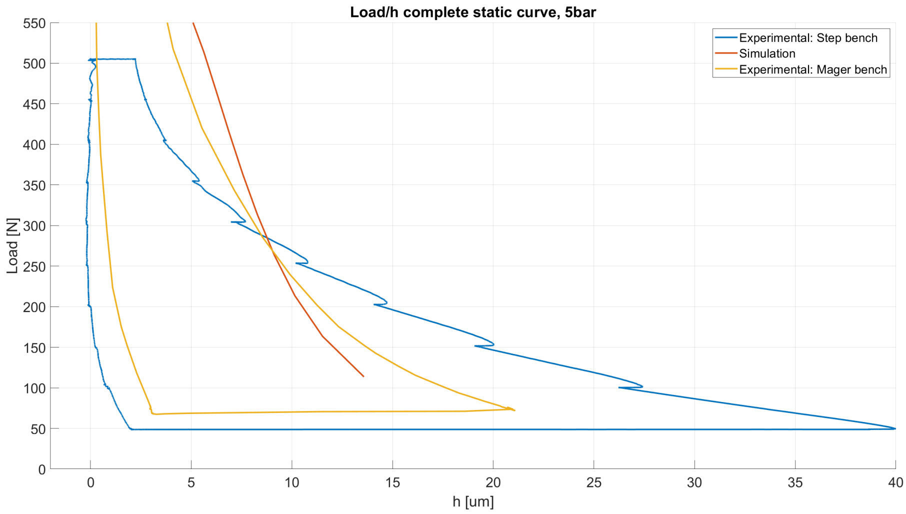


Figure 20.3. Comparison between the simulation and the laboratory results of the Load vs air-film height graph.

In general, it is convenient to consider only the working range of the bearing. Outside those value, in fact, other external disturbances can occur and they are not considered in the model. For example, the tilting of the bearing can modify the pressure distribution under the bearing and make the pressure generate a force which is different from the one modelled.

Many attempts were performed to obtain a model with a good correspondence with the real values obtained, but it was hard to find a correct combination of the parameter that provided a good approximation of the laboratory results. The model is quite complex, with many different steps and subsystem inside and this makes the parameter change influence the model in many different points, making the tuning quite difficult.

Considering the static characterization graph, to get a better representation of the reality, it would be needed to obtain a simulated curve which is more inclined, thus that for the same force reports a lower meatus height value until 10 µm, while above this value, that reports higher force values for the same air film height. To do so, the value of the C_h was reduced from 0.8 to 0.3, the value C_d was brought from 0.85 to 0.6 and L_1 was lowered from 0.075 m to 0.06 m. Also the diameter of the exhaust hole was reduced to 0.2 mm.

The result is the graph in figure 20.4. Another attempt was done in graph 20.5 where many parameters were modified:

- C_h from 0.8 to 0.4;

- P_c/P_m from 3 to 2;
- C_d from 0.85 to 1.1;
- d_s from 0.25 mm to 0.35 mm;
- $L_1 \cdot L_2$ from 0.00375 m^2 to 0.0015 m^2;

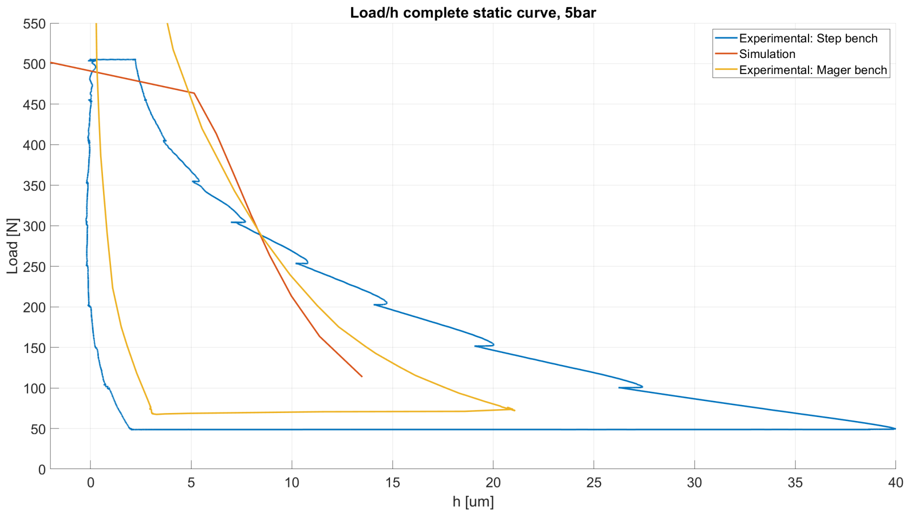


Figure 20.4. First modification of the model: comparison of the static curve.

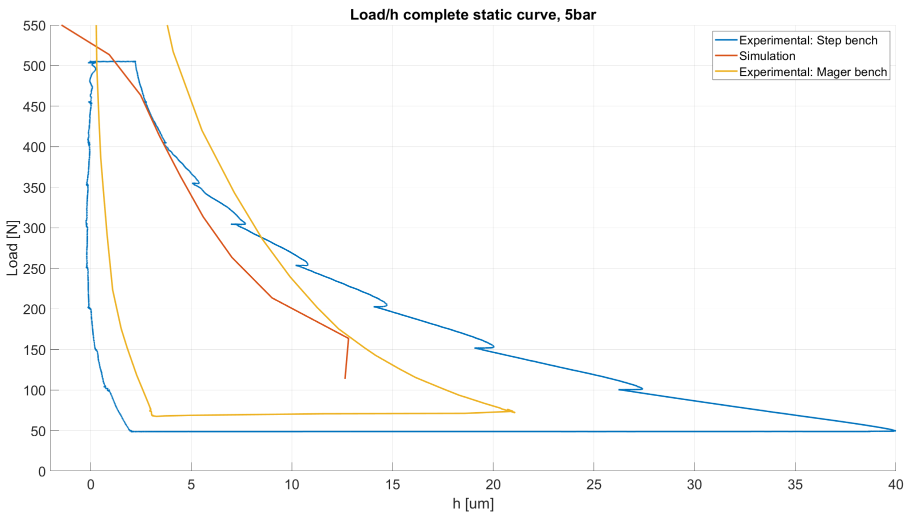


Figure 20.5. Second modification of the model: comparison of the static curve.

Even with some parameter tuning, the correspondence is not good. For this reason, it is necessary to implement some other modifications to the model, in order to obtain a more accurate representation. By looking at the comparison, the correspondence is better with the curve relative to the Mager test-bench. This happens, even if the model is deployed according to the working principles of the Step bench and not the Mager. In fact, in the model used for describing the Step bench, the vertical equation block is introduced. This subsystem takes into account that the bearing air film height only depends on the force balance over and under the bearing, thus the balance between the force generated by the load over the bearing and the force generated by the pressure distribution under the device. This point should be further investigated, in order to obtain a model with a behaviour which better reflects the reality.

Part V

Conclusions and future improvements

Chapter 21

Conclusions and future improvements

The aim of this thesis was to develop an active air bearing, able to regulate the opening of a proportional valve and keep its lift from the basement constant. A series of tests on the single components and on the complete bearing are performed in order to build and improve a knowledge about the components used and to start building the control action. Two kind of control action are developed: one based on a specific loading condition and then requiring the system to adapt to the modifications, the other unrelated to the loading conditions. For both the configurations, quite good results are obtained, especially if it is considered that it was the first approach in obtaining a working control action. The bearing generally follows the set, but it still has some troubles when the weight carried on is too big or too little. A further investigation and improvement of the program is needed.

The other aim of the thesis was to obtain a working model of the proportional valve and the complete bearing. To do so, a model of each single component of the bearing is developed in Simulink and then they are assembled together. The valve was modelled first and a quite good correspondence with the laboratory results is observed. For what concerns the model of the complete bearing, instead, the correspondence with the results obtained in the laboratory is not very good and, for this reason, further improvements and modifications are required.

In this thesis work, the test-bench used is not the same adopted for the previous works. Since some of the experiments performed were dedicated at the definition of the behaviour of the bearing when loaded in a specific way and fed with a specific inlet pressure, the obtained results using the two different benches were compared. It is discovered that the characterization of the bearing on the two test-benches analysed, the Step and the Mager, highlighted some differences. Those differences refer to the dissimilar correspondence on the two benches between the load on the bearing and its lift. This result was not expected, since the characteristic of the bearing should not depend on the kind of bench used to obtain it. Further investigations on the reasons of this diversity can be done in the next works and a static characteristic, which describes well the bearing, should be better defined.

Another investigation performed was the lifting behaviour of the bearing. It was discovered a tilting effect, preventing it from lifting parallel to the ground. It was tried to reduce this effect by eliminating possible external effects causing the unbalancing, but it was not possible to eliminate it. However, the tilting of the bearing can be neglected if verified that the bearing, during the lift, does not hit the basement with its corners. Moreover, during a possible real application of the system, the device would be fixed under a rigid machine and it is probable that more than one bearing would be used. In this way, the bearing would have a better guidance, avoiding or reducing the tilting effect.

In conclusions, this thesis contributed to carry on the development of an active air bearing, in particular its control action and its modeling, nevertheless, future improvements and investigations are required to obtain a fully working device and a good representation of it. First of all, a development of a more accurate description of the bearing is recommended, in order to obtain a better overlapping of the simulation with the real experimental results. A possible approach could also be to perform again tests in the laboratory, to be sure the real measurements are correct. Moreover, it is interesting to investigate in a deeper way the reasons why the characterization of the bearing on the two test-benches resulted to be different, with the main purpose of determining which is the best test-bench to develop the further investigations on and which one better reflects the real working conditions.

At the same time, it is convenient to keep improving the control action parameters or to develop a different control action approach with the aim of a perfect following of the required lift, despite the external disturbances. Going on with the investigation, it is then convenient to introduce the second back-pressure sensor, for a better representation of the bearing lifting. With this aim, an additional possible upgrade of the bearing could be the introduction of a higher number of back-pressure sensors, maybe integrated in the bearing itself by means of the use, for example, of a 3D printer. Those sensors could be useful in a predictive maintenance approach, allowing to monitor the possible contact between the bearing and the basement during the tilting, detecting the failure and operating to solve the problem. The last enhancement could be the introduction of a load cell over the bearing which allows to determine the loaded weight and develop a feed forward action in the control, in order to further improve the performances.

Bibliography

[1] *Air bearing*. Wikipedia. URL: https://en.wikipedia.org/w/index.php?title=Air_bearing&oldid=968294655.

[2] *Common applications for air bearings*. Linear Motion Tips. URL: https://www.linearmotiontips.com/common-applications-for-air-bearings/.

[3] Jana Schwartz, Mason Peck, and Christopher Hall. "Historical Review of Air-Bearing Spacecraft Simulators". In: *Journal of Guidance, Control, and Dynamics* 26 (May 1, 2003).

[4] Marco Maccario. "Air thrust bearing controlled with air proportional valve". PhD thesis. 2019.

[5] Tommaso Fara. "Studio di pattino pneumostatico con controllo attivo mediante valvola pneumatica proporzionale". PhD thesis. 2020.

[6] SMC. *Proportional valve SMC PVQ datasheet*.

[7] *Micro-epsilon Capacitive sensors datasheet*.

[8] *Generate voltage on the specified DAC pin - Simulink - MathWorks Italia*. URL: https://it.mathworks.com/help/supportpkg/arduino/ref/analogoutput.html.

[9] Daniela Maffiodo Federico Colombo and Terenziano Raparelli. *Active Gas Thrust Bearing With Embedded Digital Valves and Backpressure Sensors*. Tribology Transactions, 2016.

[10] Daniela Maffiodo Federico Colombo and Terenziano Raparelli. *Numerical Model of Digital Valve-Controlled Active Air Bearing*. Politecnico di Torino, 2018.

[11] Pfeiffer Vacuum. *Conductance*. URL: https://www.pfeiffer-vacuum.com/en/know-how/introduction-to-vacuum-technology/fundamentals/conductance/.

[12] Lion Precision. *Funzionamento e ottimizzazione del sensore capacitivo*. Lion Precision. URL: https://www.lionprecision.com/it/capacitive-sensor-operation-and-optimization-how-capacitive-sensors-work-and-how-to-use-them-effectively/.

[13] Guido Belforte. *Manuale di pneumatica*. Tecniche Nuove, 2019.

[14] *Air Bearing Fundamentals*. URL: `https://www.specialtycomponents.com/Resources/Technical-Articles/Air-Bearing-Fundamentals/`.

[15] Matteo Troiano. "Studio del controllo di un pattino ad aria con valvole pneumatiche integrate". PhD thesis. 2016.

[16] What's Next. *What's Next Orange datasheet*.

[17] Ladispe Polito. *Regolatori PID*.

[18] Pneumax. *Concetti base di pneumatica*.

[19] Mario Capuzzimati. *PID: Taratura dei parametri. Ziegler e Nichols*.

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POLITECNICO DI TORINO

Master's Degree in
Mechatronic Engineering

Master Thesis

Control of an active air bearing: simulation and experimental tests

Annex 1: Matlab scripts used

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Prof. Federico Colombo

Candidate
Paolo Bisiach

April 2021

Contents

Annex 1 In this annex, the most representative Matlab scripts used in the data elaboration are reported. They are subdivided into different sections, according to the type of data and type of elaboration they are used for.

Static curve with inlet air always opened

Fully opened valve

```
%prova statica per diverse pressioni in ingresso, massima ...
    apertura della valvola
%Misurazione: alimentazione chiusa, apro alimentazione, scarico ...
    5kg per volta, chiudo alimentazione

clear all
close all
clc

%variables
m_support = 6.48;
masses = [20 15 10 5 0];
g = 9.81;

%% 4 bar; fully opened valve (maximum voltage)
%data acquisition
data = load('prova_statica_bar4_1.txt');
for i = 1:4
    capac_4bar_fullV(:,i) = data(:,i);
end
loadCell_4bar_fullV = data(:,5);

%plot(capac_4bar_fullV(:,1))
%hold on

%move mean
for i = 1:4
    capac_4bar_fullV(:,i) = movmean(capac_4bar_fullV(:,i),100);
end

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_4bar_fullV(i) = ...
        mean(capac_4bar_fullV((1:3000),i));
end
base_mean_capac_4bar_fullV
for i = 1:4
    capac_4bar_fullV(:,i) = -1*(capac_4bar_fullV(:,i) - ...
        base_mean_capac_4bar_fullV(1,i)); %change sign
```

```
end
%estrapolation single values for caracterization
%   single_values_4bar_fullV =[              capac1  capac2  ...
    capac3  capac4
%                                 no_air
%                                 20kg
%                                 15kg
%                                 10kg
%                                 5kg
%                                 0kg
%                                 no_air ]
for i = 1:4
    single_values_4bar_fullV(1,i) = ...
       mean(capac_4bar_fullV((1:3000),i));
    single_values_4bar_fullV(2,i) = ...
       mean(capac_4bar_fullV((4000:7000),i));
    single_values_4bar_fullV(3,i) = ...
       mean(capac_4bar_fullV((8000:10000),i));
    single_values_4bar_fullV(4,i) = ...
       mean(capac_4bar_fullV((11000:13000),i));
    single_values_4bar_fullV(5,i) = ...
       mean(capac_4bar_fullV((14500:16000),i));
    single_values_4bar_fullV(6,i) = ...
       mean(capac_4bar_fullV((18000:21000),i));
    single_values_4bar_fullV(7,i) = ...
       mean(capac_4bar_fullV((22000:end),i));
end
single_values_4bar_fullV
for i = 1:7
    single_values_4bar_fullV_mean(i) = ...
       mean(single_values_4bar_fullV(i,:));
end

for i = 2:6
    y_4bar_fullV(i-1) = (masses(i-1)+m_support)*g; %conversion ...
       to NEWTON
    x_4bar_fullV(i-1) = single_values_4bar_fullV_mean(i);
end

%% 5 bar; fully opened valve (maximum voltage)
%data acquisition
data = load('prova_statica_bar5_1.txt');
for i = 1:4
    capac_5bar_fullV(:,i) = data(:,i);
end
loadCell_5bar_fullV = data(:,5);

%plot(capac_4bar_fullV(:,1))
%hold on

```

```
%move mean
for i = 1:4
    capac_5bar_fullV(:,i) = movmean(capac_5bar_fullV(:,i),100);
end

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_fullV(i) = ...
       mean(capac_5bar_fullV((1:3000),i));
end
base_mean_capac_5bar_fullV
for i = 1:4
    capac_5bar_fullV(:,i) = -1*(capac_5bar_fullV(:,i) - ...
       base_mean_capac_5bar_fullV(1,i)); %change sign
end

%estrapolation single values for caracterization
%   single_values_5bar_fullV =[              capac1  capac2  ...
   capac3  capac4
%                                   no_air
%                                   20kg
%                                   15kg
%                                   10kg
%                                   5kg
%                                   0kg
%                                   no_air ]
for i = 1:4
    single_values_5bar_fullV(1,i) = ...
       mean(capac_5bar_fullV((1:3000),i));
    single_values_5bar_fullV(2,i) = ...
       mean(capac_5bar_fullV((4000:6000),i));
    single_values_5bar_fullV(3,i) = ...
       mean(capac_5bar_fullV((8000:10000),i));
    single_values_5bar_fullV(4,i) = ...
       mean(capac_5bar_fullV((11000:13000),i));
    single_values_5bar_fullV(5,i) = ...
       mean(capac_5bar_fullV((14500:16000),i));
    single_values_5bar_fullV(6,i) = ...
       mean(capac_5bar_fullV((18000:21000),i));
    single_values_5bar_fullV(7,i) = ...
       mean(capac_5bar_fullV((22000:end),i));
end
single_values_5bar_fullV
for i = 1:7
    single_values_5bar_fullV_mean(i) = ...
       mean(single_values_5bar_fullV(i,:));
end
single_values_5bar_fullV_mean

for i = 2:6
```

```
    y_5bar_fullV(i-1) = (masses(i-1)+m_support)*g; %conversion ...
        to NEWTON
    x_5bar_fullV(i-1) = single_values_5bar_fullV_mean(i);
end

%% 6 bar; fully opened valve (maximum voltage)
%data acquisition
data = load('prova_statica_bar6_1.txt');
for i = 1:4
    capac_6bar_fullV(:,i) = data(:,i);
end
loadCell_6bar_fullV = data(:,5);

%plot(capac_6bar_fullV(:,1))
%hold on

%move mean
for i = 1:4
    capac_6bar_fullV(:,i) = movmean(capac_6bar_fullV(:,i),100);
end

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_6bar_fullV(i) = ...
        mean(capac_6bar_fullV((1:3000),i));
end
base_mean_capac_6bar_fullV
for i = 1:4
    capac_6bar_fullV(:,i) = -1*(capac_6bar_fullV(:,i) - ...
        base_mean_capac_6bar_fullV(1,i)); %change sign
end
%estrapolation single values for caracterization
%   single_values_6bar_fullV =[             capac1  capac2  ...
   capac3  capac4
%                               no_air
%                               20kg
%                               15kg
%                               10kg
%                               5kg
%                               0kg
%                               no_air ]
for i = 1:4
    single_values_6bar_fullV(1,i) = ...
        mean(capac_6bar_fullV((1:3000),i));
    single_values_6bar_fullV(2,i) = ...
        mean(capac_6bar_fullV((4000:6000),i));
    single_values_6bar_fullV(3,i) = ...
        mean(capac_6bar_fullV((9000:10000),i));
    single_values_6bar_fullV(4,i) = ...
        mean(capac_6bar_fullV((11500:13500),i));
```

```
    single_values_6bar_fullV(5,i) = ...
        mean(capac_6bar_fullV((15000:17000),i));
    single_values_6bar_fullV(6,i) = ...
        mean(capac_6bar_fullV((18500:21500),i));
    single_values_6bar_fullV(7,i) = ...
        mean(capac_6bar_fullV((23000:end),i));
end
single_values_6bar_fullV
for i = 1:7
    single_values_6bar_fullV_mean(i) = ...
        mean(single_values_6bar_fullV(i,:));
end
single_values_6bar_fullV_mean

for i = 2:6
    y_6bar_fullV(i-1) = (masses(i-1)+m_support)*g; %conversion ...
        to NEWTON
    x_6bar_fullV(i-1) = single_values_6bar_fullV_mean(i);
end

%% PLOTS
figure(1)
hold on
%plot of first capacitive sensor
for i = 1:4
    plot(capac_4bar_fullV(:,i),'r')
    plot(capac_5bar_fullV(:,i),'b')
    plot(capac_6bar_fullV(:,i),'k')
end
grid on;
xlabel('Time');
ylabel('h [μm]');
legend('4 bar','5 bar','6 bar');
title('Meatus h at different relative inlet pressure');

figure(2)
hold on
plot(x_4bar_fullV,y_4bar_fullV)
plot(x_5bar_fullV,y_5bar_fullV)
plot(x_6bar_fullV,y_6bar_fullV)
grid on;
xlabel('h [μm]');
ylabel('Load [N]');
legend('4 bar','5 bar','6 bar');
title('load/h at different relative inlet pressure');
```

Partially opened valve

```matlab
%prova statica per diverse pressioni in ingresso, diverse ...
    aperture della valvola
%Misurazione: alimentazione chiusa, apro alimentazione, scarico ...
    5kg per volta, chiudo alimentazione

% 1.3v
% 1.4v
% 1.5V
% 1.62V
% 1.7V              50%
% 2V                  75%
% 2.3V              100%
% max volt

% diverse pressioni relative:
% 4 bar
% 5 bar
% 6 bar

clear all
close all
clc

%variables
m_support = 6.480; %kg
masses = [20 15 10 5 0];
g = 9.81;

%% 5 bar; 1,20V
%data acquisition
data = load('prova_statica_bar5_1_1.20V.txt');
for i = 1:4
    capac_5bar_1_20V(:,i) = data(:,i);
end
loadCell_5bar_1_20V = data(:,5);

%move mean
for i = 1:4
    capac_5bar_1_20V(:,i) = movmean(capac_5bar_1_20V(:,i),100);
end

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_1_20V(i) = ...
        mean(capac_5bar_1_20V((1:3000),i));
end
base_mean_capac_5bar_1_20V
```

```
for i = 1:4
    capac_5bar_1_20V(:,i) = -1*(capac_5bar_1_20V(:,i) - ...
        base_mean_capac_5bar_1_20V(1,i)); %change sign
end
%estrapolation single values for caracterization
%   single_values_4bar_fullV =[              capac1  capac2  ...
    capac3  capac4
%                                   no_air
%                                   20kg
%                                   15kg
%                                   10kg
%                                   5kg
%                                   0kg
%                                   no_air ]
for i = 1:4
    single_values_5bar_1_20V(1,i) = ...
        mean(capac_5bar_1_20V((1:8000),i));
    single_values_5bar_1_20V(2,i) = ...
        mean(capac_5bar_1_20V((14500:17000),i));
    single_values_5bar_1_20V(3,i) = ...
        mean(capac_5bar_1_20V((19500:22000),i));
    single_values_5bar_1_20V(4,i) = ...
        mean(capac_5bar_1_20V((23500:25500),i));
    single_values_5bar_1_20V(5,i) = ...
        mean(capac_5bar_1_20V((27500:29000),i));
    single_values_5bar_1_20V(6,i) = ...
        mean(capac_5bar_1_20V((31200:3300),i));
    single_values_5bar_1_20V(7,i) = ...
        mean(capac_5bar_1_20V((3500:end),i));
end
single_values_5bar_1_20V
for i = 1:7
    single_values_5bar_1_20V_mean(i) = ...
        mean(single_values_5bar_1_20V(i,:));
end
single_values_5bar_1_20V_mean   %mean between the 4 capacitive ...
    sensors for each load

for i = 6:-1:2
    y_5bar_1_20V(i-1) = (masses(i-1)+m_support)*g; %conversion ...
        to NEWTON
    x_5bar_1_20V(i-1) = single_values_5bar_1_20V_mean(i);
end

%% 5 bar; 1,30V
%data acquisition
data = load('prova_statica_bar5_1_1.30V.txt');
for i = 1:4
    capac_5bar_1_30V(:,i) = data(:,i);
end
```

```
loadCell_5bar_1_30V = data(:,5);

%move mean
for i = 1:4
    capac_5bar_1_30V(:,i) = movmean(capac_5bar_1_30V(:,i),100);
end

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_1_30V(i) = ...
        mean(capac_5bar_1_30V((1:3000),i));
end
base_mean_capac_5bar_1_30V
for i = 1:4
    capac_5bar_1_30V(:,i) = -1*(capac_5bar_1_30V(:,i) - ...
        base_mean_capac_5bar_1_30V(1,i)); %change sign
end

%estrapolation single values for caracterization
%   single_values_4bar_fullV =[             capac1  capac2  ...
    capac3  capac4
%                                  no_air
%                                  20kg
%                                  15kg
%                                  10kg
%                                  5kg
%                                  0kg
%                                  no_air ]
for i = 1:4
    single_values_5bar_1_30V(1,i) = ...
        mean(capac_5bar_1_30V((1:2800),i));
    single_values_5bar_1_30V(2,i) = ...
        mean(capac_5bar_1_30V((4500:6000),i));
    single_values_5bar_1_30V(3,i) = ...
        mean(capac_5bar_1_30V((7200:9600),i));
    single_values_5bar_1_30V(4,i) = ...
        mean(capac_5bar_1_30V((10500:12700),i));
    single_values_5bar_1_30V(5,i) = ...
        mean(capac_5bar_1_30V((13600:15700),i));
    single_values_5bar_1_30V(6,i) = ...
        mean(capac_5bar_1_30V((17700:21000),i));
    single_values_5bar_1_30V(7,i) = ...
        mean(capac_5bar_1_30V((22900:end),i));
end
single_values_5bar_1_30V
for i = 1:7
    single_values_5bar_1_30V_mean(i) = ...
        mean(single_values_5bar_1_30V(i,:));
end
```

```
single_values_5bar_1_30V_mean   %mean between the 4 capacitive sensors for each load

for i = 6:-1:2
    y_5bar_1_30V(i-1) = (masses(i-1)+m_support)*g; %conversion to NEWTON
    x_5bar_1_30V(i-1) = single_values_5bar_1_30V_mean(i);
end

%% 5 bar; 1,40V
%data acquisition
data = load('prova_statica_bar5_1_1.40V.txt');
for i = 1:4
    capac_5bar_1_40V(:,i) = data(:,i);
end
loadCell_5bar_1_40V = data(:,5);

%move mean
for i = 1:4
    capac_5bar_1_40V(:,i) = movmean(capac_5bar_1_40V(:,i),100);
end

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_1_40V(i) = ...
        mean(capac_5bar_1_40V((1:3000),i));
end
base_mean_capac_5bar_1_40V
for i = 1:4
    capac_5bar_1_40V(:,i) = -1*(capac_5bar_1_40V(:,i) - ...
        base_mean_capac_5bar_1_40V(1,i)); %change sign
end

%estrapolation single values for caracterization
%    single_values_4bar_fullV =[               capac1   capac2   capac3   capac4
%                                  no_air
%                                  20kg
%                                  15kg
%                                  10kg
%                                  5kg
%                                  0kg
%                                  no_air ]
for i = 1:4
    single_values_5bar_1_40V(1,i) = ...
        mean(capac_5bar_1_40V((1:3700),i));
    single_values_5bar_1_40V(2,i) = ...
        mean(capac_5bar_1_40V((5500:7300),i));
    single_values_5bar_1_40V(3,i) = ...
        mean(capac_5bar_1_40V((8300:10800),i));
```

```
    single_values_5bar_1_40V(4,i) = ...
        mean(capac_5bar_1_40V((11700:13600),i));
    single_values_5bar_1_40V(5,i) = ...
        mean(capac_5bar_1_40V((14800:16300),i));
    single_values_5bar_1_40V(6,i) = ...
        mean(capac_5bar_1_40V((17300:20000),i));
    single_values_5bar_1_40V(7,i) = ...
        mean(capac_5bar_1_40V((22500:end),i));
end
single_values_5bar_1_40V
for i = 1:7
    single_values_5bar_1_40V_mean(i) = ...
        mean(single_values_5bar_1_40V(i,:));
end
single_values_5bar_1_40V_mean   %mean between the 4 capacitive ...
    sensors for each load

for i = 6:-1:2
    y_5bar_1_40V(i-1) = (masses(i-1)+m_support)*g; %conversion ...
        to NEWTON
    x_5bar_1_40V(i-1) = single_values_5bar_1_40V_mean(i);
end

%% 5 bar; 1,50V
%data acquisition
data = load('prova_statica_bar5_1_1.50V.txt');
for i = 1:4
    capac_5bar_1_50V(:,i) = data(:,i);
end
loadCell_5bar_1_50V = data(:,5);

%move mean
for i = 1:4
    capac_5bar_1_50V(:,i) = movmean(capac_5bar_1_50V(:,i),100);
end

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_1_50V(i) = ...
        mean(capac_5bar_1_50V((1:3000),i));
end
base_mean_capac_5bar_1_50V
for i = 1:4
    capac_5bar_1_50V(:,i) = -1*(capac_5bar_1_50V(:,i) - ...
        base_mean_capac_5bar_1_50V(1,i)); %change sign
end

%estrapolation single values for caracterization
%   single_values_4bar_fullV =[              capac1   capac2   ...
    capac3   capac4
```

```
%                                 no_air
%                                 20kg
%                                 15kg
%                                 10kg
%                                 5kg
%                                 0kg
%                                 no_air ]
for i = 1:4
    single_values_5bar_1_50V(1,i) = ...
       mean(capac_5bar_1_50V((1:3500),i));
    single_values_5bar_1_50V(2,i) = ...
       mean(capac_5bar_1_50V((5000:6700),i));
    single_values_5bar_1_50V(3,i) = ...
       mean(capac_5bar_1_50V((7500:10000),i));
    single_values_5bar_1_50V(4,i) = ...
       mean(capac_5bar_1_50V((11000:13300),i));
    single_values_5bar_1_50V(5,i) = ...
       mean(capac_5bar_1_50V((14700:17400),i));
    single_values_5bar_1_50V(6,i) = ...
       mean(capac_5bar_1_50V((18700:21400),i));
    single_values_5bar_1_50V(7,i) = ...
       mean(capac_5bar_1_50V((23500:end),i));
end
single_values_5bar_1_50V
for i = 1:7
    single_values_5bar_1_50V_mean(i) = ...
       mean(single_values_5bar_1_50V(i,:));
end
single_values_5bar_1_50V_mean   %mean between the 4 capacitive ...
   sensors for each load

for i = 6:-1:2
    y_5bar_1_50V(i-1) = (masses(i-1)+m_support)*g; %conversion ...
       to NEWTON
    x_5bar_1_50V(i-1) = single_values_5bar_1_50V_mean(i);
end

%% 5 bar; 1,62V
%data acquisition
data = load('prova_statica_bar5_1_1.62V.txt');
for i = 1:4
    capac_5bar_1_62V(:,i) = data(:,i);
end
loadCell_5bar_1_62V = data(:,5);

%move mean
for i = 1:4
    capac_5bar_1_62V(:,i) = movmean(capac_5bar_1_62V(:,i),100);
end

```

```
%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_1_62V(i) = ...
        mean(capac_5bar_1_62V((1:3000),i));
end
base_mean_capac_5bar_1_62V
for i = 1:4
    capac_5bar_1_62V(:,i) = -1*(capac_5bar_1_62V(:,i) - ...
        base_mean_capac_5bar_1_62V(1,i)); %change sign
end

%estrapolation single values for caracterization
%   single_values_4bar_fullV =[             capac1  capac2  ...
    capac3  capac4
%                                  no_air
%                                  20kg
%                                  15kg
%                                  10kg
%                                  5kg
%                                  0kg
%                                  no_air ]
for i = 1:4
    single_values_5bar_1_62V(1,i) = ...
        mean(capac_5bar_1_62V((1:8000),i));
    single_values_5bar_1_62V(2,i) = ...
        mean(capac_5bar_1_62V((14500:17000),i));
    single_values_5bar_1_62V(3,i) = ...
        mean(capac_5bar_1_62V((19500:22000),i));
    single_values_5bar_1_62V(4,i) = ...
        mean(capac_5bar_1_62V((23500:25500),i));
    single_values_5bar_1_62V(5,i) = ...
        mean(capac_5bar_1_62V((27500:29000),i));
    single_values_5bar_1_62V(6,i) = ...
        mean(capac_5bar_1_62V((31200:33700),i));
    single_values_5bar_1_62V(7,i) = ...
        mean(capac_5bar_1_62V((38500:end),i));
end
single_values_5bar_1_62V
for i = 1:7
    single_values_5bar_1_62V_mean(i) = ...
        mean(single_values_5bar_1_62V(i,:));
end
single_values_5bar_1_62V_mean   %mean between the 4 capacitive ...
    sensors for each load

for i = 6:-1:2
    y_5bar_1_62V(i-1) = (masses(i-1)+m_support)*g; %conversion ...
        to NEWTON
    x_5bar_1_62V(i-1) = single_values_5bar_1_62V_mean(i);
end
```

```
%% 5 bar; 1,70V
%data acquisition
data = load('prova_statica_bar5_1_1.70V.txt');
for i = 1:4
    capac_5bar_1_70V(:,i) = data(:,i);
end
loadCell_5bar_1_70V = data(:,5);

%move mean
for i = 1:4
    capac_5bar_1_70V(:,i) = movmean(capac_5bar_1_70V(:,i),100);
end

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_1_70V(i) = ...
       mean(capac_5bar_1_70V((1:3000),i));
end
for i = 1:4
    capac_5bar_1_70V(:,i) = -1*(capac_5bar_1_70V(:,i) - ...
       base_mean_capac_5bar_1_70V(1,i)); %change sign
end

%estrapolation single values for caracterization
%   single_values_4bar_fullV =[             capac1  capac2  ...
   capac3  capac4
%                                  no_air
%                                  20kg
%                                  15kg
%                                  10kg
%                                  5kg
%                                  0kg
%                                  no_air ]
for i = 1:4
    single_values_5bar_1_70V(1,i) = ...
       mean(capac_5bar_1_70V((1:3000),i));
    single_values_5bar_1_70V(2,i) = ...
       mean(capac_5bar_1_70V((5500:7000),i));
    single_values_5bar_1_70V(3,i) = ...
       mean(capac_5bar_1_70V((8500:11000),i));
    single_values_5bar_1_70V(4,i) = ...
       mean(capac_5bar_1_70V((12900:14800),i));
    single_values_5bar_1_70V(5,i) = ...
       mean(capac_5bar_1_70V((16500:18500),i));
    single_values_5bar_1_70V(6,i) = ...
       mean(capac_5bar_1_70V((20500:23000),i));
    single_values_5bar_1_70V(7,i) = ...
       mean(capac_5bar_1_70V((26000:end),i));
end
```

```
single_values_5bar_1_70V
for i = 1:7
    single_values_5bar_1_70V_mean(i) = ...
        mean(single_values_5bar_1_70V(i,:));
end
single_values_5bar_1_70V_mean   %mean between the 4 capacitive ...
    sensors for each load

for i = 6:-1:2
    y_5bar_1_70V(i-1) = (masses(i-1)+m_support)*g; %conversion ...
        to NEWTON
    x_5bar_1_70V(i-1) = single_values_5bar_1_70V_mean(i);
end

%% 5 bar; 2.00V
%data acquisition
data = load('prova_statica_bar5_1_2.00V.txt');
for i = 1:4
    capac_5bar_2_00V(:,i) = data(:,i);
end
loadCell_5bar_2_00V = data(:,5);

%move mean
for i = 1:4
    capac_5bar_2_00V(:,i) = movmean(capac_5bar_2_00V(:,i),100);
end

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_2_00V(i) = ...
        mean(capac_5bar_2_00V((1:3000),i));
end
base_mean_capac_5bar_2_00V
for i = 1:4
    capac_5bar_2_00V(:,i) = -1*(capac_5bar_2_00V(:,i) - ...
        base_mean_capac_5bar_2_00V(1,i)); %change sign
end

%estrapolation single values for caracterization
%    single_values_4bar_fullV =[             capac1  capac2  ...
    capac3  capac4
%                                   no_air
%                                   20kg
%                                   15kg
%                                   10kg
%                                   5kg
%                                   0kg
%                                   no_air ]
for i = 1:4
```

```
    single_values_5bar_2_00V(1,i) = ...
        mean(capac_5bar_2_00V((1:3800),i));
    single_values_5bar_2_00V(2,i) = ...
        mean(capac_5bar_2_00V((4800:7900),i));
    single_values_5bar_2_00V(3,i) = ...
        mean(capac_5bar_2_00V((8800:11400),i));
    single_values_5bar_2_00V(4,i) = ...
        mean(capac_5bar_2_00V((12300:14800),i));
    single_values_5bar_2_00V(5,i) = ...
        mean(capac_5bar_2_00V((15800:17800),i));
    single_values_5bar_2_00V(6,i) = ...
        mean(capac_5bar_2_00V((19300:22300),i));
    single_values_5bar_2_00V(7,i) = ...
        mean(capac_5bar_2_00V((23800:end),i));
end
single_values_5bar_2_00V
for i = 1:7
    single_values_5bar_2_00V_mean(i) = ...
        mean(single_values_5bar_2_00V(i,:));
end
single_values_5bar_2_00V_mean   %mean between the 4 capacitive ...
    sensors for each load

for i = 6:-1:2
    y_5bar_2_00V(i-1) = (masses(i-1)+m_support)*g; %conversion ...
        to NEWTON
    x_5bar_2_00V(i-1) = single_values_5bar_2_00V_mean(i);
end

%% 5 bar; 2.30V
%data acquisition
data = load('prova_statica_bar5_1_2.30V.txt');
for i = 1:4
    capac_5bar_2_30V(:,i) = data(:,i);
end
loadCell_5bar_2_30V = data(:,5);

%move mean
for i = 1:4
    capac_5bar_2_30V(:,i) = movmean(capac_5bar_2_30V(:,i),100);
end

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_2_30V(i) = ...
        mean(capac_5bar_2_30V((1:3000),i));
end
base_mean_capac_5bar_2_30V
for i = 1:4
```

```matlab
    capac_5bar_2_30V(:,i) = -1*(capac_5bar_2_30V(:,i) - ...
        base_mean_capac_5bar_2_30V(1,i)); %change sign
end

% plot(capac_5bar_2_30V(:,1))
% hold on

%estrapolation single values for caracterization
%   single_values_4bar_fullV =[             capac1  capac2  ...
    capac3  capac4
%                                       no_air
%                                       20kg
%                                       15kg
%                                       10kg
%                                       5kg
%                                       0kg
%                                       no_air ]
for i = 1:4
    single_values_5bar_2_30V(1,i) = ...
        mean(capac_5bar_2_30V((1:3400),i));
    single_values_5bar_2_30V(2,i) = ...
        mean(capac_5bar_2_30V((4400:6400),i));
    single_values_5bar_2_30V(3,i) = ...
        mean(capac_5bar_2_30V((7200:9900),i));
    single_values_5bar_2_30V(4,i) = ...
        mean(capac_5bar_2_30V((11200:14100),i));
    single_values_5bar_2_30V(5,i) = ...
        mean(capac_5bar_2_30V((15000:17800),i));
    single_values_5bar_2_30V(6,i) = ...
        mean(capac_5bar_2_30V((18700:21700),i));
    single_values_5bar_2_30V(7,i) = ...
        mean(capac_5bar_2_30V((22900:end),i));
end
single_values_5bar_2_30V
for i = 1:7
    single_values_5bar_2_30V_mean(i) = ...
        mean(single_values_5bar_2_30V(i,:));
end
single_values_5bar_2_30V_mean   %mean between the 4 capacitive ...
    sensors for each load


for i = 6:-1:2
    y_5bar_2_30V(i-1) = (masses(i-1)+m_support)*g; %conversion ...
        to NEWTON
    x_5bar_2_30V(i-1) = single_values_5bar_2_30V_mean(i);
end


%% 5 bar; fully opened valve (maximum voltage)
```

```
%data acquisition
data = load('prova_statica_bar5_1.txt');
for i = 1:4
    capac_5bar_fullV(:,i) = data(:,i);
end
loadCell_5bar_fullV = data(:,5);

%plot(capac_4bar_fullV(:,1))
%hold on

%move mean
for i = 1:4
    capac_5bar_fullV(:,i) = movmean(capac_5bar_fullV(:,i),100);
end

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_fullV(i) = ...
        mean(capac_5bar_fullV((1:3000),i));
end
base_mean_capac_5bar_fullV
for i = 1:4
    capac_5bar_fullV(:,i) = -1*(capac_5bar_fullV(:,i) - ...
        base_mean_capac_5bar_fullV(1,i)); %change sign
end

%estrapolation single values for caracterization
%   single_values_5bar_fullV =[            capac1  capac2  ...
   capac3  capac4
%                                 no_air
%                                 20kg
%                                 15kg
%                                 10kg
%                                 5kg
%                                 0kg
%                                 no_air ]
for i = 1:4
    single_values_5bar_fullV(1,i) = ...
        mean(capac_5bar_fullV((1:3000),i));
    single_values_5bar_fullV(2,i) = ...
        mean(capac_5bar_fullV((4000:6000),i));
    single_values_5bar_fullV(3,i) = ...
        mean(capac_5bar_fullV((8000:10000),i));
    single_values_5bar_fullV(4,i) = ...
        mean(capac_5bar_fullV((11000:13000),i));
    single_values_5bar_fullV(5,i) = ...
        mean(capac_5bar_fullV((14500:16000),i));
    single_values_5bar_fullV(6,i) = ...
        mean(capac_5bar_fullV((18000:21000),i));
```

```
    single_values_5bar_fullV(7,i) = ...
        mean(capac_5bar_fullV((22000:end),i));
end
single_values_5bar_fullV
for i = 1:7
    single_values_5bar_fullV_mean(i) = ...
        mean(single_values_5bar_fullV(i,:));
end
single_values_5bar_fullV_mean


for i = 2:6
    y_5bar_fullV(i-1) = (masses(i-1)+m_support)*g; %conversion ...
        to NEWTON
    x_5bar_fullV(i-1) = single_values_5bar_fullV_mean(i);
end

%% PLOTS 5 bar
figure(1)
hold on
%plot of first capacitive sensor
for i = 1:4 %1.2v e 1.3v non ha senso plottarli
    plot(capac_5bar_1_40V(:,i),'c')
    plot(capac_5bar_1_50V(:,i),'y')
    plot(capac_5bar_1_62V(:,i),'r')
    plot(capac_5bar_1_70V(:,i),'b')
    plot(capac_5bar_2_00V(:,i),'g')
    plot(capac_5bar_2_30V(:,i),'k')
    plot(capac_5bar_fullV(:,i),'b')
end
grid on;
xlabel('Time [ms]');
ylabel('h [μm]');
lgd = legend('1.4V','1.5V','1.62V','1.70V','2.00V','2.30V','full');
ttl = title('h/time at 5 bar, differente valve opening, four ...
    capacitive sensors separated for each colour');
lgd.FontSize = 16;
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);

figure(2)
hold on
plot(x_5bar_1_20V,y_5bar_1_20V)
plot(x_5bar_1_30V,y_5bar_1_30V)
plot(x_5bar_1_40V,y_5bar_1_40V)
plot(x_5bar_1_50V,y_5bar_1_50V)
plot(x_5bar_1_62V,y_5bar_1_62V)
plot(x_5bar_1_70V,y_5bar_1_70V)
plot(x_5bar_2_00V,y_5bar_2_00V)
plot(x_5bar_2_30V,y_5bar_2_30V)
```

```
plot(x_5bar_fullV,y_5bar_fullV)
grid on;
ylabel('Load [N]');
xlabel('h [μm]');
xlim([0 60]);
lgd = legend('1.2V','1.3V','1.4V','1.5V','1.62V','1.70V','2.00V',
'2.30V','fullV');
ttl = title('Load/h at 5 bar relative, different valve opening');
lgd.FontSize = 16;
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);

figure(3)
hold on
grid on
plot(x_5bar_1_40V,y_5bar_1_40V)
plot(x_5bar_1_50V,y_5bar_1_50V)
plot(x_5bar_1_62V,y_5bar_1_62V)
plot(x_5bar_1_70V,y_5bar_1_70V)
ylabel('Load [N]');
xlabel('h [μm]');
legend('1.4V','1.5V','1.62V','1.70V');
title('Load/h at 5 bar but different valve opening');

%dati raccolti
i_in = [85,75,65,55,55,45];
v_in = [2.5,2.1,1.8,1.5,1.2];
h_00kg = [85,80,70,56,35];
h_05kg = [66,63,56,44,27];
h_10kg = [56,54,47,37,23];
h_15kg = [50,47,42,33,20];

%dati da usare
h_2_5V = [85,66,56,50];
h_2_1V = [80,63,54,47];
h_1_8V = [70,56,47,42];
h_1_5V = [56,44,37,33];
h_1_2V = [35,27,23,20];

F = [0,50,100,150];

subplot(2,1,1)
hold on
grid on
plot(h_2_5V,F)
plot(h_2_1V,F)
plot(h_1_8V,F)
plot(h_1_5V,F)
plot(h_1_2V,F)
ylabel('Load [N]');
```

```
xlabel('h [μm]');
legend('2.5V','2.1V','1.8V','1.5V','1.2V');
title('Model');
xlim([-10 90])


subplot(2,1,2)

figure(4)
hold on
grid on
plot(x_5bar_1_20V,y_5bar_1_20V)
plot(x_5bar_1_30V,y_5bar_1_30V)
plot(x_5bar_1_40V,y_5bar_1_40V)
plot(x_5bar_1_50V,y_5bar_1_50V)
plot(x_5bar_1_62V,y_5bar_1_62V)
plot(x_5bar_1_70V,y_5bar_1_70V)
plot(x_5bar_2_00V,y_5bar_2_00V)
plot(x_5bar_2_30V,y_5bar_2_30V)
plot(x_5bar_fullV,y_5bar_fullV)
ylabel('Load [N]');
xlabel('h [μm]');
legend('1.2V','1.3V','1.4V','1.5V','1.62V','1.70V','2.00V',
'2.30V','fullV');
title('Experiments');
xlim([-10 90])
```

Complete cycle static curve

Static curve

```
% tensioni usate
% 1.7V              50%
% 2V                  75%
% max volt

% diverse pressioni relative:
% 4 bar
% 5 bar
% 6 bar

clear all
close all
clc

%variables
m_support = 6.480; %kg
masses = [45 40 35 30 25 20 15 10 5 0];
g = 9.81;

%% 5 bar; 1,70V
%data acquisition
data = load('prova_statica_ciclo_completo_5bar_1_70V__1.txt');
for i = 1:4
    capac_5bar_1_70V(:,i) = data(:,i);
end
loadCell_5bar_1_70V = data(:,5)+(45+m_support)*g;

% % % move mean
for i = 1:4
    capac_5bar_1_70V(:,i) = movmean(capac_5bar_1_70V(:,i),100);
end
loadCell_5bar_1_70V = movmean(loadCell_5bar_1_70V,100);

%  % zeroing of capacitive sensors

% figure(1)
% plot(capac_5bar_1_70V)

for i = 1:4
    base_mean_capac_5bar_1_70V(i) = ...
        mean(capac_5bar_1_70V((1:3000),i));
end
base_mean_capac_5bar_1_70V
for i = 1:4
```

```
    capac_5bar_1_70V(:,i) = -1*(capac_5bar_1_70V(:,i) - ...
        base_mean_capac_5bar_1_70V(1,i)); %change sign
end

for i = 1:length(capac_5bar_1_70V(:,1))
    capac_5bar_1_70V_mean(i) = mean(capac_5bar_1_70V(i,:));
end
clear data

%% 5 bar; 2_00V
%data acquisition
data = load('prova_statica_ciclo_completo_5bar_2_00V__1.txt');
for i = 1:4
    capac_5bar_2_00V(:,i) = data(:,i);
end
loadCell_5bar_2_00V = data(:,5)*10+(45+m_support)*g; %*10, ...
    dovuto a renge sbagliato della cella

% % % move mean
for i = 1:4
    capac_5bar_2_00V(:,i) = movmean(capac_5bar_2_00V(:,i),100);
end
loadCell_5bar_2_00V = movmean(loadCell_5bar_2_00V,100);

%  % zeroing of capacitive sensors

% figure(1)
% plot(capac_5bar_2_00V)

for i = 1:4
    base_mean_capac_5bar_2_00V(i) = ...
        mean(capac_5bar_2_00V((1:3000),i));
end
base_mean_capac_5bar_2_00V
for i = 1:4
    capac_5bar_2_00V(:,i) = -1*(capac_5bar_2_00V(:,i) - ...
        base_mean_capac_5bar_2_00V(1,i)); %change sign
end

for i = 1:length(capac_5bar_2_00V(:,1))
    capac_5bar_2_00V_mean(i) = mean(capac_5bar_2_00V(i,:));
end
clear data

%% 5 bar; fullV
%data acquisition
data = load('prova_statica_ciclo_completo_5bar_fullV__1.txt');
for i = 1:4
    capac_5bar_fullV(:,i) = data(:,i);
end
```

```
loadCell_5bar_fullV = data(:,5)+(45+m_support)*g;

% % % move mean
for i = 1:4
    capac_5bar_fullV(:,i) = movmean(capac_5bar_fullV(:,i),100);
end
loadCell_5bar_fullV = movmean(loadCell_5bar_fullV,100);

%  % zeroing of capacitive sensors

% figure(1)
% plot(capac_5bar_fullV)

for i = 1:4
    base_mean_capac_5bar_fullV(i) = ...
        mean(capac_5bar_fullV((1:3000),i));
end
base_mean_capac_5bar_fullV
for i = 1:4
    capac_5bar_fullV(:,i) = -1*(capac_5bar_fullV(:,i) - ...
        base_mean_capac_5bar_fullV(1,i)); %change sign
end

% plot(capac_5bar_fullV)
% legend('1','2','3','4')

for i = 1:length(capac_5bar_fullV(:,1))
    capac_5bar_fullV_mean(i) = mean(capac_5bar_fullV(i,:));
end
clear data

figure(1)
hold on
plot(capac_5bar_fullV_mean,loadCell_5bar_fullV)
plot(capac_5bar_2_00V_mean,loadCell_5bar_2_00V)
plot(capac_5bar_1_70V_mean,loadCell_5bar_1_70V)
grid on
xlim([-2 40])
ylim([0 550])
xlabel('h [µm]');
ylabel('Load [N]');
lgd = legend('2.75V','2.00V','1.70V');
ttl = title('Load/h complete static curve, 5bar');
lgd.FontSize = 18;
ttl.FontSize = 18;
set(findall(gca,'Type', 'Line'),'LineWidth',2);
set(gca,'FontSize',18)
% plot([55 40 30.5 23.8 18.32],[64 113 162 211 260])

%% % % finestra di esercizio valvola 5bar
```

```
% %  % dati presi dal grafico sulle "punte"
capac_5bar_fullV_punte = ...
    [5.248,7.295,10.28,14.23,19.03,26.28,39.89];
loadCell_5bar_fullV_punte = ...
    [355,304.7,254.2,203.2,156.3,109.6,61.02];

capac_5bar_2_00V_punte = [4.405,6.413,9.21,13.25,19.13,32.08];
loadCell_5bar_2_00V_punte = [303.9,253.5,202.9,152.1,100.4,52.21];

capac_5bar_1_70V_punte = [2.897,4.417,6.862,10.64,16.64,29.2];
loadCell_5bar_1_70V_punte = [304.4,254.1,203.3,152.5,101.4,51.93];

clear masses
masses = [20 15 10 5 0];

%% 5 bar; 1,40V
%data acquisition
data = load('prova_statica_bar5_1_1.40V.txt');
for i = 1:4
    capac_5bar_1_40V(:,i) = data(:,i);
end
loadCell_5bar_1_40V = data(:,5);

%move mean
for i = 1:4
    capac_5bar_1_40V(:,i) = movmean(capac_5bar_1_40V(:,i),100);
end

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_1_40V(i) = ...
        mean(capac_5bar_1_40V((1:3000),i));
end
base_mean_capac_5bar_1_40V
for i = 1:4
    capac_5bar_1_40V(:,i) = -1*(capac_5bar_1_40V(:,i) - ...
        base_mean_capac_5bar_1_40V(1,i)); %change sign
end

%estrapolation single values for caracterization
%   single_values_4bar_fullV =[             capac1  capac2  ...
    capac3  capac4
%                                 no_air
%                                 20kg
%                                 15kg
%                                 10kg
%                                 5kg
%                                 0kg
%                                 no_air ]
for i = 1:4
```

```
    single_values_5bar_1_40V(1,i) = ...
        mean(capac_5bar_1_40V((1:3700),i));
    single_values_5bar_1_40V(2,i) = ...
        mean(capac_5bar_1_40V((5500:7300),i));
    single_values_5bar_1_40V(3,i) = ...
        mean(capac_5bar_1_40V((8300:10800),i));
    single_values_5bar_1_40V(4,i) = ...
        mean(capac_5bar_1_40V((11700:13600),i));
    single_values_5bar_1_40V(5,i) = ...
        mean(capac_5bar_1_40V((14800:16300),i));
    single_values_5bar_1_40V(6,i) = ...
        mean(capac_5bar_1_40V((17300:20000),i));
    single_values_5bar_1_40V(7,i) = ...
        mean(capac_5bar_1_40V((22500:end),i));
end
single_values_5bar_1_40V
for i = 1:7
    single_values_5bar_1_40V_mean(i) = ...
        mean(single_values_5bar_1_40V(i,:));
end
single_values_5bar_1_40V_mean   %mean between the 4 capacitive ...
    sensors for each load

for i = 6:-1:2
    y_5bar_1_40V(i-1) = (masses(i-1)+m_support)*g; %conversion ...
        to NEWTON
    x_5bar_1_40V(i-1) = single_values_5bar_1_40V_mean(i);
end

%% 5 bar; 1,50V
%data acquisition
data = load('prova_statica_bar5_1_1.50V.txt');
for i = 1:4
    capac_5bar_1_50V(:,i) = data(:,i);
end
loadCell_5bar_1_50V = data(:,5);

%move mean
for i = 1:4
    capac_5bar_1_50V(:,i) = movmean(capac_5bar_1_50V(:,i),100);
end

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_1_50V(i) = ...
        mean(capac_5bar_1_50V((1:3000),i));
end
base_mean_capac_5bar_1_50V
for i = 1:4
```

```
    capac_5bar_1_50V(:,i) = -1*(capac_5bar_1_50V(:,i) - ... base_mean_capac_5bar_1_50V(1,i)); %change sign
end

%estrapolation single values for caracterization
%   single_values_4bar_fullV =[             capac1  capac2  ... capac3  capac4
%                                   no_air
%                                   20kg
%                                   15kg
%                                   10kg
%                                   5kg
%                                   0kg
%                                   no_air ]
for i = 1:4
    single_values_5bar_1_50V(1,i) = ... mean(capac_5bar_1_50V((1:3500),i));
    single_values_5bar_1_50V(2,i) = ... mean(capac_5bar_1_50V((5000:6700),i));
    single_values_5bar_1_50V(3,i) = ... mean(capac_5bar_1_50V((7500:10000),i));
    single_values_5bar_1_50V(4,i) = ... mean(capac_5bar_1_50V((11000:13300),i));
    single_values_5bar_1_50V(5,i) = ... mean(capac_5bar_1_50V((14700:17400),i));
    single_values_5bar_1_50V(6,i) = ... mean(capac_5bar_1_50V((18700:21400),i));
    single_values_5bar_1_50V(7,i) = ... mean(capac_5bar_1_50V((23500:end),i));
end
single_values_5bar_1_50V
for i = 1:7
    single_values_5bar_1_50V_mean(i) = ... mean(single_values_5bar_1_50V(i,:));
end
single_values_5bar_1_50V_mean   %mean between the 4 capacitive ... sensors for each load

for i = 6:-1:2
    y_5bar_1_50V(i-1) = (masses(i-1)+m_support)*g; %conversion ... to NEWTON
    x_5bar_1_50V(i-1) = single_values_5bar_1_50V_mean(i);
end

%% 5 bar; 1,62V
%data acquisition
data = load('prova_statica_bar5_1_1.62V.txt');
for i = 1:4
    capac_5bar_1_62V(:,i) = data(:,i);
end
```

```
loadCell_5bar_1_62V = data(:,5);

%move mean
for i = 1:4
    capac_5bar_1_62V(:,i) = movmean(capac_5bar_1_62V(:,i),100);
end

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_1_62V(i) = ...
        mean(capac_5bar_1_62V((1:3000),i));
end
base_mean_capac_5bar_1_62V
for i = 1:4
    capac_5bar_1_62V(:,i) = -1*(capac_5bar_1_62V(:,i) - ...
        base_mean_capac_5bar_1_62V(1,i)); %change sign
end

%estrapolation single values for caracterization
%   single_values_4bar_fullV =[             capac1  capac2  ...
    capac3  capac4
%                                  no_air
%                                  20kg
%                                  15kg
%                                  10kg
%                                  5kg
%                                  0kg
%                                  no_air ]
for i = 1:4
    single_values_5bar_1_62V(1,i) = ...
        mean(capac_5bar_1_62V((1:8000),i));
    single_values_5bar_1_62V(2,i) = ...
        mean(capac_5bar_1_62V((14500:17000),i));
    single_values_5bar_1_62V(3,i) = ...
        mean(capac_5bar_1_62V((19500:22000),i));
    single_values_5bar_1_62V(4,i) = ...
        mean(capac_5bar_1_62V((23500:25500),i));
    single_values_5bar_1_62V(5,i) = ...
        mean(capac_5bar_1_62V((27500:29000),i));
    single_values_5bar_1_62V(6,i) = ...
        mean(capac_5bar_1_62V((31200:33700),i));
    single_values_5bar_1_62V(7,i) = ...
        mean(capac_5bar_1_62V((38500:end),i));
end
single_values_5bar_1_62V
for i = 1:7
    single_values_5bar_1_62V_mean(i) = ...
        mean(single_values_5bar_1_62V(i,:));
end
```

```
single_values_5bar_1_62V_mean   %mean between the 4 capacitive sensors for each load


for i = 6:-1:2
    y_5bar_1_62V(i-1) = (masses(i-1)+m_support)*g; %conversion to NEWTON
    x_5bar_1_62V(i-1) = single_values_5bar_1_62V_mean(i);
end

figure(2)
hold on
grid on
plot(capac_5bar_fullV_punte,loadCell_5bar_fullV_punte)
plot(capac_5bar_2_00V_punte,loadCell_5bar_2_00V_punte)
plot(capac_5bar_1_70V_punte,loadCell_5bar_1_70V_punte)
% plot(x_5bar_1_62V,y_5bar_1_62V)
plot(x_5bar_1_50V,y_5bar_1_50V)
plot(x_5bar_1_40V,y_5bar_1_40V)
xlim([5 20])
ylim([0 550])
xlabel('h [μm]');
ylabel('Load [N]');
lgd = legend('2.75V','2.00V','1.70V','1.50V','1.40V');
% lgd = legend('1.4V','1.5V','1.62V','1.70V','2.00V','2.75V');
ttl = title('Load/h valve working zone, 5bar');
lgd.FontSize = 18;
ttl.FontSize = 18;
set(findall(gca,'Type', 'Line'),'LineWidth',2);
set(gca,'FontSize',18)
```

Comparison with back-pressure sensors static curve

```
% tensioni usate
% 1.7V              50%
% 2V                  75%
% max volt

% diverse pressioni relative:
% 4 bar
% 5 bar
% 6 bar

clear all
close all
clc

%variables
m_support = 6.480; %kg
masses = [45 40 35 30 25 20 15 10 5 0];
g = 9.81;
%% 5 bar; fullV
%data acquisition
data = load('ciclo_completo_5bar_2_30V_sens_press__3.txt');
for i = 1:4
    capac_5bar_fullV(:,i) = data(:,i);
end
loadCell_5bar_fullV = data(:,5)+(45+m_support)*g;
pressure_5bar_fullV_volt = data(:,7);

% % % move mean
for i = 1:4
    capac_5bar_fullV(:,i) = movmean(capac_5bar_fullV(:,i),100);
end
loadCell_5bar_fullV = movmean(loadCell_5bar_fullV,100);
pressure_5bar_fullV_volt = movmean(pressure_5bar_fullV_volt,100);

%   % zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_fullV(i) = ...
        mean(capac_5bar_fullV((1:3000),i));
end
base_mean_capac_5bar_fullV
for i = 1:4
    capac_5bar_fullV(:,i) = -1*(capac_5bar_fullV(:,i) - ...
        base_mean_capac_5bar_fullV(1,i)); %change sign
end
for i = 1:length(capac_5bar_fullV(:,1))
    capac_5bar_fullV_mean(i) = mean(capac_5bar_fullV(i,:));
end
```

```
figure(10)
grid on
subplot(2,1,1)
grid on
plot(pressure_5bar_fullV_volt)
title('pressure in volt/time , 5bar');
subplot(2,1,2)
grid on
plot(capac_5bar_fullV_mean)
title('capacitives in micron/time , 5bar');

times = ...
    [5084,8818,10790,14060,18000,19970,23870,26060,28690,32230];%ot
tenuti dal grafico precedente
h = capac_5bar_fullV_mean(times)';
v = pressure_5bar_fullV_volt(times);
q = polyfit(v,h,2)
pressure_5bar_fullV_micron = ...
    -606.8.*(pressure_5bar_fullV_volt.^3) ...
    +2275.3.*(pressure_5bar_fullV_volt.^2) ...
    -2849.9.*pressure_5bar_fullV_volt +  1194.7; %relazione ...
    individuata da esperimenti di caratterizzazione del sensore ...
    contropressione
% % % dati curva riga sopra presi da C:\Users\paolo\Google ...
    Drive\1-PoliTo\4. Tesi\5 Dati raccolti\5 Caratterizzazione ...
    sensore contropressione ...
    \Test2_nuovo_sensore_triangolo\caratt_sens_press.m

pressure_5bar_fullV_micron_2 = ...
    q(1).*(pressure_5bar_fullV_volt.^2) ...
    +q(2).*pressure_5bar_fullV_volt +  q(3);

figure(1)
hold on
plot(capac_5bar_fullV_mean,loadCell_5bar_fullV)
plot(pressure_5bar_fullV_micron,loadCell_5bar_fullV)
% plot(pressure_5bar_fullV_micron_2,loadCell_5bar_fullV)
grid on
xlim([-2 40])
ylim([0 550])
xlabel('h [μm]');
ylabel('Load [N]');
lgd = legend('Capacitive sensors','Back pressure sensors');
ttl = title('Load/h complete static curve, 5bar');
lgd.FontSize = 18;
ttl.FontSize = 18;
set(findall(gca,'Type', 'Line'),'LineWidth',2);
set(gca,'FontSize',18)
```

Valve characterization

```
%prova statica per diverse pressioni in ingresso, diverse ...
    aperture della valvola GESTITE DA UN COMANDO IN TENSIONE A ...
    TRIAGOLO

% diverse pressioni relative:
% 4 bar
% 5 bar
% 6 bar

%TUNING:
%plottare curva inputVoltage
%verificare intervallo con 1 solo minimo
%ridurre vettore inputVoltage a quell'intervallo
%avviare codice completo

clear all
close all
clc

%variables
m_support = 6.480; %kg
masses = [0 5 10 15 20];
g = 9.81;
forces = round((m_support+masses)*g);
soglia = 1;

%% 5 bar; 00kg
%data acquisition
data = load('TriangoloLento_bar5_1_00kg.txt');
for i = 1:4
    capac_5bar_00kg(:,i) = data(:,i);
end
loadCell_5bar_00kg = data(:,5);
inputVoltage_5bar_00kg = data(:,6);

% %tuning
% figure(9)
% plot(inputVoltage_5bar_00kg)

xx = inputVoltage_5bar_00kg((1:25000));
clear inputVoltage_5bar_00kg
inputVoltage_5bar_00kg = xx;
clear xx
[A,B] = min(inputVoltage_5bar_00kg);

```

```
%truncation on one triangular perion only (TO TUNE EACH SET OF ...
    DATA)
for i = 1:4
    xx(:,i) = capac_5bar_00kg((B-1000:B+19000),i);
end
clear capac_5bar_00kg
for i = 1:4
    capac_5bar_00kg(:,i) = xx(:,i);
end
clear xx
loadCell_5bar_00kg = loadCell_5bar_00kg(B-1000:B+19000);
inputVoltage_5bar_00kg = inputVoltage_5bar_00kg(B-1000:B+19000);

%move mean
for i = 1:4
    capac_5bar_00kg(:,i) = movmean(capac_5bar_00kg(:,i),100);
end
inputVoltage_5bar_00kg = movmean(inputVoltage_5bar_00kg,100);

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_00kg(i) = ...
        mean(capac_5bar_00kg((1:3000),i));
end
base_mean_capac_5bar_00kg;
for i = 1:4
    capac_5bar_00kg(:,i) = -1*(capac_5bar_00kg(:,i) - ...
        base_mean_capac_5bar_00kg(1,i)); %change sign
end

capac_5bar_00kg;

for i = 1:length(capac_5bar_00kg)
    single_values_5bar_00kg_mean(i) = mean(capac_5bar_00kg(i,:));
end
single_values_5bar_00kg_mean;   %mean between the 4 capacitive ...
    sensors


for i=1:length(single_values_5bar_00kg_mean)
    if single_values_5bar_00kg_mean(i)>soglia
        single_values_5bar_00kg_mean(i)
        i_00 = i
        lower_voltage_value_5bar_00kg = inputVoltage_5bar_00kg(i)
        break
    end
end

%% 4 bar; 05kg
%data acquisition
```

```
data = load('TriangoloLento_bar5_1_05kg.txt');
for i = 1:4
    capac_5bar_05kg(:,i) = data(:,i);
end
loadCell_5bar_05kg = data(:,5);
inputVoltage_5bar_05kg = data(:,6);

% %tuning
% figure(9)
% plot(inputVoltage_5bar_05kg)

xx = inputVoltage_5bar_05kg((1:30000));
clear inputVoltage_5bar_05kg
inputVoltage_5bar_05kg = xx;
clear xx
[A,B] = min(inputVoltage_5bar_05kg);

%truncation on one triangular perion only (TO TUNE EACH SET OF ...
   DATA)
for i = 1:4
    xx(:,i) = capac_5bar_05kg((B-1000:B+19000),i);
end
clear capac_5bar_05kg
for i = 1:4
    capac_5bar_05kg(:,i) = xx(:,i);
end
clear xx
loadCell_5bar_05kg = loadCell_5bar_05kg(B-1000:B+19000);
inputVoltage_5bar_05kg = inputVoltage_5bar_05kg(B-1000:B+19000);

%move mean
for i = 1:4
    capac_5bar_05kg(:,i) = movmean(capac_5bar_05kg(:,i),100);
end
inputVoltage_5bar_05kg = movmean(inputVoltage_5bar_05kg,100);

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_4bar_05kg(i) = ...
       mean(capac_5bar_05kg((1:3000),i));
end
base_mean_capac_4bar_05kg;
for i = 1:4
    capac_5bar_05kg(:,i) = -1*(capac_5bar_05kg(:,i) - ...
       base_mean_capac_4bar_05kg(1,i)); %change sign
end

capac_5bar_05kg;

for i = 1:length(capac_5bar_05kg)
```

```
    single_values_5bar_05kg_mean(i) = mean(capac_5bar_05kg(i,:));
end
single_values_5bar_05kg_mean;   %mean between the 4 capacitive ...
    sensors


for i=1:length(single_values_5bar_05kg_mean)
    if single_values_5bar_05kg_mean(i)>soglia
        single_values_5bar_05kg_mean(i)
        i_05 = i
        lower_voltage_value_5bar_05kg = inputVoltage_5bar_05kg(i)
        break
    end
end

%% 5 bar; 10kg
%data acquisition
data = load('TriangoloLento_bar5_1_10kg_modificato.txt');
for i = 1:4
    capac_5bar_10kg(:,i) = data(:,i);
end
loadCell_5bar_10kg = data(:,5);
inputVoltage_5bar_10kg = data(:,6);

% %tuning
% figure(9)
% plot(inputVoltage_5bar_10kg)

xx = inputVoltage_5bar_10kg((1:34000));
clear inputVoltage_5bar_10kg
inputVoltage_5bar_10kg = xx;
clear xx

[A,B] = min(inputVoltage_5bar_10kg);

%truncation on one triangular perion only (TO TUNE EACH SET OF ...
    DATA)
for i = 1:4
    xx(:,i) = capac_5bar_10kg((B-1000:B+19000),i);
end
clear capac_5bar_10kg
for i = 1:4
    capac_5bar_10kg(:,i) = xx(:,i);
end
clear xx
loadCell_5bar_10kg = loadCell_5bar_10kg(B-1000:B+19000);
inputVoltage_5bar_10kg = inputVoltage_5bar_10kg(B-1000:B+19000);

%move mean
for i = 1:4
```

```
    capac_5bar_10kg(:,i) = movmean(capac_5bar_10kg(:,i),100);
end
inputVoltage_5bar_10kg = movmean(inputVoltage_5bar_10kg,100);

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_10kg(i) = ...
        mean(capac_5bar_10kg((1:3000),i));
end
base_mean_capac_5bar_10kg;
for i = 1:4
    capac_5bar_10kg(:,i) = -1*(capac_5bar_10kg(:,i) - ...
        base_mean_capac_5bar_10kg(1,i)); %change sign
end

capac_5bar_10kg;

for i = 1:length(capac_5bar_10kg)
    single_values_5bar_10kg_mean(i) = mean(capac_5bar_10kg(i,:));
end
single_values_5bar_10kg_mean;   %mean between the 4 capacitive ...
    sensors

for i=1:length(single_values_5bar_10kg_mean)
    if single_values_5bar_10kg_mean(i)>soglia
        single_values_5bar_10kg_mean(i)
        i_10 = i
        lower_voltage_value_5bar_10kg = inputVoltage_5bar_10kg(i)
        break
    end
end

%% 5 bar; 15kg
%data acquisition
data = load('TriangoloLento_bar5_1_15kg.txt');
for i = 1:4
    capac_5bar_15kg(:,i) = data(:,i);
end
loadCell_5bar_15kg = data(:,5);
inputVoltage_5bar_15kg = data(:,6);

% %tuning
% figure(9)
% plot(inputVoltage_5bar_15kg)

xx = inputVoltage_5bar_15kg((1:21500));
clear inputVoltage_5bar_15kg
inputVoltage_5bar_15kg = xx;
clear xx

```

```
[A,B] = min(inputVoltage_5bar_15kg);

%truncation on one triangular perion only (TO TUNE EACH SET OF ...
    DATA)
for i = 1:4
    xx(:,i) = capac_5bar_15kg((B-1000:B+19000),i);
end
clear capac_5bar_15kg
for i = 1:4
    capac_5bar_15kg(:,i) = xx(:,i);
end
clear xx
loadCell_5bar_15kg = loadCell_5bar_15kg(B-1000:B+19000);
inputVoltage_5bar_15kg = inputVoltage_5bar_15kg(B-1000:B+19000);

%move mean
for i = 1:4
    capac_5bar_15kg(:,i) = movmean(capac_5bar_15kg(:,i),100);
end
inputVoltage_5bar_15kg = movmean(inputVoltage_5bar_15kg,100);

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_15kg(i) = ...
        mean(capac_5bar_15kg((1:3000),i));
end
base_mean_capac_5bar_15kg;
for i = 1:4
    capac_5bar_15kg(:,i) = -1*(capac_5bar_15kg(:,i) - ...
        base_mean_capac_5bar_00kg(1,i)); %change sign
end

capac_5bar_15kg;

for i = 1:length(capac_5bar_15kg)
    single_values_5bar_15kg_mean(i) = mean(capac_5bar_15kg(i,:));
end
single_values_5bar_15kg_mean;   %mean between the 4 capacitive ...
    sensors

for i=1:length(single_values_5bar_15kg_mean)
    if single_values_5bar_15kg_mean(i)>soglia
        single_values_5bar_15kg_mean(i)
        i_15 = i
        lower_voltage_value_5bar_15kg = inputVoltage_5bar_15kg(i)
        break
    end
end

%% 5 bar; 20kg
```

```
%data acquisition
data = load('TriangoloLento_bar5_1_20kg.txt');
for i = 1:4
    capac_5bar_20kg(:,i) = data(:,i);
end
loadCell_5bar_20kg = data(:,5);
inputVoltage_5bar_20kg = data(:,6);

% %tuning
% figure(9)
% plot(inputVoltage_5bar_20kg)

xx = inputVoltage_5bar_20kg((1:23000));
clear inputVoltage_5bar_20kg
inputVoltage_5bar_20kg = xx;

clear xx

[A,B] = min(inputVoltage_5bar_20kg);

%truncation on one triangular perion only (TO TUNE EACH SET OF ...
    DATA)
for i = 1:4
    xx(:,i) = capac_5bar_20kg((B-1000:B+19000),i);
end
clear capac_5bar_20kg
for i = 1:4
    capac_5bar_20kg(:,i) = xx(:,i);
end

clear xx
loadCell_5bar_20kg = loadCell_5bar_20kg(B-1000:B+19000);
inputVoltage_5bar_20kg = inputVoltage_5bar_20kg(B-1000:B+19000);

%move mean
for i = 1:4
    capac_5bar_20kg(:,i) = movmean(capac_5bar_20kg(:,i),100);
end
inputVoltage_5bar_20kg = movmean(inputVoltage_5bar_20kg,100);

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_20kg(i) = ...
        mean(capac_5bar_20kg((1:3000),i));
end
base_mean_capac_5bar_20kg;
for i = 1:4
    capac_5bar_20kg(:,i) = -1*(capac_5bar_20kg(:,i) - ...
        base_mean_capac_5bar_20kg(1,i)); %change sign
end
```

```
capac_5bar_20kg;

% plot(capac_5bar_20kg)
% legend('1','2','3','4')

for i = 1:length(capac_5bar_20kg)
    single_values_5bar_20kg_mean(i) = mean(capac_5bar_20kg(i,:));
end
single_values_5bar_20kg_mean;   %mean between the 4 capacitive ...
    sensors

for i=1:length(single_values_5bar_20kg_mean)
    if single_values_5bar_20kg_mean(i)>soglia
        single_values_5bar_20kg_mean(i)
        i_20 = i
        lower_voltage_value_5bar_20kg = inputVoltage_5bar_20kg(i)
        break
    end
end

%% PLOTS

x = 1:length(single_values_5bar_00kg_mean);

figure(1)
subplot(2,1,1)
ttl = title('Voltage valve input, 5 bar')
hold on
plot(x, inputVoltage_5bar_00kg)
grid on
xlabel('Time [ms]')
ylabel('Input Voltage to valve [V]')
ttl.FontSize = 18;
set(findall(gca,'Type', 'Line'),'LineWidth',2);
set(gca,'FontSize',18)

subplot(2,1,2)
hold on
plot(x, single_values_5bar_00kg_mean)
plot(x, single_values_5bar_05kg_mean)
plot(x, single_values_5bar_10kg_mean)
plot(x, single_values_5bar_15kg_mean)
plot(x, single_values_5bar_20kg_mean)
grid on
ttl = title('Bearing lift, 5 bar');
xlabel('Time [ms]')
ylabel('h [μm]')
% lgd = legend('0kg','5kg','10kg','15kg','20kg');
```

```
lgd = legend(sprintf('%dN', forces(1)),sprintf('%dN', ...
    forces(2)),sprintf('%dN', forces(3)),sprintf('%dN', ...
    forces(4)),sprintf('%dN', forces(5)));
lgd.FontSize = 18;
ttl.FontSize = 18;
set(findall(gca,'Type', 'Line'),'LineWidth',2);
set(gca,'FontSize',18)

figure(11)
hold on
grid on
title('h/voltage, 0 kg, 5 bar')
xlabel('Valve voltage [V]')
ylabel('h [µm]')
plot(inputVoltage_5bar_00kg(i_00:11000),single_values_5bar_00kg
_mean(i_00:11000)) %curva meato h vs tensione valvola 4 bar
xlim([1 3]);
ylim([0 60]);
formattazioneGrafico()
figure(12)
hold on
grid on
title('h/voltage, 5 kg, 5 bar')
xlabel('Valve voltage [V]')
ylabel('h [µm]')
plot(inputVoltage_5bar_05kg(i_05:11000),single_values_5bar_05kg
_mean(i_05:11000)) %curva meato h vs tensione valvola 4 bar
formattazioneGrafico()
figure(13)
hold on
grid on
title('h/voltage, 10 kg, 5 bar')
xlabel('Valve voltage [V]')
ylabel('h [µm]')
plot(inputVoltage_5bar_10kg(i_10:11000),single_values_5bar_10kg
_mean(i_10:11000)) %curva meato h vs tensione valvola 4 bar
formattazioneGrafico()
figure(14)
hold on
grid on
title('h/voltage, 15 kg, 5 bar')
xlabel('Valve voltage [V]')
ylabel('h [µm]')
plot(inputVoltage_5bar_15kg(i_15:11000),single_values_5bar_15kg
_mean(i_15:11000)) %curva meato h vs tensione valvola 4 bar
formattazioneGrafico()
figure(15)
hold on
grid on
ttl = title('h/voltage, 20 kg (260 N tot), 5 bar');
```

```
xlabel('Valve voltage [V]')
ylabel('h [µm]')
plot(inputVoltage_5bar_20kg(i_20:11000),single_values_5bar_20k
g_mean(i_20:11000)) %curva meato h vs tensione valvola 4 bar
plot([1.544 1.938],[0 20])
formattazioneGrafico()
lgd = legend('Laboratory curve','Linear interpolation');
lgd.FontSize = 16;
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);
set(gca,'FontSize',18)

figure(20)
formattazioneGrafico()
ttl = title('Valve characteristic: h/voltage, comparison ...
    different weights, 5 bar')
plot(inputVoltage_5bar_00kg(i_00:11000),single_values_5bar_00k
g_mean(i_00:11000)) %curva meato h vs tensione valvola 4 bar
plot(inputVoltage_5bar_05kg(i_05:11000),single_values_5bar_05k
g_mean(i_05:11000)) %curva meato h vs tensione valvola 4 bar
plot(inputVoltage_5bar_10kg(i_10:11000),single_values_5bar_10k
g_mean(i_10:11000)) %curva meato h vs tensione valvola 4 bar
plot(inputVoltage_5bar_15kg(i_15:11000),single_values_5bar_15k
g_mean(i_15:11000)) %curva meato h vs tensione valvola 4 bar
plot(inputVoltage_5bar_20kg(i_20:11000),single_values_5bar_20k
g_mean(i_20:11000)) %curva meato h vs tensione valvola 4 bar
lgd = legend(sprintf('%dN', forces(1)),sprintf('%dN', ...
    forces(2)),sprintf('%dN', forces(3)),sprintf('%dN', ...
    forces(4)),sprintf('%dN', forces(5)));
lgd.FontSize = 16;
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);
set(gca,'FontSize',18)
```

Test-benches comparison

Comparison with the previous thesis data

```
clear all
close all
clc

%variables
m_support = 6.480; %kg
masses = [45 40 35 30 25 20 15 10 5 0];
g = 9.81;

%% prova completa 5 bar
% % % FARA data
load provacompleta5barFARA.txt
capacitivo_3_fara = provacompleta5barFARA(:,1);
[max3] = max(capacitivo_3_fara(:));
capacitivo_a3_fara = max3 - capacitivo_3_fara;
capacitivo_0_fara = provacompleta5barFARA(:,2);
[max0] = max(capacitivo_0_fara(:));
capacitivo_a0_fara = max0 - capacitivo_0_fara;
capacitivo_1_fara = provacompleta5barFARA(:,3);
[max1] = max(capacitivo_1_fara(:));
capacitivo_a1_fara = max1 - capacitivo_1_fara;
capacitivo_2_fara = provacompleta5barFARA(:,4);
[max2] = max(capacitivo_2_fara(:));
capacitivo_a2_fara = max2 - capacitivo_2_fara;
newton = provacompleta5barFARA(:,5);

for i = 1:length(capacitivo_a0_fara)
    capacitivo_mean_fara(i) = mean([capacitivo_a0_fara(i) ...
        capacitivo_a1_fara(i) capacitivo_a2_fara(i) ...
        capacitivo_a3_fara(i)]);
end

%% % % BISIACH data
% % 5 bar; fullV
%data acquisition
data = load('prova_statica_ciclo_completo_5bar_fullV__1.txt');
for i = 1:4
    capac_5bar_fullV(:,i) = data(:,i);
end
loadCell_5bar_fullV = data(:,5)+(45+m_support)*g;

% % % move mean
for i = 1:4
    capac_5bar_fullV(:,i) = movmean(capac_5bar_fullV(:,i),100);
```

```
end
loadCell_5bar_fullV = movmean(loadCell_5bar_fullV,100);

%  % zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_fullV(i) = ...
        mean(capac_5bar_fullV((1:3000),i));
end
base_mean_capac_5bar_fullV
for i = 1:4
    capac_5bar_fullV(:,i) = -1*(capac_5bar_fullV(:,i) - ...
        base_mean_capac_5bar_fullV(1,i)); %change sign
end

for i = 1:length(capac_5bar_fullV(:,1))
    capac_5bar_fullV_mean(i) = mean(capac_5bar_fullV(i,:));
end
clear data

%% % % PLOTS
figure(1);
hold on;
h(1) = plot(capacitivo_a0_fara, newton, 'r');
h(2) = plot(capacitivo_a1_fara, newton, 'r');
h(3) = plot(capacitivo_a2_fara, newton, 'r');
h(4) = plot(capacitivo_a3_fara, newton, 'r');

for i = 1:4
    h(4+i) = plot(capac_5bar_fullV(:,i),loadCell_5bar_fullV,'b')
end

grid on;
xlabel('h [um]');
ylabel('Load [N]');
title('Open loop, 5bar relative, fully opened valve (old ...
    testbench vs new testbench) all capacitors');
legend([h(1) h(5)],{'Capacitives old testbench ...
    (FARA)','Capacitives new testbench'})
xlim([-5 40])
ylim([0 550])

figure(2);
hold on;
plot(capacitivo_mean_fara, newton, 'r');
plot(capac_5bar_fullV_mean,loadCell_5bar_fullV,'b')
grid on;
xlabel('h [um]');
ylabel('Load [N]');
ttl = title('Static curve, Mager bench (last thesis data) and ...
    Step bench comparison, 5bar relative, fully opened valve');
```

```
lgd = legend('Mager test-bench','Step test-bench')
xlim([-2 40])
ylim([0 550])
lgd.FontSize = 16;
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);
%%
figure(3);
close figure 3
figure(3);
hold on;
plot(capacitivo_a2_fara, newton, 'r');
plot(capac_5bar_fullV(:,3),loadCell_5bar_fullV,'b')
grid on;
xlabel('h [um]');
ylabel('Load [N]');
ttl = title('Static curve, Mager bench (last thesis data) and ...
    Step bench comparison, 5bar relative, fully opened valve');
lgd = legend('Mager test-bench','Step test-bench')
xlim([-2 40])
ylim([0 550])
lgd.FontSize = 16;
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);
```

Comparison with this thesis data

```
% % % CONFRONTO CICLO COMPLETO BANCO VECCHIO-NUOVO
clear all
close all
clc

%variables
m_support = 6.480; %kg
masses = [45 40 35 30 25 20 15 10 5 0];
g = 9.81;

%% 5 bar; 2_30V NUOVO
%data acquisition
data = load('ciclo_completo_5bar_2_30V_sens_press__3.txt');
for i = 1:4
    capac_5bar_2_30V(:,i) = data(:,i);
end
loadCell_5bar_2_30V = data(:,5)+(45+m_support)*g; % NEWTON

% % % move mean
for i = 1:4
    capac_5bar_2_30V(:,i) = movmean(capac_5bar_2_30V(:,i),100);
end
loadCell_5bar_2_30V = movmean(loadCell_5bar_2_30V,100);

figure(10)
hold on
% subplot(2,2,1)
% plot(capac_5bar_2_30V)
% title('NEW: capacitive sensors (raw), 5bar, 2,30V')
% grid on
subplot(3,1,1)
plot(loadCell_5bar_2_30V)
xlabel('Time [ms]');
ylabel('Load [N]')
ttl = title('Step bench: load cell, 5bar, valve signal: 2,30V')
grid on
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);

%  % zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_2_30V(i) = ...
        mean(capac_5bar_2_30V((1:3000),i));
end
base_mean_capac_5bar_2_30V;
for i = 1:4
```

```
    capac_5bar_2_30V(:,i) = -1*(capac_5bar_2_30V(:,i) - ...
        base_mean_capac_5bar_2_30V(1,i)); %change sign
end
subplot(3,1,2)
plot(capac_5bar_2_30V)
xlabel('Time [ms]');
ylabel('h [μm]')
ttl = title('Step bench: capacitive sensors, 5bar, valve ...
    signal: 2,30V')
grid on
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);

for i = 1:length(capac_5bar_2_30V(:,1))
    capac_5bar_2_30V_mean(i) = mean(capac_5bar_2_30V(i,:));
end
subplot(3,1,3)
plot(capac_5bar_2_30V_mean)
xlabel('Time [ms]');
ylabel('h [μm]')
ttl = title('Step bench: capacitive sensors mean, 5bar, valve ...
    signal: 2,30V')
grid on
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);

clear data

%% 5 bar; 2_30V VECCHIO
%data acquisition
data = ...
    load('bancovecchio_5bar_2_30V__a3_senza_peso_su_volantino.txt');
%data = ...
    load('bancovecchio_5bar_2_30V__a3_senza_peso_su_volantino.txt');
for i = 1:4
    capac_5bar_2_30V_old(:,i) = data(:,i);
end
loadCell_5bar_2_30V_old = data(:,5);

% % % move mean
for i = 1:4
    capac_5bar_2_30V_old(:,i) = ...
        movmean(capac_5bar_2_30V_old(:,i),100);
end
loadCell_5bar_2_30V_old = movmean(loadCell_5bar_2_30V_old,100);

figure(20)
hold on
% subplot(2,2,1)
% plot(capac_5bar_2_30V_old)
```

```
% title('OLD: capacitive sensors (raw), 5bar, 2,30V')
% grid on
subplot(3,1,1)
plot(loadCell_5bar_2_30V_old)
grid on
ttl = title('Mager bench: load vell, 5bar, valve signal: 2,30V')
xlabel('Time [ms]');
ylabel('Load [N]');
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);

%  % zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_2_30V_old(i) = ...
        mean(capac_5bar_2_30V_old((1:3000),i));
end
base_mean_capac_5bar_2_30V_old;
for i = 1:4
    capac_5bar_2_30V_old(:,i) = -1*(capac_5bar_2_30V_old(:,i) - ...
        base_mean_capac_5bar_2_30V_old(1,i)); %change sign
end
subplot(3,1,2)
plot(capac_5bar_2_30V_old)
grid on
ttl = title('Mager bench: capacitive sensors, 5bar, valve ...
    signal: 2,30V')
xlabel('Time [ms]');
ylabel('h [µm]');
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);

for i = 1:length(capac_5bar_2_30V_old(:,1))
    capac_5bar_2_30V_mean_old(i) = mean(capac_5bar_2_30V_old(i,:));
end
subplot(3,1,3)
plot(capac_5bar_2_30V_mean_old)
grid on
ttl = title('Mager bench: capacitive sensors mean, 5bar, valve ...
    signal: 2,30V')
xlabel('Time [ms]');
ylabel('h [µm]');
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);

%% % % % PLOTS
figure(1)
hold on
plot(capac_5bar_2_30V_mean,loadCell_5bar_2_30V)
plot(capac_5bar_2_30V_mean_old,loadCell_5bar_2_30V_old)
plot(capac_5bar_2_30V_old(:,1),loadCell_5bar_2_30V_old)
```

```
plot(capac_5bar_2_30V_old(:,2),loadCell_5bar_2_30V_old)
plot(capac_5bar_2_30V_old(:,3),loadCell_5bar_2_30V_old)
plot(capac_5bar_2_30V_old(:,4),loadCell_5bar_2_30V_old)
grid on
xlim([-2 40])
ylim([0 550])
xlabel('h [μm]');
ylabel('Load [N]');
legend('New mean','Old mean','Old1','Old2','Old3','Old4');
title('Comparison OLD-NEW testbenches. Without subtracrion: ...
    With Air - Without Air');

%% % % DA AGGIUSTARE VALORI DI INIZIO E FINE CURVA DA INTERPOLARE

% % % CALCOLI PER SOTTRAZIONE CURVA AIR-NOAIR

% % % SU FIGURA 20, CAPACITORS MEAN

% inizio e fine curva NO air
inizio = 41700          %   aggiustare
inizio_1 = inizio;
fine = 52200            %   aggiustare
fine_1 = fine;
p = polyfit(capac_5bar_2_30V_mean_old(inizio:fine)',
loadCell_5bar_2_30V_old(inizio:fine),5)
p_inv = polyfit(loadCell_5bar_2_30V_old(inizio:fine),
capac_5bar_2_30V_mean_old(inizio:fine)',10)
figure(30) % test interpolazione
hold on
grid on
plot(capac_5bar_2_30V_mean_old(inizio:fine)',loadCell_
5bar_2_30V_old(inizio:fine))
plot(linspace(capac_5bar_2_30V_mean_old(fine),capac_5bar_
2_30V_mean_old(inizio)),polyval(p,linspace(capac_5bar_2_30V_
mean_old(fine),capac_5bar_2_30V_mean_old(inizio))))

% inizio e fine curva SI air
inizio = 14500          %   aggiustare
inizio_2 = inizio;
fine = 28000            %   aggiustare
fine_2 = fine;
q = polyfit(capac_5bar_2_30V_mean_old(inizio:fine)',
loadCell_5bar_2_30V_old(inizio:fine),5)
q_inv = polyfit(loadCell_5bar_2_30V_old(inizio:fine),
capac_5bar_2_30V_mean_old(inizio:fine)',10)
% figure(40) % test interpolazione
hold on
grid on
plot(capac_5bar_2_30V_mean_old(inizio:fine)',
loadCell_5bar_2_30V_old(inizio:fine))
```

```
plot(linspace(capac_5bar_2_30V_mean_old(fine),
capac_5bar_2_30V_mean_old(inizio)),polyval(q,linspace(capac_5bar_
2_30V_mean_old(fine),capac_5bar_2_
30V_mean_old(inizio))))
in = min(polyval(p,capac_5bar_2_30V_mean_old(fine_1)),
polyval(q,capac_5bar_2_30V_mean_old(fine_2))) % forza
fin = max(polyval(p,capac_5bar_2_30V_mean_old(inizio_2)),
polyval(q,capac_5bar_2_30V_mean_old(inizio_2))) % forza
y = linspace(in,fin);
x = polyval(q_inv,y)-polyval(p_inv,y)
plot(x,y)
% confronto con sottrazione parte dovuta rigidezza banco
figure(2)
hold on
plot(capac_5bar_2_30V_mean,loadCell_5bar_2_30V)
plot(capac_5bar_2_30V_mean_old,loadCell_5bar_2_30V_old)
plot(x,y)
grid on
xlim([-2 40])
ylim([0 550])
xlabel('h [μm]');
ylabel('Load [N]');
lgd = legend('Step test-bench','Mager test-bench (no ...
    subtraction)','Mager test-bench (with subtraction)')
ttl = title('Static curve, Mager bench (this thesis data) and ...
    Step bench comparison, 5bar relative, fully opened valve');
lgd.FontSize = 16;
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);

%%
figure(3)
close figure 3
figure(3)
hold on
plot(capac_5bar_2_30V,loadCell_5bar_2_30V, 'b')
plot(capac_5bar_2_30V_old,loadCell_5bar_2_30V_old, 'r')
grid on
xlim([-2 40])
ylim([0 550])
xlabel('h [μm]');
ylabel('Load [N]');
lgd = legend('Step test-bench','','','','Mager test-bench (no ...
    subtraction)')
ttl = title('Static curve, Mager bench (this thesis data) and ...
    Step bench comparison, 5bar relative, fully opened valve');
lgd.FontSize = 16;
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);
```

Tilting test

```
clear all
close all
clc

%test svolto partedno da alimentazione aria chiusa, 0 kg, ...
    valvola aperta al massimo. In seguito si apre e si chiude ...
    l'alimentazione

%variables
m_support = 6.480; %kg
g = 9.81;

%% 5 bar; TEST1   % % NO SCOTCH
%data acquisition
data = load('1_no_scotch.txt');
for i = 1:4
    capac_5bar_test1(:,i) = data(:,i);
end

% % % move mean
for i = 1:4
    capac_5bar_test1(:,i) = movmean(capac_5bar_test1(:,i),100);
end

%  % zeroing of capacitive sensors

% figure(1)
% plot(capac_5bar_test1(:,4))

for i = 1:4
    base_mean_capac_5bar_test1(i) = ...
        mean(capac_5bar_test1((1:2500),i));
end
base_mean_capac_5bar_test1
for i = 1:4
    capac_5bar_test1(:,i) = -1*(capac_5bar_test1(:,i) - ...
        base_mean_capac_5bar_test1(1,i)); %change sign
end

%% 5 bar; TEST2    % % SCOTCH SU CAVI ELETTRICI
%data acquisition
data = load('2_scotch_su_cavi.txt');
for i = 1:4
    capac_5bar_test2(:,i) = data(:,i);
end

```

```
% % % move mean
for i = 1:4
    capac_5bar_test2(:,i) = movmean(capac_5bar_test2(:,i),100);
end

%  % zeroing of capacitive sensors

% figure(1)
% plot(capac_5bar_fullV(:,1))

for i = 1:4
    base_mean_capac_5bar_test2(i) = ...
        mean(capac_5bar_test2((1:3000),i));
end
base_mean_capac_5bar_test2
for i = 1:4
    capac_5bar_test2(:,i) = -1*(capac_5bar_test2(:,i) - ...
        base_mean_capac_5bar_test2(1,i)); %change sign
end

%% 5 bar; TEST3      % % SCOTCH SU CAVI ELETTRICI E TUBI BLU
%data acquisition
data = load('3_scotch_anche_su_tubi_blu.txt');
for i = 1:4
    capac_5bar_test3(:,i) = data(:,i);
end

% % % move mean
for i = 1:4
    capac_5bar_test3(:,i) = movmean(capac_5bar_test3(:,i),100);
end

%  % zeroing of capacitive sensors

% figure(1)
% plot(capac_5bar_fullV(:,1))

for i = 1:4
    base_mean_capac_5bar_test3(i) = ...
        mean(capac_5bar_test3((1:3000),i));
end
base_mean_capac_5bar_test3
for i = 1:4
    capac_5bar_test3(:,i) = -1*(capac_5bar_test3(:,i) - ...
        base_mean_capac_5bar_test3(1,i)); %change sign
end

clear data

%% VARIANZA sui picchi
```

```
clear picchi

picchi = [varianzaPicchi(capac_5bar_test1,3)];
picchi = [picchi varianzaPicchi(capac_5bar_test2,3)];
picchi = [picchi varianzaPicchi(capac_5bar_test3,3)];
% picchi = [picchi varianzaPicchi(capac_5bar_test4,10)];

variance = var(picchi')'
std_dev = sqrt(variance)

mean_picchi = mean(picchi')'
scarto = picchi - mean_picchi

%% % %  PLOTS
figure(1)
subplot(3,1,1)
hold on
grid on
for i = 1:4
    plot(capac_5bar_test1(:,i))
end
xlabel('Time [ms]');
ylabel('h [μm]');
lgd = ...
    legend('Capacitive1','Capacitive2','Capacitive3','Capacitive4');
ttl = title('Capacitive sensors over time, NO cable fixing, 5bar');
xlim([0,length(capac_5bar_test1)])
ylim([0,40])
lgd.FontSize = 16;
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);

subplot(3,1,2)
hold on
grid on
for i = 1:4
    plot(capac_5bar_test2(:,i))
end
xlabel('Time [ms]');
ylabel('h [μm]');
lgd = ...
    legend('Capacitive1','Capacitive2','Capacitive3','Capacitive4');
ttl = title('Capacitive sensors over time, WITH electric cable ...
    fixing, 5bar');
xlim([0,length(capac_5bar_test2)])
ylim([0,40])
lgd.FontSize = 16;
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);

```

```
% figure(2)
subplot(3,1,3)
hold on
grid on
for i = 1:4
    plot(capac_5bar_test3(:,i))
end
xlabel('Time [ms]');
ylabel('h [μm]');
lgd = ...
    legend('Capacitive1','Capacitive2','Capacitive3','Capacitive4');
ttl = title('Capacitive sensors over time, WITH electric and ...
    pneumatic cable fixing, 5bar');
xlim([0,length(capac_5bar_test3)])
ylim([0,40])
lgd.FontSize = 16;
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);

figure(3)
img = imread('pattino_stilizzato.png');
imshow(img)
```

```
function [picchi] = varianzaPicchi(matrice_valori,n_picchi)
%restituisce matrice con 4 righe, in ogni riga i picchi dei ...
    singoli sens
%capacitivi
for j = 1:4
    fin_old = 1;
    scarto = 500;
for i = 1:n_picchi
    pos_in = find(matrice_valori(fin_old:end,j)>2,1);
    in = pos_in + fin_old + scarto;
    pos_fin = find(matrice_valori(in:end,j)<2,1);
    fin = pos_fin + in - scarto;
    in_old = in;
    fin_old = fin+1000;
    if in>fin
        fin = in;
    end
    picchi(j,i) = mean(matrice_valori(in:fin,j));
end
end

end
```

Closed loop

```
%dell'anello chiuso: kp costante, vario ki. 20 kg sopra pattino
clear all
close all
clc

file = cell(5,1);
file{1} = '5bar_20kg_kp0_80_ki0__41.txt'
file{2} = '5bar_20kg_kp0_80_ki1__42_2.txt'
file{3} = '5bar_20kg_kp0_80_ki10__43.txt'
file{4} = '5bar_20kg_kp0_80_ki50__44.txt'
file{5} = '5bar_20kg_kp0_80_ki100__45.txt'
ki = [0 1 10 50 100];
kp = [0.8 0.8 0.8 0.8 0.8]

%data acquisition
for k = 1:5
clearvars -except k file ki kp

data = load(file{k,1});
for i = 1:4
    capac(:,i) = data(:,i);
end
loadCell = data(:,5);
inputVoltage = data(:,6);
pressureSensor = data(:,7);

%move mean
for i = 1:4
    capac(:,i) = movmean(capac(:,i),100);
end
pressureSensor = movmean(pressureSensor,100);

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac(i) = mean(capac((1:3000),i));
end

for i = 1:4
    capac(:,i) = -1*(capac(:,i) - base_mean_capac(1,i)); ...
        %change sign
end

%PLOTS
figure(3)
subplot(5,2,2*k-1)
hold on
```

```
grid on
for i = 1:4
    plot(capac(:,i))
end
legend('capac_0','capac_1','capac_2','capac_3');
title(['BEARING LIFT: 5bar set = 10 microm  Kp = ...
    ',num2str(kp(k)),'  Ki = ',num2str(ki(k))]);
ylim([0 15]);
xlabel('time [ms]')
ylabel('h [μm]')

subplot(5,2,2*k)
hold on
grid on
plot(inputVoltage)
title(['VALVE VOLTAGE: 5bar set = 10 microm  Kp = ...
    ',num2str(kp(k)),'  Ki = ',num2str(ki(k))]);
ylim([0 3]);
xlabel('time [ms]')
ylabel('Valve signal [V]')

% only considering the capacitive closer to backpressure (0 and 2)
mean_1_3 = (capac(:,1)+capac(:,3))/2;
figure(4)
subplot(5,1,k)
hold on
grid on
plot(capac(:,1))
plot(capac(:,3))
plot(mean_1_3)
lgd = legend('capac1','capac3','mean');
ttl = title(['BEARING LIFT: 5bar set = 10 microm  Kp = ...
    ',num2str(kp(k)),'  Ki = ',num2str(ki(k))]);
ylim([0 15]);
xlabel('time [ms]')
ylabel('h [μm]')
lgd.FontSize = 16;
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);
set(gca,'FontSize',18);

% confronto feedback dato da backpressure sensors con set
pressureSensor_micron = -606.761483*pressureSensor.^3 ...
    +2275.345253*pressureSensor.^2 -2849.851081*pressureSensor ...
    +1194.707195;
figure(2)
subplot(5,1,k)
hold on
grid on
plot(pressureSensor_micron)
```

```
plot([1 length(pressureSensor_micron)],[10 10])
legend('feedback backpressure','set');
ttl = title(['BEARING LIFT: 5bar, set = 10 μm,  Kp = ...
    ',num2str(kp(k)),'  Ki = ',num2str(ki(k)),', 20 kg (260 N ...
    tot)']);
ylim([0 11]);
xlabel('time [ms]')
ylabel('h [μm]')
ttl.FontSize = 14;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);
set(gca,'FontSize',14);

% confronto tra medie tra 2 capacitivi vicino a sensore
mean_1_3 = movmean(mean_1_3,1000);
figure(1)
hold on
grid on
% plot(mean_1_3(7000:10000))
plot(mean_1_3)
legend('ki = 0','ki = 1','ki = 10','ki = 50','ki = 100');
xlabel('time [ms]')
ylabel('h [μm]')
end
```

Back-pressure sensor characterization

```
clear all
close all
clc

%% 00kg
data = load('caratt_sens_press_test2_00kg__1.txt');

figure(100)
for i = 1:4
    capac_00kg(:,i) = data(:,i);
end
for i = 1:4
    base_mean_capac_00kg(i) = capac_00kg(6417,i);
end
for i = 1:4
    capac_00kg(:,i) = movmean(capac_00kg(:,i),100);
end
for i = 1:4
    capac_00kg(:,i) = -1*(capac_00kg(:,i) - ...
        base_mean_capac_00kg(1,i)); %change sign
end
for i = 1:length(capac_00kg(:,1))
    single_values_capac_00kg(i,:) = mean(capac_00kg(i,:));
end
valveVolt_00kg_all = data(:,6);
sensPress_00kg_all = data(:,7); %acquired in VOLT
valveVolt_00kg_all = movmean(valveVolt_00kg_all,100);
sensPress_00kg_all = movmean(sensPress_00kg_all,100);
subplot(3,1,1)
hold on
grid on
plot(valveVolt_00kg_all)
xlabel('Time [ms]');
ylabel('Valve signal [V]');
ttl = title('Valve voltage signal over the time, no masses on ...
    the bearing, 5 bar');
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);

subplot(3,1,2)
hold on
grid on
plot(sensPress_00kg_all)
xlabel('Time [ms]');
ylabel('Back pressure signal [V]');
ttl = title('Back pressure signal over the time, 5bar');
```

```
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);

subplot(3,1,3)
hold on
grid on
plot(single_values_capac_00kg)
xlabel('Time [ms]');
ylabel('h [μm]');
ttl = title('Capacitive mean measurement in [μm] over the time, ...
    5bar');
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);

%% %%
clear all
data = load('caratt_sens_press_test2_00kg__1.txt');

m_support = 6.48;
masses = [20 15 10 5 0];
g = 9.81;

for i = 1:4
    capac_00kg(:,i) = data((9350:16420),i); %TUNING: take ...
        values of descending curve
end
sensPress_00kg = data(9350:16420,7); %acquired in VOLT

% move mean
for i = 1:4
    capac_00kg(:,i) = movmean(capac_00kg(:,i),100);
end
sensPress_00kg = movmean(sensPress_00kg,100);

%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_00kg(i) = capac_00kg(1,i);
end

for i = 1:4
    capac_00kg(:,i) = -1*(capac_00kg(:,i) - ...
        base_mean_capac_00kg(1,i)); %change sign
end

for i = 1:length(capac_00kg(:,1))
    single_values_capac_00kg(i,:) = mean(capac_00kg(i,:));
end

%% 05kg
%data acquisition
```

```
data = load('caratt_sens_press_test2_05kg__1.txt');

for i = 1:4
    capac_05kg(:,i) = data((14300:20000),i); %TUNING: take ...
        values of descending curve
end
sensPress_05kg = data((14300:20000),7);

% move mean
for i = 1:4
    capac_05kg(:,i) = movmean(capac_05kg(:,i),100);
end
sensPress_05kg = movmean(sensPress_05kg,100);

%zeroing of capacitive sensors
for i = 1:4
%     base_mean_capac_05kg(i) = mean(capac_05kg((13000:18000),i));
    base_mean_capac_05kg(i) = capac_05kg(1,i)
end
base_mean_capac_05kg

for i = 1:4
    capac_05kg(:,i) = -1*(capac_05kg(:,i) - ...
        base_mean_capac_05kg(1,i)); %change sign
end

for i = 1:length(capac_05kg(:,1))
    single_values_capac_05kg(i,:) = mean(capac_05kg(i,:));
end

%% 10kg
%data acquisition
data = load('caratt_sens_press_test2_10kg__1.txt');

for i = 1:4
    capac_10kg(:,i) = data((5150:12580),i); %TUNING: take ...
        values of descending curve
end
sensPress_10kg = data(5150:12580,7);

% move mean
for i = 1:4
    capac_10kg(:,i) = movmean(capac_10kg(:,i),100);
end
sensPress_10kg = movmean(sensPress_10kg,100);

%zeroing of capacitive sensors
for i = 1:4
%     base_mean_capac_10kg(i) = mean(capac_10kg((13000:18000),i));
    base_mean_capac_10kg(i) = capac_10kg(1,i);
```

```
end
base_mean_capac_10kg

for i = 1:4
    capac_10kg(:,i) = -1*(capac_10kg(:,i) - ...
        base_mean_capac_10kg(1,i)); %change sign
end

for i = 1:length(capac_10kg(:,1))
    single_values_capac_10kg(i,:) = mean(capac_10kg(i,:));
end

%% 15kg
%data acquisition
data = load('caratt_sens_press_test2_15kg__1.txt');

for i = 1:4
    capac_15kg(:,i) = data((9850:17000),i); %TUNING: take ...
        values of descending curve
end
sensPress_15kg = data(9850:17000,7);

% move mean
for i = 1:4
    capac_15kg(:,i) = movmean(capac_15kg(:,i),100);
end
sensPress_15kg = movmean(sensPress_15kg,100);

%zeroing of capacitive sensors
for i = 1:4
%     base_mean_capac_15kg(i) = mean(capac_15kg((13000:18000),i));
    base_mean_capac_15kg(i) = capac_15kg(1,i);
end
base_mean_capac_15kg

for i = 1:4
    capac_15kg(:,i) = -1*(capac_15kg(:,i) - ...
        base_mean_capac_15kg(1,i)); %change sign
end

for i = 1:length(capac_15kg(:,1))
    single_values_capac_15kg(i,:) = mean(capac_15kg(i,:));
end

%% 20kg
%data acquisition
data = load('caratt_sens_press_test2_20kg__1.txt');

for i = 1:4
```

```
    capac_20kg(:,i) = data((8660:16260),i); %TUNING: take ...
        values of descending curve
end
sensPress_20kg = data(8660:16260,7);

% move mean
for i = 1:4
    capac_20kg(:,i) = movmean(capac_20kg(:,i),100);
end
sensPress_20kg = movmean(sensPress_20kg,100);

%zeroing of capacitive sensors
for i = 1:4
%     base_mean_capac_20kg(i) = mean(capac_20kg((13000:18000),i));
    base_mean_capac_20kg(i) = capac_20kg(1,i);
end
base_mean_capac_20kg

for i = 1:4
    capac_20kg(:,i) = -1*(capac_20kg(:,i) - ...
        base_mean_capac_20kg(1,i)); %change sign
end

for i = 1:length(capac_20kg(:,1))
    single_values_capac_20kg(i,:) = mean(capac_20kg(i,:));
end

%% PLOTS
figure(1)
hold on
grid on
xlim([0 40])
ylim([0.8 1.15])
plot(single_values_capac_00kg,sensPress_00kg)
plot(single_values_capac_05kg,sensPress_05kg)
plot(single_values_capac_10kg,sensPress_10kg)
plot(single_values_capac_15kg,sensPress_15kg)
plot(single_values_capac_20kg,sensPress_20kg)

%% rispetto alla figura 1, 15 kg sembra la pi  significativa ...
    perch    il carico pi  vicino alla realt  e range 5-15 ...
    micron (20kg non arriva a 15 micron)

iniz_interp = find(single_values_capac_15kg>5,1)
fine_interp = find(single_values_capac_15kg>15,1)
p = polyfit(single_values_capac_15kg(iniz_interp:fine_interp),
sensPress_15kg(iniz_interp:fine_interp),3)

plot(linspace(5,15),polyval(p,linspace(5,15)),'k','LineWidth',2)
lgd = legend('63N','113N','163N','213N','263N','interpolation');
```

```
lgd.FontSize = 14;
ylabel('Sensor Voltage [V]');
xlabel('h [μm]');
ttl = title('Characteristic of the pressure sensors: ...
    Voltage-Air Film Height');
ttl.FontSize = 14;
% text(20,1,['\leftarrow y = ',num2str(p(1)),'x^3 ...
    ',num2str(p(2)),'x^2 ',num2str(p(3)),'x + ',num2str(p(4))])
sprintf('p:  y = %f x^3 %f x^2 %f x + %f',p(1),p(2),p(3),p(4))

%% DA VOLT A MEATO
% p = polyfit(single_values_capac_05kg,sensPress_05kg,2)
q = polyfit(sensPress_15kg(iniz_interp:fine_interp),
single_values_capac_15kg(iniz_interp:fine_interp),3) %usare ...
    questi valore: da V a Meato
sprintf('q:   y = %f x^3 %f x^2 %f x + %f',q(1),q(2),q(3),q(4))
```

Voltage to current box characterization

```
clear all
close all
clc
% V_in = [0 0.8 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2 2.1 2.2 ...
    2.3 2.4 2.5];
% I_out = [20.3 29.2 36.3 39.7 43.4 47.2 50.6 54.3 58 61.4 65.1 ...
    68.9 72.3 76 79.4 83.1 86.8 90.2];
data = load('Caratterizzazione_scatola_tensione_corrente.txt');
V_in = data(:,1);
I_out = data(:,2);

figure(1)
plot(V_in(2:end),I_out(2:end),'b')
grid on
hold on
xlabel('Voltage DAC [V]');
ylabel('Current to the valve [mA]');
ttl = title('Static characteristic of the voltage-current ...
    converting box');

p = polyfit(V_in(2:end),I_out(2:end),1)
plot(V_in(2:end),polyval(p,V_in(2:end)),'g')

% % % FARA
% Caratteristica statica circuito ausiliario nuovo
V_in_fara = [0.8 1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2 2.2 2.3 ...
    2.4 2.5]; %tensione in uscita dal DAC
i_out_fara = [30 37 44 48 51 54 58 62 66 69 72 80 83 84 84]; ...
    %corrente in uscita dal circuito LT3092
plot(V_in_fara, i_out_fara, 'r');

lgd = legend('experimental results','linear ...
    interpolation','previous thesis');
tx = text(1.4,50,['\leftarrow y = ...
    ',num2str(round(p(1),4,'significant')),'x + ...
    ',num2str(round(p(2),3,'significant'))]);
lgd.FontSize = 16;
lgd.Location = 'SouthEast'
tx.FontSize = 16;
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);
```

HBM load cell calibration

```
clear all
close all
clc

masses = [0 1.046 23.514 42.249 60.999 80.979 99.729];
g = 9.81;

CellVolt = load('TaraturaCellaMager_5.txt');

figure(1)
plot(CellVolt)
grid on
title('pressure in volt/time , 5bar');

% % % ricavati a mano dal grafico

newton = masses * g;
CellValues = [0 0.051 1.01 1.84 2.635 3.503 4.295];

figure(2)
hold on
grid on
plot(CellValues,newton)
plot(CellValues,newton,'o')
xlabel('Load cell signal [V]');
ylabel('Load [N]');
ttl = title('Load/V   LoadCell HBM U9C');
lgd.FontSize = 18;
ttl.FontSize = 18;
set(findall(gca,'Type', 'Line'),'LineWidth',2);
set(gca,'FontSize',18)

p = polyfit(CellValues,newton,1)
```

Models simulations

Valve simulation

```
% modello anello aperto:
%           figure(1)-confronto G vs I valvola modello-laboratorio
%           figure(2)-conftonto h vs V pattino modello-laboratorio
%           figure(3)-confronto in curvaa statica F vs h ...
    modello-laboratorio

% % ATTENZIONE, su modello:
%       1-2- switch su rampa tensione e forza statica   ...
    SWITCHES SU
%        3- switch su tensione costante e scala forza   ...
    SWITCHES GIU'

%Parametri per il modello matematico dell'anello aperto
clear all
close all
clc

run('config_originali')
% run('config_mod01')
% run('config_mod02')
% run('config_mod03')

%%
open('..\Paolo_valvola.slx')
sim('..\Paolo_valvola.slx')

%% comparison model-lab
close all
load('..\2FileTxt\prova35bar.txt') %prova migliore prova35bar
airflow = prova35bar(:,1);
portata = movmean(airflow, 10);
tension = prova35bar(:,2);
tensione = movmean(tension, 10);
corrente = tensione.*(35.33); %coefficiente angolare dalla ...
    linearizzazione del circuito elettrico
load('..\2FileTxt\nopattino35bar.txt') %prova migliore ...
    nopattino35bar
airflow2 = nopattino35bar(:,1);
portata2 = movmean(airflow2, 10);
tension2 = nopattino35bar(:,2);
tensione2 = movmean(tension2, 10);
corrente2 = tensione2.*(35.33); %coefficiente angolare dalla ...
    linearizzazione del circuito elettrico

```

```
figure(1);    % grafico corrente portata (per CONDUTTANZA VALVOLA)
hold on;
grid on;
g = movmean(ans.G_v.data, 200);
i = movmean(ans.Input_current.data, 200);
% plot(ans.Input_current.data, ans.G_v.data, 'r');
 plot(i,g,'r');
plot(corrente2, portata2, 'b');
plot(corrente, portata, 'k');
xlabel('Valve input current [mA]');
ylabel('Valve airflow [l/min (ANR)]');
lgd = legend('Simulation', 'Valve alone','Valve with bearing');
% lgd = legend('Experiment no bearing','Experiment with bearing');
ttl = title('Valve alone: Airflow/Current, 5 bar, model and ...
    experiment comparison'); %cambiare in configurazione ...
    conductance_values5
% ttl = title('Valve with bearing: Airflow/Current, 5 bar, ...
    model and experiment comparison');  %cambiare in ...
    configurazione conductance_values5
lgd.FontSize = 16;
lgd.Location = 'SouthEast'
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);
set(gca,'FontSize',18)
```

Complete bearing simulation

```
% modello anello aperto:
%           figure(1)-confronto G vs I valvola modello-laboratorio
%           figure(2)-conftonto h vs V pattino modello-laboratorio
%           figure(3)-confronto in curvaa statica F vs h ...
    modello-laboratorio

% % ATTENZIONE, su modello:
%       1-2- switch su rampa tensione e forza statica   ...
    SWITCHES SU
%        3- switch su tensione costante e scala forza   ...
    SWITCHES GIU'

%Parametri per il modello matematico dell'anello aperto
clear all
close all
clc

run('config_originali')
% run('config_mod01')
% run('config_mod02')
% run('config_mod03')
%%
% %Apertura e run Simulink
open('..\Paolo_anello_aperto.slx')
sim('..\Paolo_anello_aperto.slx')
% load('..\data_folder\somefile.mat')
%%
% open('Paolo_valvola')
% sim('Paolo_valvola')
%% comparison model-lab
load('..\2FileTxt\prova35bar.txt') %prova migliore prova35bar
airflow = prova35bar(:,1);
portata = movmean(airflow, 10);
tension = prova35bar(:,2);
tensione = movmean(tension, 10);
corrente = tensione.*(35.33); %coefficiente angolare dalla ...
    linearizzazione del circuito elettrico
load('..\2FileTxt\nopattino35bar.txt') %prova migliore ...
    nopattino35bar
airflow2 = nopattino35bar(:,1);
portata2 = movmean(airflow2, 10);
tension2 = nopattino35bar(:,2);
tensione2 = movmean(tension2, 10);
corrente2 = tensione2.*(35.33); %coefficiente angolare dalla ...
    linearizzazione del circuito elettrico

figure(1);   % grafico corrente portata (per CONDUTTANZA VALVOLA)
```

```
hold on;
grid on;
g = movmean(ans.G_v.data, 200);
i = movmean(ans.Input_current.data, 200);
% plot(ans.Input_current.data, ans.G_v.data, 'r');
plot(i,g,'r');
plot(corrente2, portata2, 'b');
plot(corrente, portata, 'k');
xlabel('Valve input current [mA]');
ylabel('Valve airflow [l/min (ANR)]');
lgd = legend('Simulation', 'Experiment no bearing','Experiment ...
    with bearing');
ttl = title('Complete beairng: Airflow/Current, 5 bar, model ...
    and experiment comparison');
lgd.FontSize = 16;
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);
set(gca,'FontSize',18)
%% 5 bar; 20kg
%data acquisition
clear capac_5bar_20kg
soglia = 1;
data = load('..\2FileTxt\TriangoloLento_bar5_1_20kg.txt');
for i = 1:4
    capac_5bar_20kg(:,i) = data(:,i);
end
loadCell_5bar_20kg = data(:,5);
inputVoltage_5bar_20kg = data(:,6);
% %tuning
% figure(9)
% plot(inputVoltage_5bar_20kg)

xx = inputVoltage_5bar_20kg((1:23000));
clear inputVoltage_5bar_20kg
inputVoltage_5bar_20kg = xx;
clear xx
[A,B] = min(inputVoltage_5bar_20kg);
%truncation on one triangular perion only (TO TUNE EACH SET OF ...
    DATA)
for i = 1:4
    xx(:,i) = capac_5bar_20kg((B-1000:B+19000),i);
end
clear capac_5bar_20kg
for i = 1:4
    capac_5bar_20kg(:,i) = xx(:,i);
end
clear xx
loadCell_5bar_20kg = loadCell_5bar_20kg(B-1000:B+19000);
inputVoltage_5bar_20kg = inputVoltage_5bar_20kg(B-1000:B+19000);
%move mean
```

```
for i = 1:4
    capac_5bar_20kg(:,i) = movmean(capac_5bar_20kg(:,i),100);
end
inputVoltage_5bar_20kg = movmean(inputVoltage_5bar_20kg,100);
%zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_20kg(i) = ...
        mean(capac_5bar_20kg((1:3000),i));
end
base_mean_capac_5bar_20kg;
for i = 1:4
    capac_5bar_20kg(:,i) = -1*(capac_5bar_20kg(:,i) - ...
        base_mean_capac_5bar_20kg(1,i)); %change sign
end
for i = 1:length(capac_5bar_20kg)
    single_values_5bar_20kg_mean(i) = mean(capac_5bar_20kg(i,:));
end
single_values_5bar_20kg_mean;   %mean between the 4 capacitive ...
    sensors

for i=1:length(single_values_5bar_20kg_mean)
    if single_values_5bar_20kg_mean(i)>soglia
%           single_values_5bar_20kg_mean(i);
        i_20 = i;
        lower_voltage_value_5bar_20kg = inputVoltage_5bar_20kg(i);
        break
    end
end
% PLOTS
x = 1:length(single_values_5bar_20kg_mean);

figure(2)  % h vs voltage VALIDO PER 20 KG DI MASSE
hold on
grid on
ylabel('h [μm]');
xlabel('Valve signal [V]');
plot(inputVoltage_5bar_20kg(i_20:11000),single_values_5bar_20kg_
mean(i_20:11000)) %curva meato h vs tensione valvola 4 bar
plot(ans.V_in.data,ans.h.data*10^6)
ttl = title('Valve signal/air film h, comparison with total ...
    load of 260 N, 5 bar')
lgd = legend('Laboratory','Simulation');
lgd.FontSize = 16;
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);
set(gca,'FontSize',18)

%% %variables
m_support = 6.480; %kg
masses = [45 40 35 30 25 20 15 10 5 0];
```

```
g = 9.81;

% % 5 bar; fullV
%data acquisition
data = ...
    load('..\2FileTxt\ciclo_completo_5bar_2_30V_sens_press__3.txt');
for i = 1:4
    capac_5bar_fullV(:,i) = data(:,i);
end
loadCell_5bar_fullV = data(:,5)+(45+m_support)*g;
pressure_5bar_fullV_volt = data(:,7);   % PROBABILEMTE VALORI ...
    SONO SBAGLIATI (SONO NEGATIVI, NON HA SENSO, DIVERSO DA ...
    TUTTE LE ALTRE MISURE FATTE PRECEDENTEMENTE)

% % % move mean
for i = 1:4
    capac_5bar_fullV(:,i) = movmean(capac_5bar_fullV(:,i),100);
end
loadCell_5bar_fullV = movmean(loadCell_5bar_fullV,100);
pressure_5bar_fullV_volt = movmean(pressure_5bar_fullV_volt,100);

%  % zeroing of capacitive sensors
for i = 1:4
    base_mean_capac_5bar_fullV(i) = ...
        mean(capac_5bar_fullV((1:3000),i));
end
base_mean_capac_5bar_fullV
for i = 1:4
    capac_5bar_fullV(:,i) = -1*(capac_5bar_fullV(:,i) - ...
        base_mean_capac_5bar_fullV(1,i)); %change sign
end

for i = 1:length(capac_5bar_fullV(:,1))
    capac_5bar_fullV_mean(i) = mean(capac_5bar_fullV(i,:));
end

% % comparison model-lab ciclo completo prova statica
for i = 1:round(t_sim)
    in = 1000*i-700;
    fin = 1000*i-300;
    h_model(i) = mean(ans.h.data(in:fin)*10^6); % microns
    f_model(i) = (mean(ans.f_ext.data(in:fin)) + m_support*g); ...
        %newton
end
% h_model = ans.h.data*10^6; % microns
% f_model = ans.f_ext.data + m_support*g; %newton
figure(3)   % COMPARISON STATIC CICLE
hold on
grid on
plot(capac_5bar_fullV_mean,loadCell_5bar_fullV)
```

```
plot(h_model , f_model)
xlim([-2 40])
ylim([0 600])
xlabel('h [µm]');
ylabel('Load [N]');
lgd = legend('Capacitive sensors','model');
ttl = title('Load/h complete static curve, 5bar');
lgd.FontSize = 16;
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);
set(gca,'FontSize',18)

% % % CONFRONTO CON DATI FARA
% % % FARA data
load('..\2FileTxt\provacompleta5barFARA.txt')
capacitivo_3_fara = provacompleta5barFARA(:,1);
[max3] = max(capacitivo_3_fara(:));
capacitivo_a3_fara = max3 - capacitivo_3_fara;
capacitivo_0_fara = provacompleta5barFARA(:,2);
[max0] = max(capacitivo_0_fara(:));
capacitivo_a0_fara = max0 - capacitivo_0_fara;
capacitivo_1_fara = provacompleta5barFARA(:,3);
[max1] = max(capacitivo_1_fara(:));
capacitivo_a1_fara = max1 - capacitivo_1_fara;
capacitivo_2_fara = provacompleta5barFARA(:,4);
[max2] = max(capacitivo_2_fara(:));
capacitivo_a2_fara = max2 - capacitivo_2_fara;
newton = provacompleta5barFARA(:,5);
for i = 1:length(capacitivo_a0_fara)
    capacitivo_mean_fara(i) = mean([capacitivo_a0_fara(i) ...
        capacitivo_a1_fara(i) capacitivo_a2_fara(i) ...
        capacitivo_a3_fara(i)]);
end
plot(capacitivo_mean_fara, newton);
xlabel('h [um]');
ylabel('Load [N]');
xlim([-2 40])
ylim([0 550])
lgd = legend('Experimental: Step ...
    bench','Simulation','Experimental: Mager bench');
lgd.FontSize = 16;
ttl.FontSize = 16;
set(findall(gca, 'Type', 'Line'),'LineWidth',2);
set(gca,'FontSize',18)
```

Configurations

Configuration: original .

```
% Parametri modello anello aperto ORIG
t_sim = 10; %tempo di simulazione
t_step = 0.001; %intervallo di tempo simulazione

% costanti
I_ref =85 ; %corrente in input di riferimento [mA] (default 85)
V_ref = 2.3;
F_ext = 200; % N
P_up = 6*10^5; %pressione di alimentazione assoluta [Pa]
Pamb = 1*10^5; %pressione ambiente assoluta [Pa]
b = 0.528; %rapporto critico   0.528
omega_n = 35*2*pi; %[rad/s]
zita = 0.2;
g = 9.81; %m/s^2
Ti = 288; %temperatura ambiente [K]
Tm = 293; %temperatura meato [K]
Psi = 0.685/(sqrt(287*288)); %costante psi    0.685
n = 1; %esponente politropica
R = 287; %costante gas ideale [J/kgK]
Volume = 739.2*10^-9; %volume camera interna [m^3]
I0=1;                   %corrente iniziale [mA]
I_slope=(90-I0)/t_sim;  %pendenza rampa corrente [mA/s]

% da modificare
Ch = 0.8;% originale:0.8        buono  0.5
Pc_div_Pm = 3; % originale 3
c_d = 0.85; %coefficiente di flusso,originale 0.85     buono: ...
        1
ds = 0.25*10^-3; %diametro foro pattino [m]  ...
    originale:0.268*10^-3     buono 0.4
M = 6.480; %kg (massa pattino + struttura porta pesi) ...
    originali: 6.480  buono 0.48
L1 = 0.075; %lunghezza pattino [m] originali: 0.075  buono 0.15
L2 = 0.050; %larghezza pattino [m] originali: 0.050   buono 0.1

conductance_values5 = [0 0 3.2 3.75 4 4]*(0.00002044)/(6*10^5); ...
             % senza pattino %valori ricavati dalla ...
    caratteristica con isteresi della valvola senza pattino ...
    [kg/(s*Pa)]
% conductance_values5 = [0 0 2.5 2.6 2.7 ...
    2.8]*(0.00002044)/(6*10^5);        % con pattino   ...
    %modificati per seguire la curva
current_values5 = [0 41 65 70 75 85]; %[mA]

Forces = [50 100 150 200 250 300 350 400 450 500]';
```

Configuration: modification one .

```
% Parametri modello anello aperto MOD 01
t_sim = 10; %tempo di simulazione
t_step = 0.001; %intervallo di tempo simulazione

% costanti
I_ref =85 ; %corrente in input di riferimento [mA] (default 85)
V_ref = 2.3;
F_ext = 200; % N
P_up = 6*10^5; %pressione di alimentazione assoluta [Pa]
Pamb = 1*10^5; %pressione ambiente assoluta [Pa]
b = 0.528; %rapporto critico   0.528
omega_n = 35*2*pi; %[rad/s]
zita = 0.2;
g = 9.81; %m/s^2
Ti = 288; %temperatura ambiente [K]
Tm = 293; %temperatura meato [K]
Psi = 0.685/(sqrt(287*288)); %costante psi    0.685
n = 1; %esponente politropica
R = 287; %costante gas ideale [J/kgK]
Volume = 739.2*10^-9; %volume camera interna [m^3]
I0=1;                      %corrente iniziale [mA]
I_slope=(90-I0)/t_sim;     %pendenza rampa corrente [mA/s]

% da modificare
Ch = 0.3;% originale:0.8        buono  0.5
Pc_div_Pm = 3; % originale 3
c_d = 0.6; %coefficiente di flusso,originale 0.85     buono: ...
        1
ds = 0.2*10^-3; %diametro foro pattino [m]  ...
    originale:0.268*10^-3     buono 0.4
M = 6.480; %kg (massa pattino + struttura porta pesi) ...
    originali: 6.480  buono 0.48
L1 = 0.06; %lunghezza pattino [m] originali: 0.075  buono 0.15
L2 = 0.050; %larghezza pattino [m] originali: 0.050   buono 0.1

conductance_values5 = [0 0 3.2 3.75 4 4]*(0.00002044)/(6*10^5); ...
                % senza pattino %valori ricavati dalla ...
    caratteristica con isteresi della valvola senza pattino ...
    [kg/(s*Pa)]
% conductance_values5 = [0 0 2.5 2.6 2.7 ...
    2.8]*(0.00002044)/(6*10^5);         % con pattino   ...
    %modificati per seguire la curva
current_values5 = [0 41 65 70 75 85]; %[mA]

Forces = [50 100 150 200 250 300 350 400 450 500]';
```

Configuration: modification two .

```
% Parametri modello anello aperto MOD 02
t_sim = 10; %tempo di simulazione
t_step = 0.001; %intervallo di tempo simulazione

% costanti
I_ref =85 ; %corrente in input di riferimento [mA] (default 85)
V_ref = 2.3;
F_ext = 200; % N
P_up = 6*10^5; %pressione di alimentazione assoluta [Pa]
Pamb = 1*10^5; %pressione ambiente assoluta [Pa]
b = 0.528; %rapporto critico   0.528
omega_n = 35*2*pi; %[rad/s]
zita = 0.2;
g = 9.81; %m/s^2
Ti = 288; %temperatura ambiente [K]
Tm = 293; %temperatura meato [K]
Psi = 0.685/(sqrt(287*288)); %costante psi    0.685
n = 1; %esponente politropica
R = 287; %costante gas ideale [J/kgK]
Volume = 739.2*10^-9; %volume camera interna [m^3]
I0=1;                    %corrente iniziale [mA]
I_slope=(90-I0)/t_sim;   %pendenza rampa corrente [mA/s]

% da modificare
Ch = 0.4;% originale:0.8        buono  0.5
Pc_div_Pm = 2; % originale 3
c_d = 1.1; %coefficiente di flusso,originale 0.85     buono: ...
        1
ds = 0.35*10^-3; %diametro foro pattino [m]  ...
    originale:0.268*10^-3     buono 0.4
M = 6.480; %kg (massa pattino + struttura porta pesi) ...
    originali: 6.480  buono 0.48
L1 = 0.05; %lunghezza pattino [m] originali: 0.075  buono 0.15
L2 = 0.030; %larghezza pattino [m] originali: 0.050   buono 0.1

conductance_values5 = [0 0 3.2 3.75 4 4]*(0.00002044)/(6*10^5); ...
              % senza pattino %valori ricavati dalla ...
    caratteristica con isteresi della valvola senza pattino ...
    [kg/(s*Pa)]
% conductance_values5 = [0 0 2.5 2.6 2.7 ...
    2.8]*(0.00002044)/(6*10^5);        % con pattino   ...
    %modificati per seguire la curva
current_values5 = [0 41 65 70 75 85]; %[mA]

Forces = [50 100 150 200 250 300 350 400 450 500]';
```

Configuration: modification three .

```
% Parametri modello anello aperto MOD 03
t_sim = 10; %tempo di simulazione
t_step = 0.001; %intervallo di tempo simulazione

% costanti
I_ref =85 ; %corrente in input di riferimento [mA] (default 85)
V_ref = 2.3;
F_ext = 200; % N
P_up = 6*10^5; %pressione di alimentazione assoluta [Pa]
Pamb = 1*10^5; %pressione ambiente assoluta [Pa]
b = 0.528; %rapporto critico   0.528
omega_n = 35*2*pi; %[rad/s]
zita = 0.2;
g = 9.81; %m/s^2
Ti = 288; %temperatura ambiente [K]
Tm = 293; %temperatura meato [K]
Psi = 0.685/(sqrt(287*288)); %costante psi    0.685
n = 1; %esponente politropica
R = 287; %costante gas ideale [J/kgK]
Volume = 739.2*10^-9; %volume camera interna [m^3] originale : ...
    739.2*10^-9
I0=1;                    %corrente iniziale [mA]
I_slope=(90-I0)/t_sim;   %pendenza rampa corrente [mA/s]

% da modificare
Ch = 0.8;% originale:0.8        buono  0.5
Pc_div_Pm = 3; % originale 3
c_d = 0.8; %coefficiente di flusso,originale 0.85     buono: ...
        1
ds = 0.25*10^-3; %diametro foro pattino [m]  ...
    originale:0.268*10^-3     buono 0.4
M = 6.480; %kg (massa pattino + struttura porta pesi) ...
    originali: 6.480  buono 0.48
L1 = 0.075; %lunghezza pattino [m] originali: 0.075  buono 0.15
L2 = 0.050; %larghezza pattino [m] originali: 0.050   buono 0.1

conductance_values5 = [0 0 3.2 3.75 4 4]*(0.00002044)/(6*10^5); ...
               % senza pattino %valori ricavati dalla ...
    caratteristica con isteresi della valvola senza pattino ...
    [kg/(s*Pa)]
% conductance_values5 = [0 0 2.5 2.6 2.7 ...
    2.8]*(0.00002044)/(6*10^5);        % con pattino   ...
    %modificati per seguire la curva
current_values5 = [0 41 65 70 75 85]; %[mA]

Forces = [50 100 150 200 250 300 350 400 450 500]';
```

POLITECNICO DI TORINO

Master's Degree in
Mechatronic Engineering

Master Thesis

Control of an active air bearing: simulation and experimental tests

Annex 2: closed loop tests results

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April 2021

Introduction In this annex, all the graphs obtained during the closed loop tests are reported. The different tests performed in the laboratory are reported in the following table. The experiments are divided in two groups: one based on a control algorithm with the unit of measure conversion block and the other without this block.

	K_p	K_i	Loaded Masses [kg]
WITH unit of measure conversion block			
Tests			
	0.8	40	30
	1	40	20-15-20-25
Fixed K_p			
	1	40-100	20-15-20-25
Fixed K_i			
	1-10-40	0	20
	1-10-40	40	20
WITHOUT unit of measure conversion block			
Tests			
	0.17	20	10
	0.17	20	20-10-20
	0.17	20	45
Fixed K_p			
	0.17	1-10-20	20
	0.8	0-1-10-50-100	20
	1.75	1-10-100	20
	2.75	1-10-100	20
Fixed K_i			
	0.5-0.8-1.2-1.75-2.75	0	20
	0.1-0.17-0.8	20	10
Other tests			
Load-Unload with 50 N steps each time			$45 \rightarrow 0 \rightarrow 45$ [kg]
Gradual inlet pressure increase			$5 \rightarrow 8$ [bar]

Part I

Control action with unit of measure conversion block

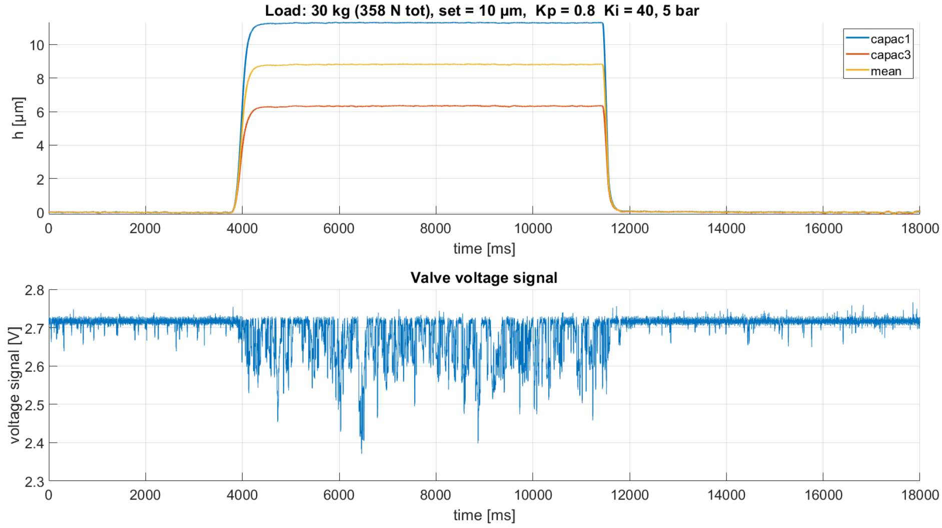

Figure 1. Control action with conversion block. Capacitive sensors and valve voltage over the time. Inlet air pressure: 5 bar relative. Air film height set=10 µm. K_p=0.8. K_i=40. Mass loaded: 30 kg. Total weight loaded: 358 N

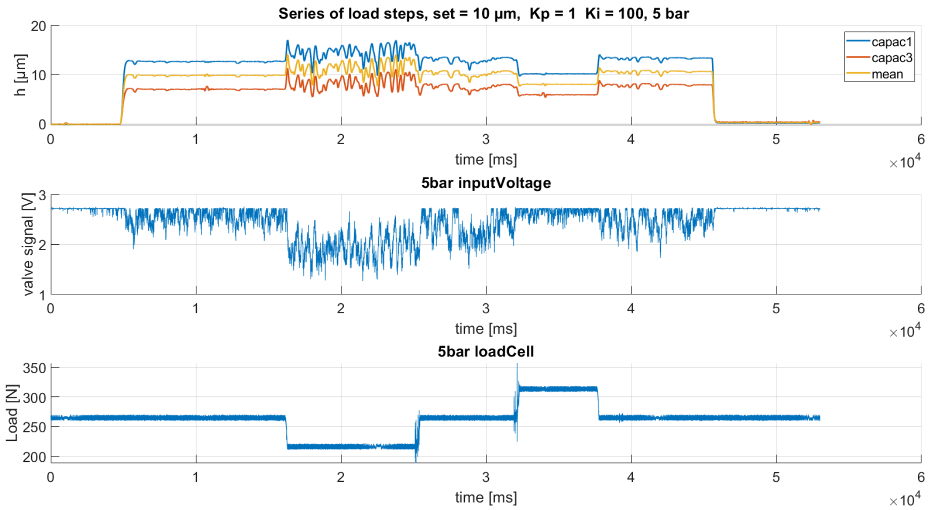

Figure 2. Control action with conversion block. Capacitive sensors, valve voltage and load over the time. Inlet air pressure: 5 bar relative. Air film height set=10 µm. K_p=1. K_i=40. Mass loaded: 20-15-20-25 kg. Total weight loaded: 260-211-260-309 N

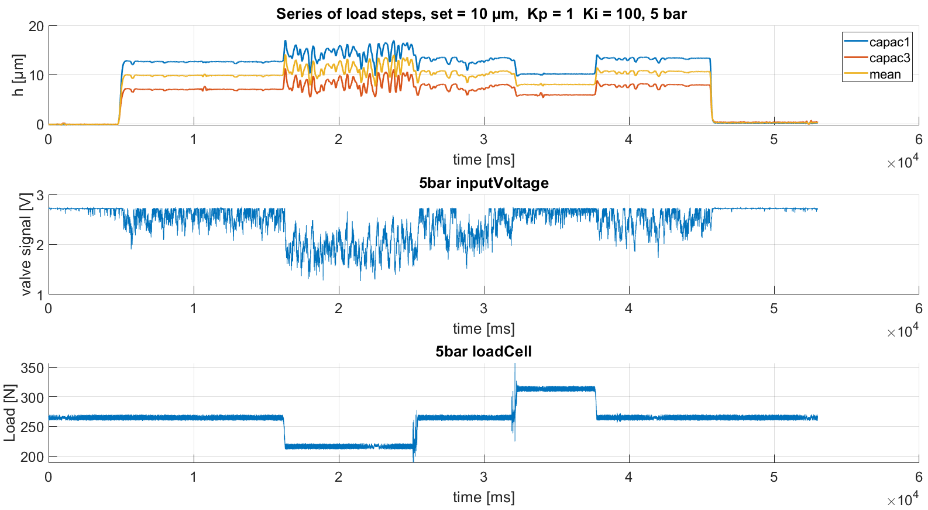

Figure 3. Control action with conversion block. Capacitive sensors, valve voltage and load over the time. Inlet air pressure: 5 bar relative. Air film height set=10 µm. K_p=1. K_i=100. Mass loaded: 20-15-20-25 kg. Total weight loaded: 260-211-260-309 N

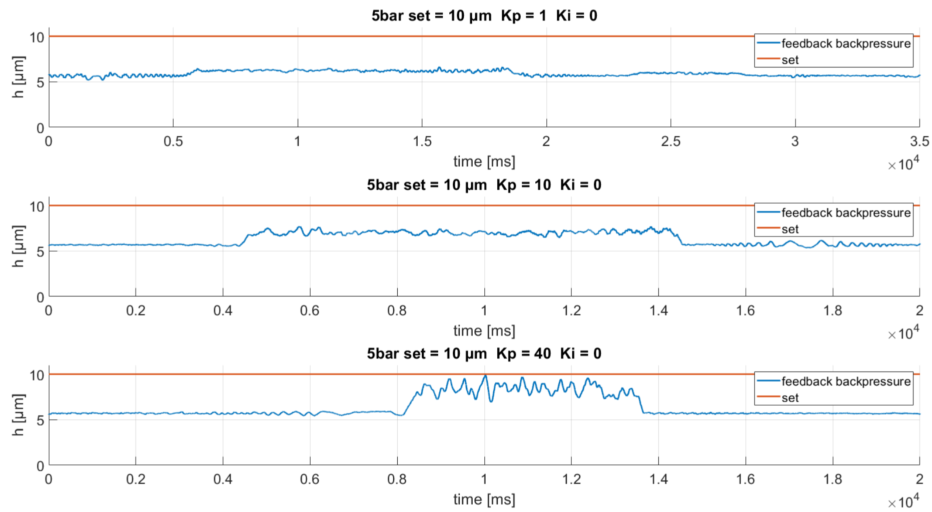

Figure 4. Control action with conversion block. Feedback in µm and set representation over the time. Inlet air pressure: 5 bar relative. Air film height set=10 µm. K_p=1-10-40. K_i=0. Mass loaded: 20 kg. Total weight loaded: 260 N

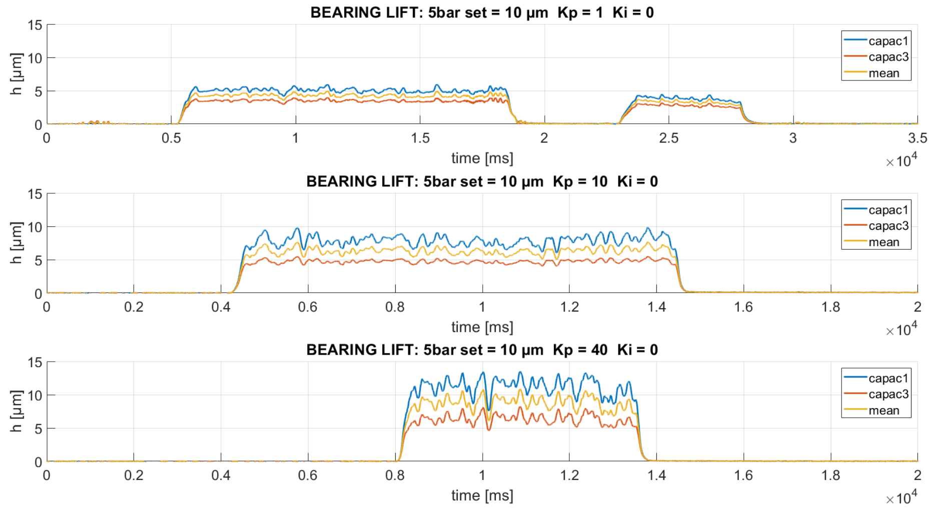

Figure 5. Control action with conversion block. Capacitive sensors over the time. Inlet air pressure: 5 bar relative. Air film height set=10 µm. K_p=1-10-40. K_i=0. Mass loaded: 20 kg. Total weight loaded: 260 N

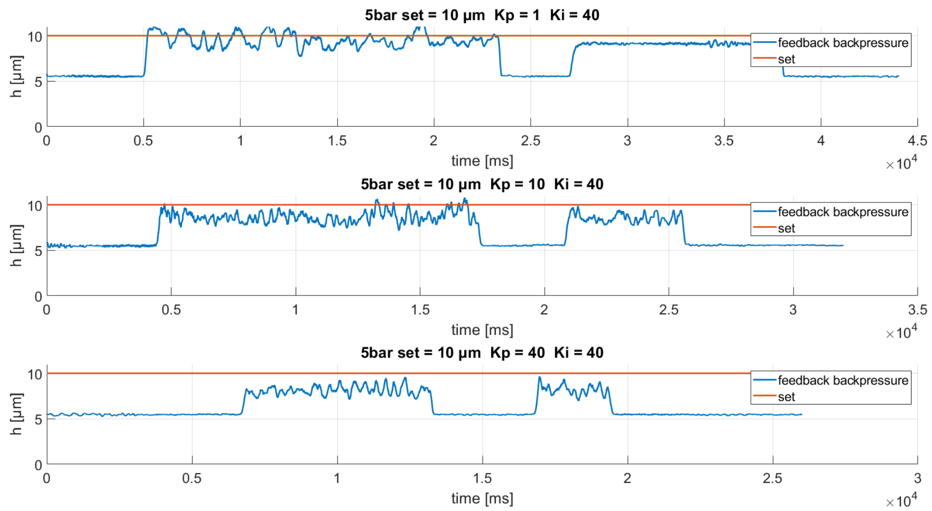

Figure 6. Control action with conversion block. Feedback in µm and set representation over the time. Inlet air pressure: 5 bar relative. Air film height set=10 µm. K_p=1-10-40. K_i=40. Mass loaded: 20 kg. Total weight loaded: 260 N

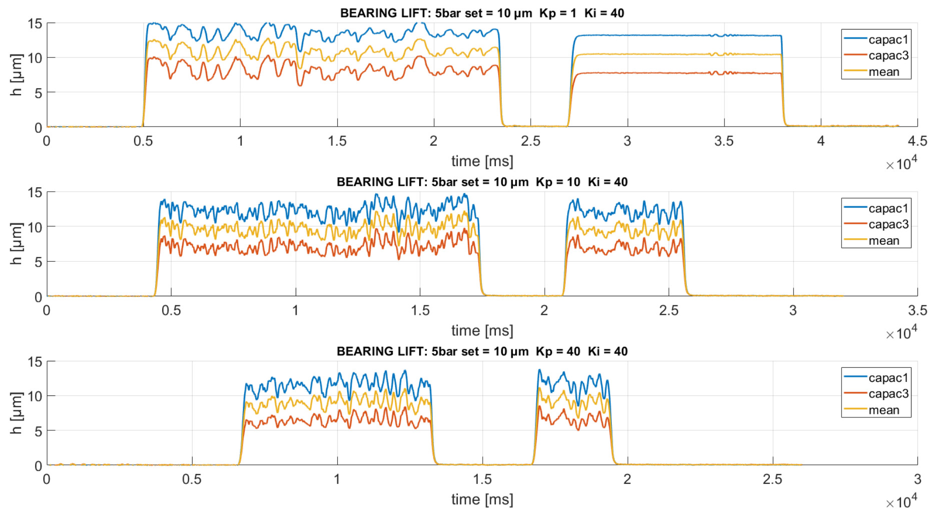

Figure 7. Control action with conversion block. Capacitive sensors over the time. Inlet air pressure: 5 bar relative. Air film height set=10 μm. K_p=1-10-40. K_i=40. Mass loaded: 20 kg. Total weight loaded: 260 N

Part II

Control action without unit of measure conversion block

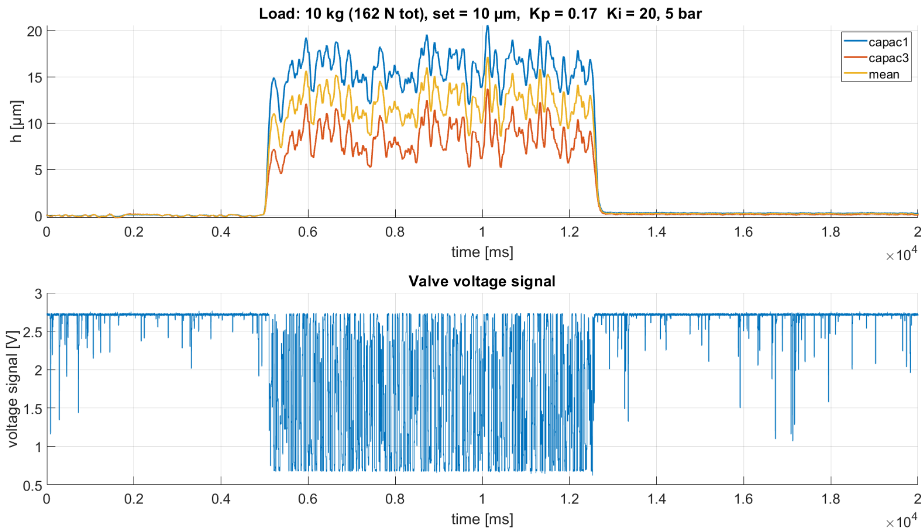

Figure 8. Control action without conversion block. Capacitive sensors and valve voltage over the time. Inlet air pressure: 5 bar relative. Air film height set=10 µm. K_p=0.17. K_i=20. Mass loaded: 10 kg. Total weight loaded: 162 N

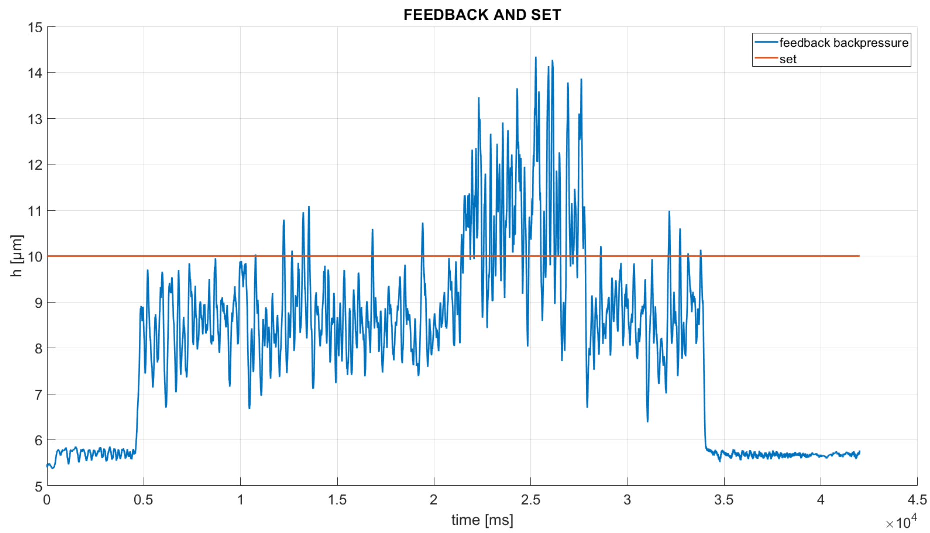

Figure 9. Control action without conversion block. Feedback in µm and set representation over the time. Inlet air pressure: 5 bar relative. Air film height set=10 µm. K_p=0.17. K_i=20. Mass loaded: 20-10-20 kg. Total weight loaded: 260-162-260 N

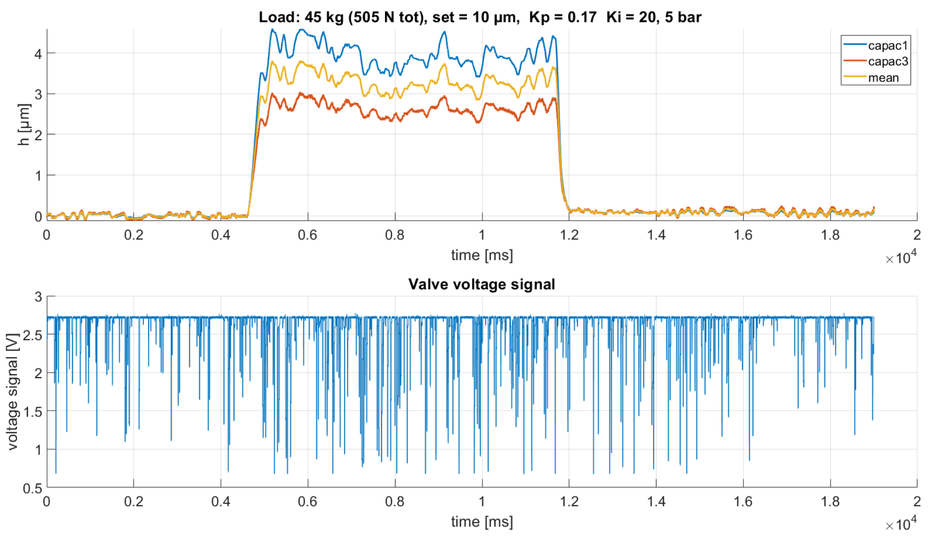

Figure 10. Control action without conversion block. Capacitive sensors and valve voltage over the time. Inlet air pressure: 5 bar relative. Air film height set=10 µm. K_p=0.17. K_i=20. Mass loaded: 45 kg. Total weight loaded: 505 N

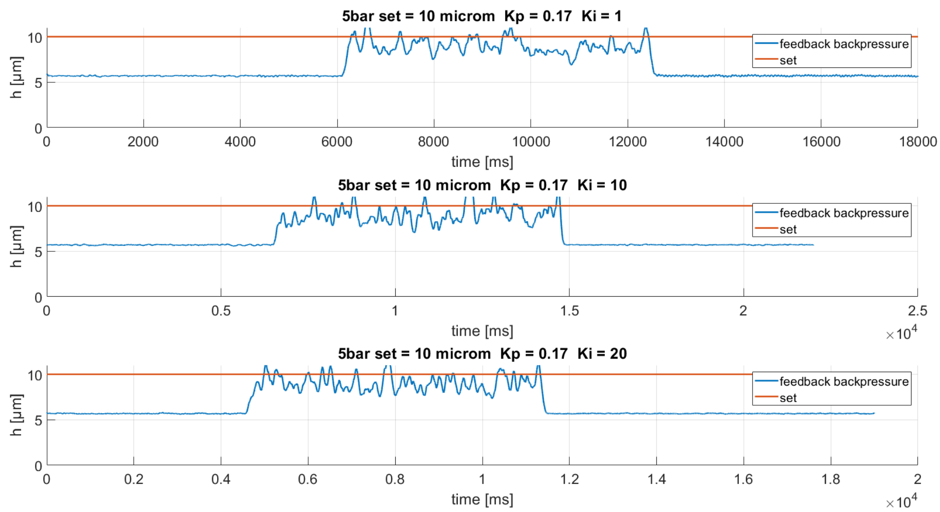

Figure 11. Control action without conversion block. Feedback in µm and set representation over the time. Inlet air pressure: 5 bar relative. Air film height set=10 µm. K_p=0.17. K_i=1-10-20. Mass loaded: 20 kg. Total weight loaded: 260 N

Figure 12. Control action without conversion block. Capacitive sensors over the time. Inlet air pressure: 5 bar relative. Air film height set=10 µm. K_p=0.17. K_i=1-10-20. Mass loaded: 20 kg. Total weight loaded: 260 N

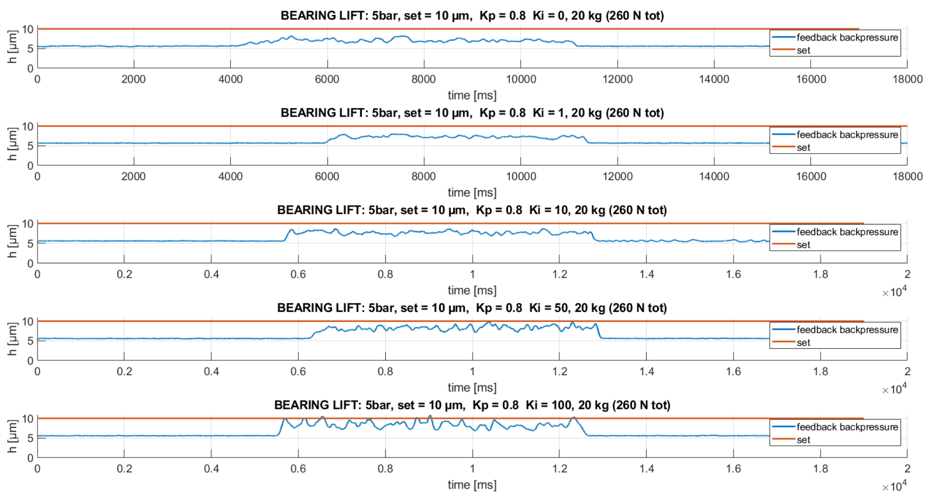

Figure 13. Control action without conversion block. Feedback in µm and set representation over the time. Inlet air pressure: 5 bar relative. Air film height set=10 µm. K_p=0.8. K_i=0-1-10-50-100. Mass loaded: 20 kg. Total weight loaded: 260 N

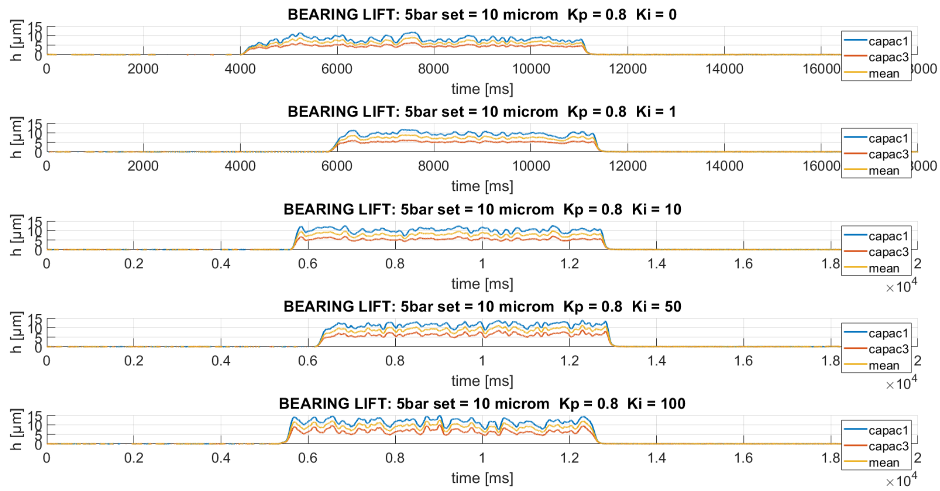

Figure 14. Control action without conversion block. Capacitive sensors over the time. Inlet air pressure: 5 bar relative. Air film height set=10 µm. K_p=0.8. K_i=0-1-10-50-100. Mass loaded: 20 kg. Total weight loaded: 260 N

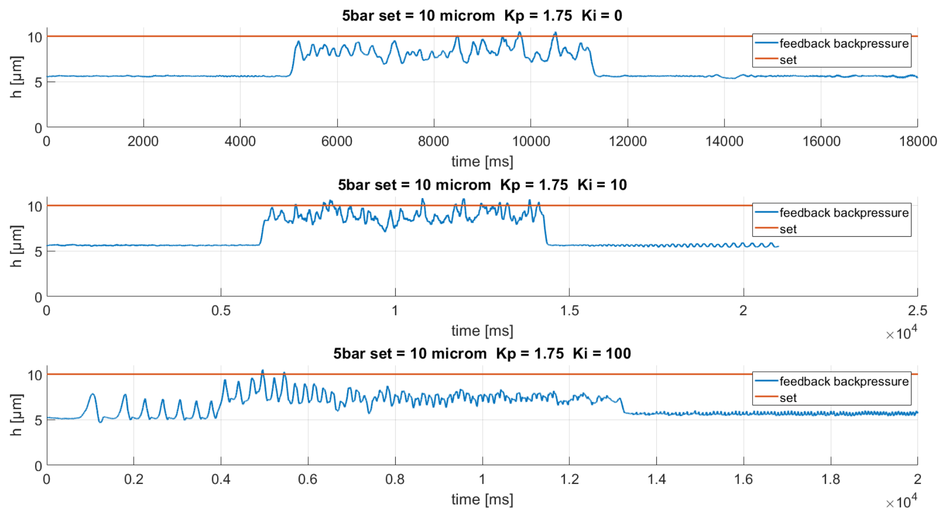

Figure 15. Control action without conversion block. Feedback in µm and set representation over the time. Inlet air pressure: 5 bar relative. Air film height set=10 µm. K_p=1.75. K_i=0-10-100. Mass loaded: 20 kg. Total weight loaded: 260 N

Figure 16. Control action without conversion block. Capacitive sensors over the time. Inlet air pressure: 5 bar relative. Air film height set=10 µm. K_p=1.75. K_i=0-10-100. Mass loaded: 20 kg. Total weight loaded: 260 N

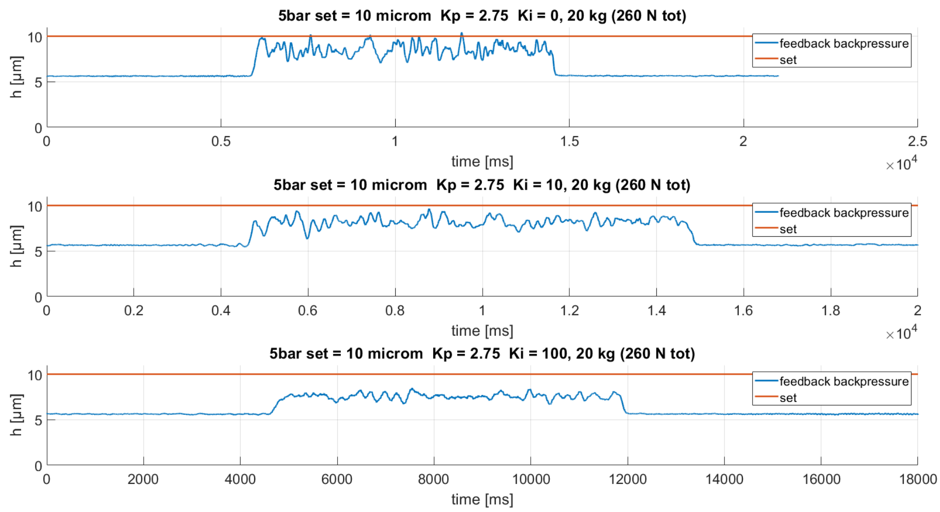

Figure 17. Control action without conversion block. Feedback in µm and set representation over the time. Inlet air pressure: 5 bar relative. Air film height set=10 µm. K_p=2.75. K_i=0-10-100. Mass loaded: 20 kg. Total weight loaded: 260 N

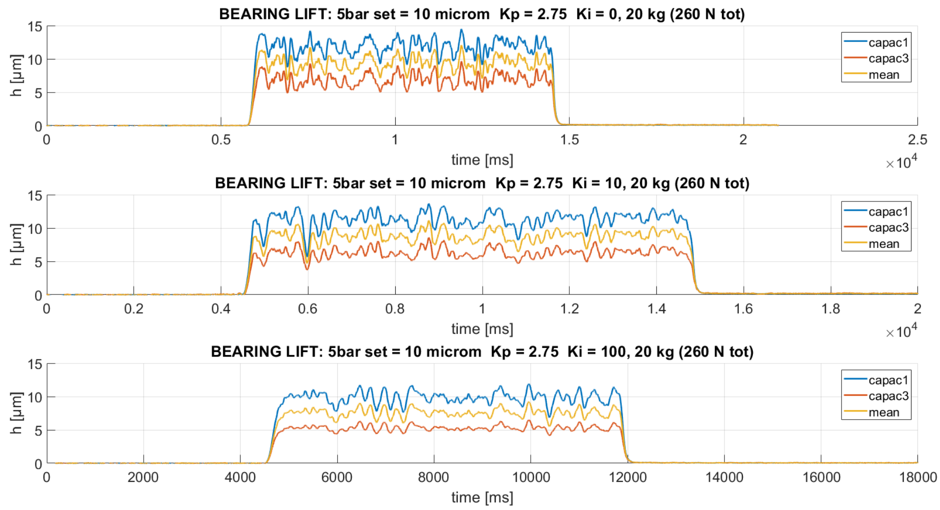

Figure 18. Control action without conversion block. Capacitive sensors over the time. Inlet air pressure: 5 bar relative. Air film height set=10 µm. K_p=2.75. K_i=0-10-100. Mass loaded: 20 kg. Total weight loaded: 260 N

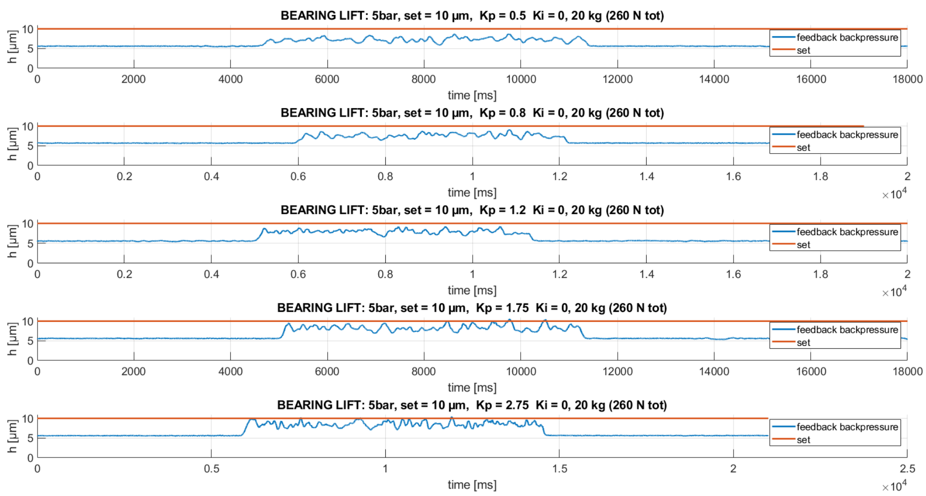

Figure 19. Control action without conversion block. Feedback in µm and set representation over the time. Inlet air pressure: 5 bar relative. Air film height set=10 µm. K_p=0.5-0.8-1.2-1.75-2.75. K_i=0. Mass loaded: 20 kg. Total weight loaded: 260 N

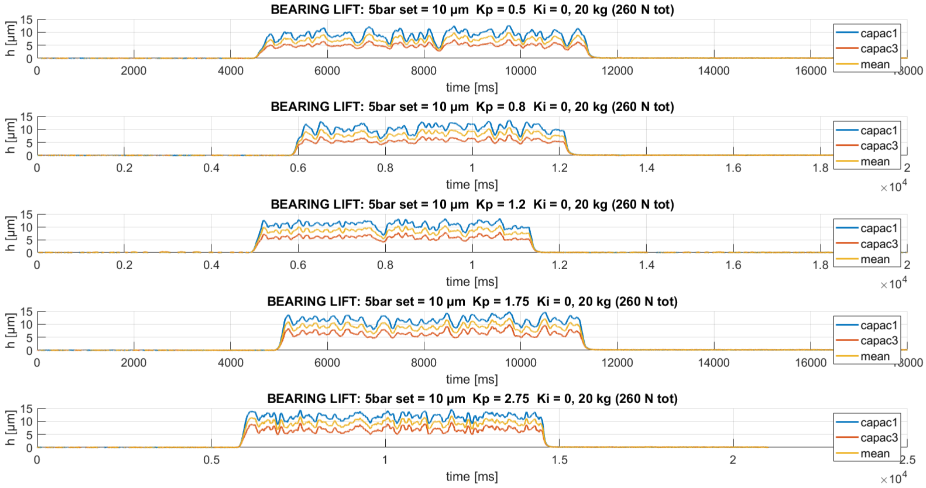

Figure 20. Control action without conversion block. Capacitive sensors over the time. Inlet air pressure: 5 bar relative. Air film height set=10 µm. K_p=0.5-0.8-1.2-1.75-2.75. K_i=0. Mass loaded: 20 kg. Total weight loaded: 260 N

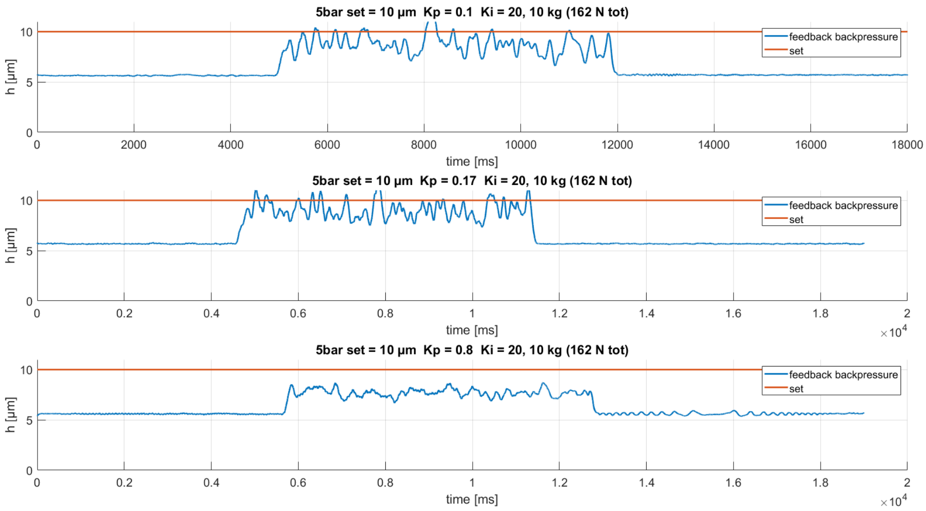

Figure 21. Control action without conversion block. Feedback in µm and set representation over the time. Inlet air pressure: 5 bar relative. Air film height set=10 µm. K_p=0.1-0.17-0.8. K_i=20. Mass loaded: 10 kg. Total weight loaded: 162 N

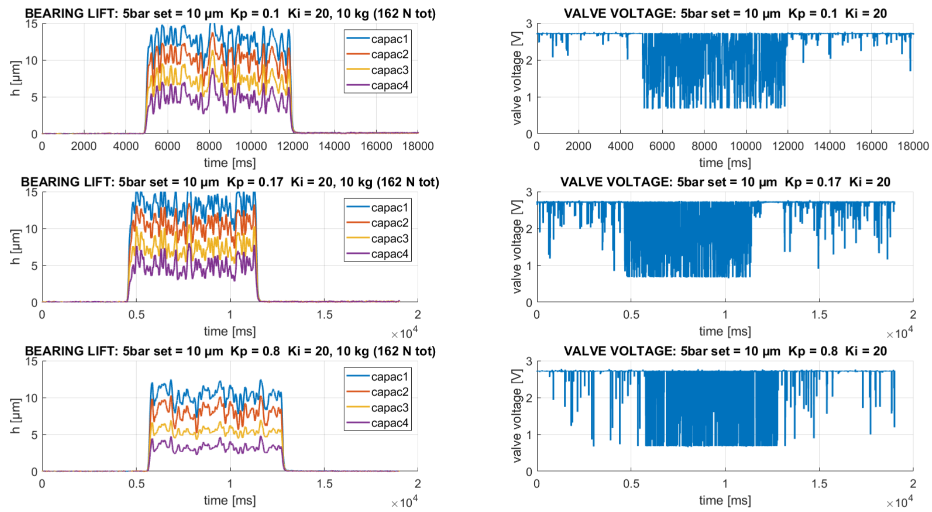

Figure 22. Control action without conversion block. Capacitive sensors and valve voltage over the time. Inlet air pressure: 5 bar relative. Air film height set=10 μm. K_p=0.1-0.17-0.8. K_i=20. Mass loaded: 10 kg. Total weight loaded: 162 N

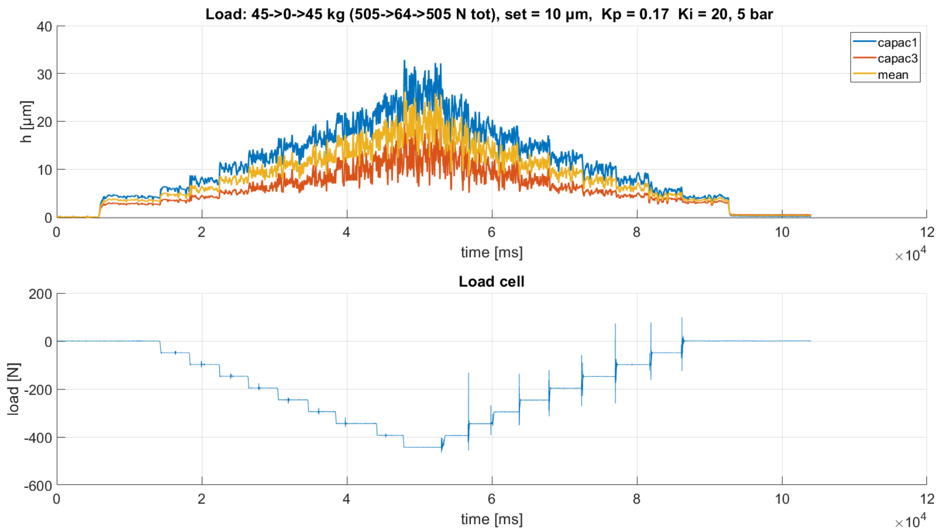

Figure 23. Control action without conversion block. Capacitive sensors and load over the time. Inlet air pressure: 5 bar relative. Air film height set=10 μm. K_p=0.17. K_i=20. Mass loaded: 45→0→45 kg. Total weight loaded: 505→64→505 N

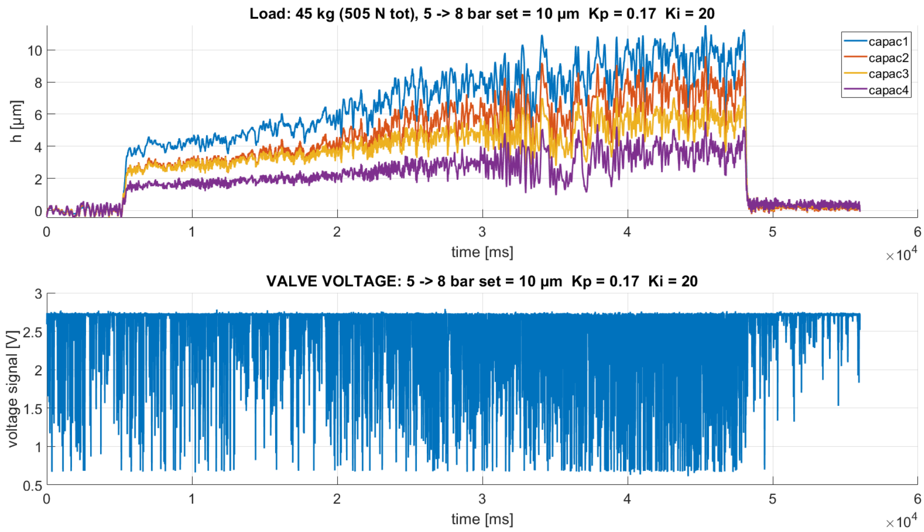

Figure 24. Control action without conversion block. Capacitive sensors and valve voltage over the time. Inlet air pressure: from 5 to 8 bar relative, gradually increased. Air film height set=10 µm. K_p=0.17. K_i=20. Mass loaded: 45 kg. Total weight loaded: 505 N

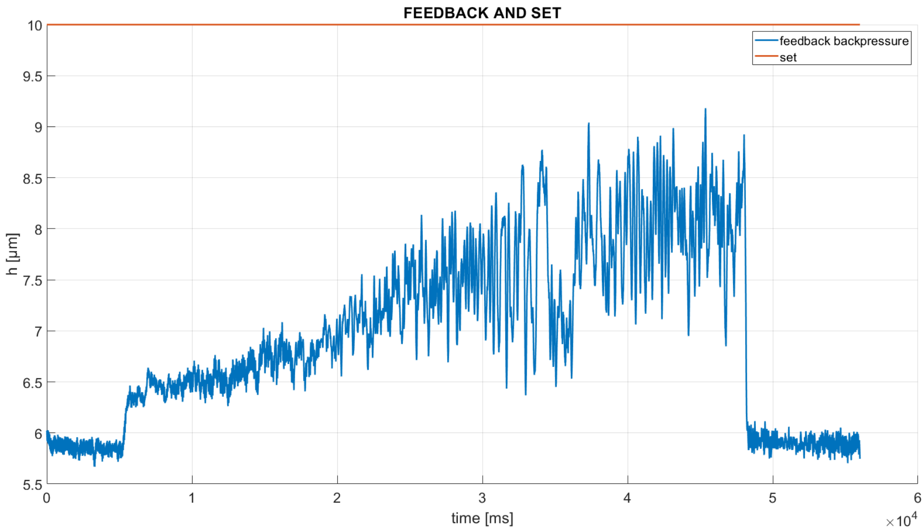

Figure 25. Control action without conversion block. Feedback in µm and set representation over the time. Inlet air pressure: from 5 to 8 bar relative, gradually increased. Air film height set=10 µm. K_p=0.17. K_i=20. Mass loaded: 45 kg. Total weight loaded: 505 N

POLITECNICO DI TORINO

Master's Degree in
Mechatronic Engineering

Master Thesis

Control of an active air bearing: simulation and experimental tests

Annex 3: Technical drawing of the capacitive sensors support

Academic supervisors
Prof. Daniela Maffiodo
Prof. Terenziano Raparelli
Prof. Federico Colombo

Candidate
Paolo Bisiach

April 2021

Introduction In this annex, the technical drawing of the capacitive sensors support is reported.