POLITECNICO DI TORINO

Master's Degree in Mechatronic Engineering

Specialized Degree Thesis

Air trust bearing controlled with air proportional valve

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Preface

In the field of mechanical movement, it is required that the precision of the mechanical system is improved as much as possible. Therefore, pneumatic bearings are increasingly used due to the fact that, since no contact is present between the moving components, friction is much more reduced than in traditional bearings. This allow to have a better performance in systems requiring a high precision movement when low power is needed.

The work of thesis presented here is about a pneumatic bearing powered by an electromagnetic proportional pneumatic valve controlled by an electronic board. The board is a WhatsNext Orange board which is the analogous of the Arduino Due, which has a two digital-to-analog pins that allow to deliver a proportional voltage signal adapt to control a proportional valve. Since the electronic board itself is not capable to deliver the power requested by the electromagnetic valve, which can be considered as a solenoid from the point of view of electronics, an electronic circuit has been designed. With the use of few components, which are some resistors of proper values, an operational amplifier, a transistor, a diode and two voltage supplies, the control signal coming from the digital-to-analog converter of the electronic board is able to handle a power signal into the valve and open it proportionally.

The air supplied to the bearing by the pneumatic valve flows into the pneumatic bearing and out of it, thus forming an air film able to lift the pneumatic bearing. The air film is proportional to the load applied vertically to the bearing.

The tests exposed in this work of thesis are made considering the bearing alone, supplying the pressured air without the use of the valve, and with the valve proportionally open feeding the bearing. After that a model has been created, with the use of the software Simulink/Matlab, which reflect the behavior of the system as accurate as possible. The model allows to evaluate possible modification to the system without modifying the real mechanical system.

Mechanical bearings

Bearing types

A bearing is an element that allows a specific motion between moving parts. It can provide free linear movement or free rotation around a fixed axis with the aim of minimize the friction force due to the relative movement. Bearings are much used when the mechanical system requires a very good precision and repeatability, or there is an high speed between the moving components. They are widely used in measuring system, working machine, like lathes, for light processing or guide systems for quality check.

Bearings can be classified in five different categories based on their working principles:

-Plain bearing, the simplest one, made by a bearing surface without a rolling element (e.g. shaft rotating into a hole). It's the simplest one and usually they allow a rotational movement between the moving components attached to it. Since kinetic friction is present, a lubricant film is required in order to not reach too high temperature;

-Rolling-element bearing, made by two bearing rings in relative motion with rolling elements placed between in order to minimize friction. The friction reduction is performed by the rolling elements placed in between the moving components. Differently from the previous one, the friction generated from these bearing is a rolling one and consent to not have a lubricant film;

-*Jewel bearing*, a plain bearing where one of the two surfaces is made of a very hard material to minimize friction and wear. Due to their higher cost, they are used where very high precision, very low friction and long life is required (e.g. mechanical watches);

-Fluid bearing, a non-contact bearing in which the two moving parts are separated by a thin layer of flowing liquid or gas. They are widely used because no friction is present between the moving parts, except for the friction due to viscosity of the fluid film. They also reduce wear and vibration;

-Magnetic bearing, where the load is supported by magnetic field. They are much used when a very high speed is needed for the mechanical system;

Figure 1: an example of a plain bearing (left) and a rolling-element bearing (right).

Fluid bearings, as well as magnetic ones, allow the moving parts not to be in contact. The thin layer of fluid in between grants the bearing to reduce friction, wear and vibrations and have a virtually infinite working life. They can be divided in two categories based on the way to pressurize the flowing fluid. In hydrostatic bearing the fluid is externally pressurized by a pump, while in hydrodynamic bearings, the high speed of the moving part pressurizes the fluid.

Fluid bearings are greatly used because they have a very low friction, a very high stiffness which can handle greater loads, can be implemented in very high-speed systems and are cheaper and quieter than most of the other bearings. Their main drawback is that they allow contact between the moving parts when they are still, as when the system starts moving. They are mainly used in soft working machine tools, measurement instruments or driving system for metrology.

Pneumatic bearing

A pneumatic bearing is made by a circular or rectangular plate, which air can flow into by means of holes. The supply hole feeds the bearing and exhausts through a hole situated under the plate. In this way air expands from the center of the plate to its borders where there is ambient pressure. Thus, the bearing is lifted by a thin layer of air, in the order of micrometers, usually between 5 and 20 µm. Since the air film flowing under the bearing is so thin, it's necessary to use filtered air, otherwise any impurity present in the air flow could obstruct the channels inside the bearing or even close them.

The thickness of the air film under the bearing depends much on the supply pressure which is fed through its supply hole. With a constant load, the higher the supply pressure fed to the bearing the higher the pressure generated under it and consequently the thicker the layer of air will be. Alternately, given a constant pressure supply, when the load is increased the air film under the bearing is thinner and the resistance to the air flow is increased.

The main features of a pneumatic bearings determining its behavior are:

- Lift [*N*]: it determines how much force a bearing can handle, it depends on the supply pressure, the pressure produced in the air film and the pressure value under the bottom surface;
- Stiffness [*N/µm*]: it defines the force required to have a change in the air film under the bearing of 1µm;

  $$k = \frac{\partial F}{\partial h}$$

  The stiffness of a bearing is not linear: it depends on the value of the air film and to a thinner film corresponds an higher stiffness
- Air consumption [*l/min* (ANR)*]:* it represents the amount of air under standard reference atmospheric conditions (ANR) exhausted by the bearing.

Figure 2: a rectangular base pneumatic bearing

How much a pneumatic bearing can lift depends on the pressure at which air flows out of it. Its lift also depends on how the pressure trend is shaped under the bearing. If the bearing is a circular one, the pressure distribution generated will be in the shape of a cone and its lift will be

$$P = p_b \pi r^2$$

with r representing the bearing radius and p_b the pressure at the center of the bottom surface.

When the bearing is a rectangular one, as it is in this work of thesis, the pressure distribution will be in the shape of a pyramid

$$P = p_b \frac{A}{3}$$

with A representing the bearing bottom surface.

The materials used for the making of bearings are usually steel or aluminum: steel is used when it is required that the mechanical system has an high stiffness, so when it is dealing with higher loads; aluminum is used when the system weight has to be taken into account. All the pneumatic bearing bottom surfaces are lapped. Lapping is a machining process used to reduce the roughness of a surface in the order of nanometers. By means of lapping, the surface roughness does not interfere much with the air flow.

In the bottom surface of a pneumatic bearing a micro groove process is usually made: it consists of one or more very thin groove which allows a more homogeneous distribution of pressure under the bearing. This process preventing eventual tilting of the bearing during it operation. Another common problem when dealing with pneumatic bearing is their possible deformation. Since the load is applied at the center of the bearing, it is possible to have a deflection at the edges of the bearing non-negligible with respect to the air film under them. This causes a lower resistance in the air flow exhaust which decreases the bearing stiffness. To overcome this problem, pneumatic bearing are usually made lightly convex. In this way the convexity of the bottom surface counteracts the deflection of the edges.

The consume of air of the bearing depends mainly on the rate between supply and exhaust pressure. The behavior of the air flowing through a convergent-divergent nozzle depends mainly on this rate:

- When $\frac{p_2}{P_1} > 0.528$, the air is in subsonic flow

$$G_T = Ap_1\sqrt{\frac{k}{k-1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{2}{k}} - \left(\frac{p_2}{p_1}\right)^{\frac{k+1}{k}}\right]\frac{2}{RT}}$$

-When $\frac{p_2}{P_1} \leq 0.528$, the air is in sonic flow and it is constant

$$G_T = Ap_1\sqrt{k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}\frac{1}{RT}}$$

with G_T air flowing out of the exhaust hole [kg/s], A area of the exhaust hole [mm^2], p_1 supply pressure, p_2 exhaust pressure, k coefficient for isentropic transformation (for air $k = 1{,}4$), R air constant ($R = 287\frac{J}{kg\ K}$) and T temperature [K] .

Since two formulas are used to calculate the air flow depending on the rate of the supply and exhaust pressure, there are two regions in the air flow-pressure rate graph as shown in Figure 3: in the region of subsonic flow, the air flow increases from zero, when the exhaust pressure is equal to the supply pressure so the pressure rate is equal to unity, to a maximum value when the pressure rate reaches the critical ratio, which is equal to 0,528 when dealing with air; when the pressure rate is between zero and the critical rate, the air flow is in the region of sonic flow, where the air flow is constant and equal to its maximum value.

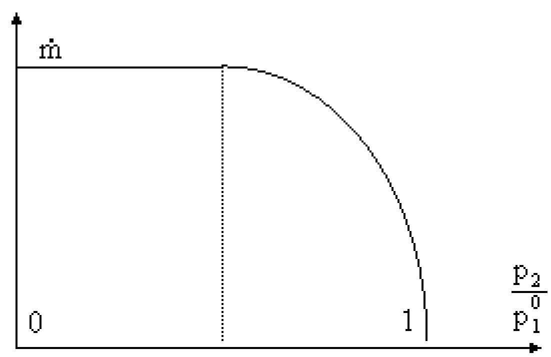


Figure 3: Pressure rate air flow graph for a convergent divergent nozzle. It is possible to see the region of sonic flow (at the left) and subsonic flow (at the right).

These formulas are valid for a convergent-divergent nozzle, so a nozzle with a not constant section, but hourglass shaped. In pneumatic bearings, the exhaust hole is cylindrical shaped for practical reasons and the air process is no more isentropic. Thus, the air flow must be corrected by a flow coefficient C_D, with a value usually around 0.8 and 0.85:

$$G = G_T C_D$$

From the precedent work of thesis about pneumatic bearing, it has been proved that, since the air film under the bearing is very thin, the flow coefficient depends also on Reynolds and Mach numbers.

Pneumatic bearing usage

Pneumatic bearings are widely used in many fields, like automotive, aerospace, textile, etc., where movement and precision are required to be very accurate. Since there is no contact between the moving parts of the bearing, friction forces are very much reduced thus implying:

- Lower forces needed for the movement of the components attached to the bearing;
- Less deterioration of the bearing which extends the bearing working life;
- No maintenance is required for the bearing itself (the supply and refrigeration systems may still need some maintenance);
- Low temperatures during use since friction is reduced, also mitigated by the air flow;
- No stick-slip phenomenon, due basically to the change of friction coefficient from static to dynamic.

Thanks to this properties, pneumatic bearings allow to reach higher precision and repeatability in positioning systems or higher rotation speed for rotors. In working machines, like loathes, it is possible to reach better surface roughness. The downside is that the lift of a pneumatic bearing is usually lower with respect to the other typology of bearings. If extraordinary very high pressure supply systems are not used, the lift is very limited basically because of the compressibility of the air. Thus, they can be used for low power applications and, considering the higher costs for precision and installation, only on a lower scale.

Active Pneumatic bearing

What is needed to make a passive bearing an active bearing is the implementation of a control system. For those application that needs an high precision in positioning it is required that the thickness of the air film under the bearing remains constant independently from the force applied. In order to do so, it is necessary to be able to modify the supply conditions of the bearing. A closed loop control system is able to do it: a component measuring the thickness of the air film acts as a feedback element and sends this information to the control system, which evaluates the error and computes the control signal in order to decrease it. In this way, even when the load applied to the bearing changes, the control system is able to respond by modifying the control signal properly.

The use of an active bearing is recommended for Coordinated measuring machines (CMM) where it is mandatory that the precision in positioning is as high as possible. The need to keep the air film thickness, and so the height of the bearing, as constant as possible is to reduce the errors in the measurement and positioning, and for the repeatability of the working, for example, for working machines.

Test bench

The test bench used for the experimental test of this work of thesis is shown in Figure 4. It is basically a press where the force is controlled by the rotation of the wheel placed above. By rotating the wheel, it is generated a linear movement, upwards or downwards thus increasing or decreasing the force applied to the bearing.

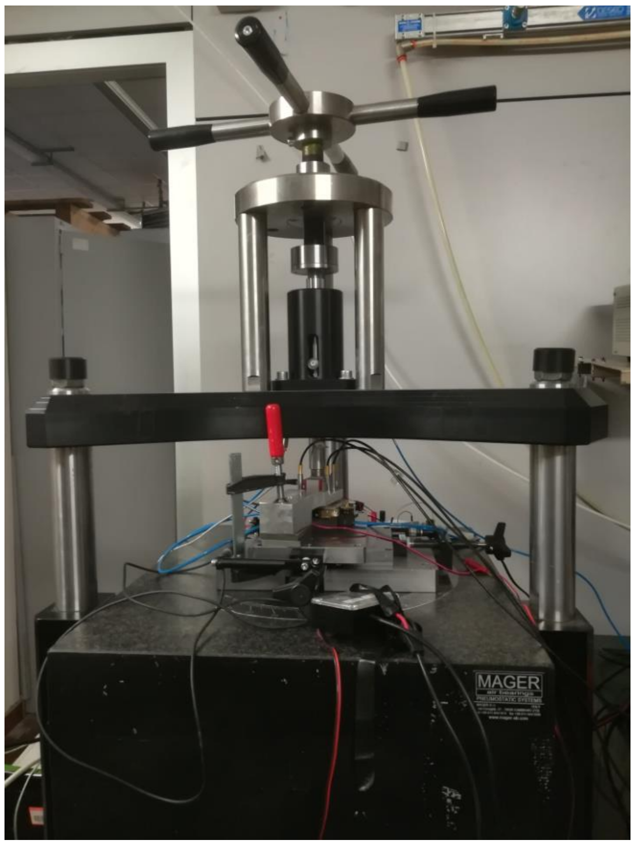


Figure 4: test bench used for experimental tests

As better shown in Figure 5, between the screw shaft of the press, which performs the linear movement, and the bearing, it is placed a load cell to evaluate the measure of the generated force. Also, between the load cell and the bearing, there is a steel sphere used to automatically align the generated force to the vertical axis so that the force applied is vertical. Under the bearing, it is present a steel plate where the bearing lies on and above which the air will flow during the test. The steel plate is placed above a granite block in order to reduce the bench compression and vibration. Since the value of the air film measured during the tests is in the order of micrometers, it is mandatory to have both the bottom surface of the bearing and the steel plate cleaned so that the air can flow freely. The thickness of the air film is measured with the use of capacitive sensors, which measure the capacitance between them and the steel plate placed above the bearing and convert it into a voltage. The air consumption is measured with both an analog and a digital flowmeter placed before the inlet of the pneumatic valve.

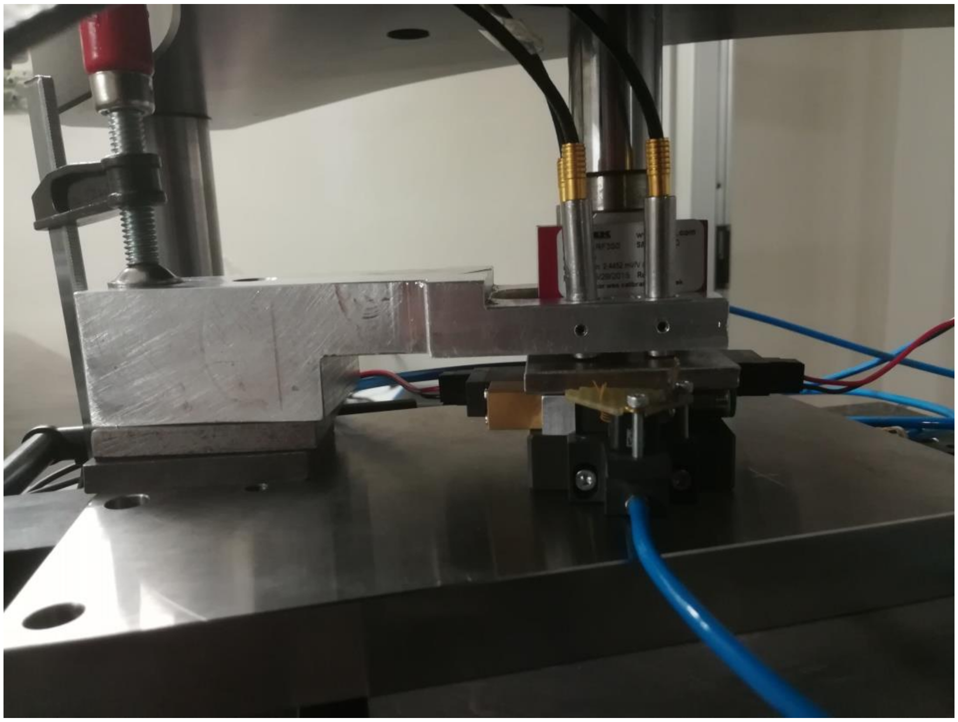


Figure 5: test bench zoomed on the pneumatic bearing and sensor carrier

Capacitive sensors

To read the value of the air film generated under the bearing three capacitive sensors have been used. With three measure of the air film it is possible to have a good evaluation by doing the average of them. Also, if analyzed independently, it is possible to know if the bearing is tilting along its width or length. The capacitive sensors used for these measures are capaNCDT 6019 S600 (Capacitive Non-contact Displacement Transducer). They can measure a distance up to 0,5*mm* with a resolution of less than 0.01% FSO (Full scale output). The operating principle of non-contact capacitive displacement measurement is based on the parallel plate capacitor, as shown in Figure 6.

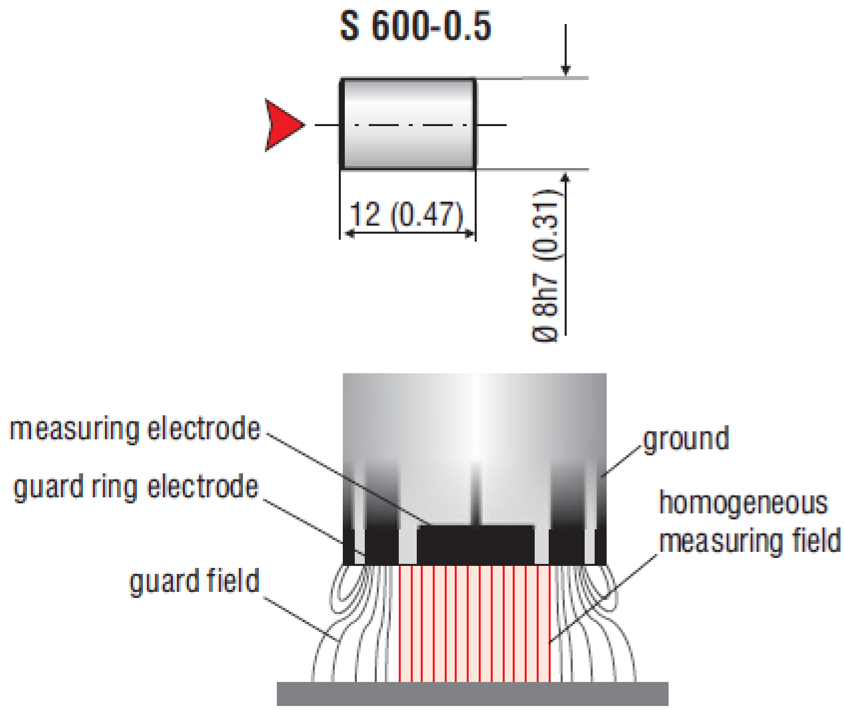


Figure 6: draft of the micro-epsilon sensor (above) and measuring principle (below)

The measurement of the distance between the sensors and the bearing is an analog voltage from 0 to 10 Volts which is converted into a distance from 0 to 500 micrometers. When a constant amplitude AC current flows through the sensor capacitor, then the amplitude of the AC current of the sensor is proportional to the distance between the two electrically conductive plates. A steel plate has to be mounted on the upper surface of the bearing so that no calibration is needed for the sensors. The steel plate, designed with the use of SolidWorks and produced in the mechanical laboratory, is shown in figure 7.

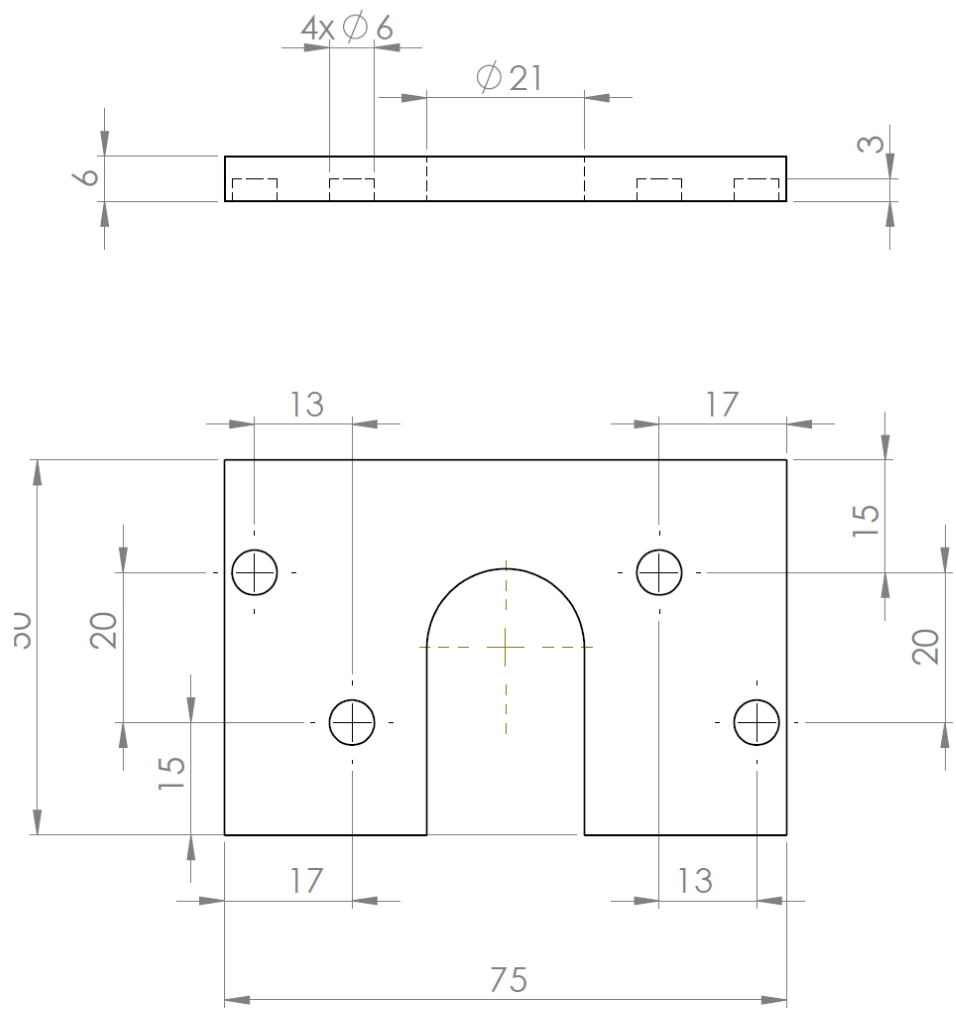


Figure 7: the draft of the steel plate mounted on the pneumatic bearing

The steel plate presents 4 holes which to adapts to the screws present on the upper surface of the bearing and it is been glued to the bearing in order to have a very precise measure of the air film during the experimental tests.

The sensors are kept in position by a steel sensor carrier attached to the test bench with the use of a clamp. For a correct measure it is needed that the clamp is held strongly so that the sensor position is constant with respect to the steel plate. The measure of the sensors, when the bearing is not supplied and there is no force applied to it, is the reference value. Then all the consequent measures are modified with respect to that initial measure.

The capacitive sensors voltage outputs are connected via a preamplifier module to a signal conditioning electronics system, capaNCDT 600. For each signal there is a demodulator module which demodulates the signal to extract the informations.

Flowmeters

In order to measure the value of the air flowing through the valve and inside and under the bearing, two different types of flowmeters have been used, one analog and one digital.

The analog one is the L742-11501, shown in Figure 8, which can measure the air flow from 0.3338 to 7.6753 *l/min* STP (Standard temperature and Pressure). It is composed by a glass pipe with a mobile conic element inside it. The air flow enters the pipe from the bottom hole and exits from the upper one. When the air is flowing through the flowmeter, the conic element will be lifted upwards. If the supply pressure is the ambient pressure, then the value of the air flow can be read directly on the flowmeter, but, if the supply is not at ambient pressure, it is necessary to convert the millimeters at which the conic element is lifted. After that, with the use of a MATLAB script, the value in millimeters is corrected accordingly to the supply pressure and the real value of the air flow is obtained.

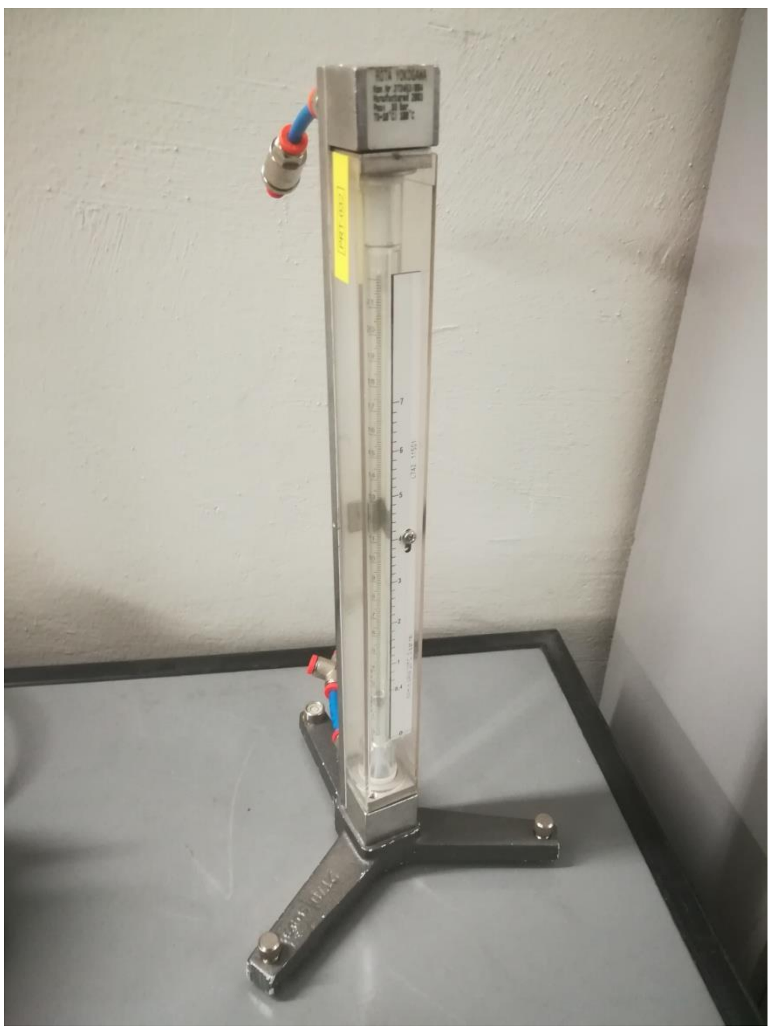


Figure 8: L742 – 11051 flowmeter

The digital flowmeter used is the SFAB-10U-WQ6-2SV-M12, shown in figure 9. The value of the air flowing trough it is automatically computed and shown on its display. It also has an analog output to deliver the measured signal to the PC for a better data analysis. It doesn't need to know the supply pressure, but it must be properly installed: the air flowing through it must be in a specific direction according to an arrow drawn on its lateral surface.

Figure 9: SFAB-10U-WQ6-2SV-M12 flowmeter

Load cell

The load cell used to measure the force applied over the pneumatic bearing is the FUTEK LRF350, shown in figure 10. It is an extensometer whose working principle is based on the Wheatstone bridge. The output of the cell is a tension proportional to the value of the force applied, both in tension and compression.

Figure 10: FUTEK LRF350 load cell

A test has been executed to evaluate the correct calibration of the cell. Some masses, which weight is known, have been loaded sequentially in order to see if the output of the load cell corresponds to the weight applied to it. The results of the weight test are proposed in figure 11. The first value obtained is the cell output with no load applied, which corresponds to the offset of the measure. Then it has been loaded with a weight holder, weighing 1,13kg. Then weights of 5kg have been loaded subsequently to evaluate the correct output given by the load cell.

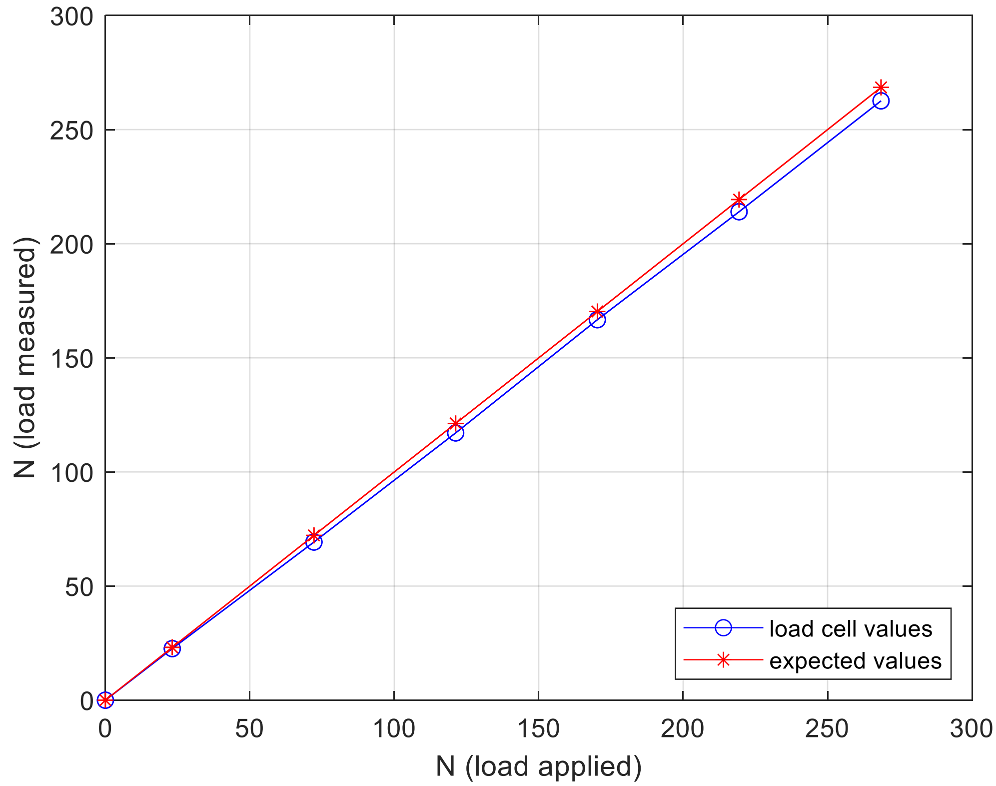


Figure 11: Weight test

The graph shows that the calibration of the cell is not needed since the value given by the load cell represent accurately what is the real weight applied.

Counterpressure sensor

The counter pressure sensor, or proximity sensor, is the component used to evaluate the air film thickness generated under the bearing and permits to close the control loop. Generally, it can compute the distance between two objects without the need of contact between them and, since there are no moving part in it and it has a very short response time, it is very adapt to this particular system. The general scheme of a counterpressure sensor is shown in figure 12.

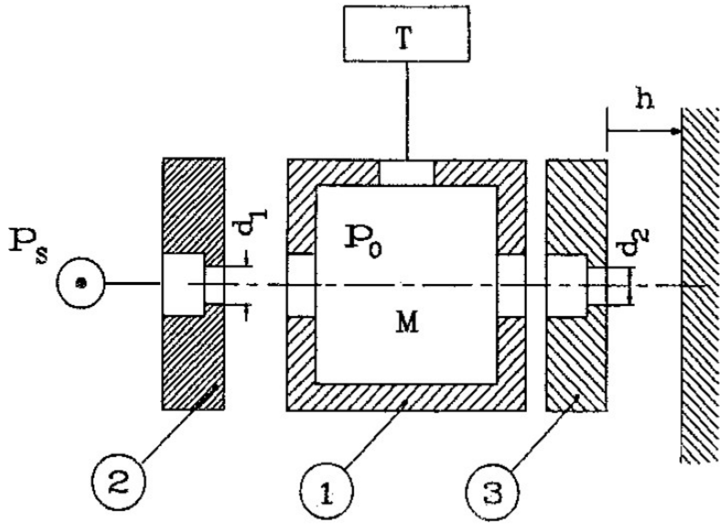


Figure 12: counterpressure sensor scheme

The counterpressure sensor is composed into three parts. The airflow, coming from the source P_S with a certain pressure, enters the first component (2) through a hole with the diameter d_1 and subsequently into the measure chamber (1). After that it flows out through the last component (3) through the hole with diameter d_2 into the ambient.

Since there are no moving components, the pressure inside the measure chamber (1) depends on the variable resistance between the last component (3) and the object which distance is to be measured. The variable resistance depends on the distance between the object and the sensor and therefore, from the value of the pressure inside the measure chamber it is possible to compute the distance value. The other two holes are also pneumatic resistance and the measure chamber is a pneumatic capacitance, but since they are fixed components, their values are constant and does not affect the measure.

The two range limits of this sensor are when the object which distance is to be measured is adherent to the sensor and when it is far away. When the object, in this case the bench surface, is adherent to the sensor, the pneumatic resistance value goes to infinite and the pressure inside the measure chamber is equal to the pressure of the source. When the object is far away from the sensor, the pneumatic resistance value goes to zero.

Pressure transducer

Since the measure of the air film thickness is managed by counterpressure sensors, it is needed to use pressure transducer in order to convert their pressure output into a voltage. By doing so, the voltage from the pressure transducer can be sent to the electronic board to close the control loop. The pressure transducer used in this work of thesis is the 40PC150G by Honeywell and it is shown in figure 13.

Figure 13: 40PC150G by Honeywell

The pressure coming from the counterpressure sensors enters the measuring chamber of the pressure transducer. An elastic membrane is present and, according to the inlet pressure, is deformed. This deformation, with the use of a Wheatstone bridge, is converted into a voltage which is sent to the output pin of the component. Since these transducers are powered at 5V, their output ranges from 0 to 5V ideally. Later on this work of thesis it is shown the test for the calibration of this sensors which shows that their actual range is from about 0,5 to 4,5V when the inlet pressure ranges from 0 to 10 relative bar.

Pneumatic valve

The pneumatic valve used in this work is the PVQ10 by SMC. It is a small size pure proportional pneumatic solenoid valve current control normally closed. The choice of the use of this valve is determined by the results of the precedent work of thesis done on this particular pneumatic bearing. The valve used was digital electrovalve whose working principle was similar to the new one but were not pure proportional valve. They can work only in two configurations, ON or OFF, and because of this, a PWM control was necessary to have a proportional air flow through them.

This type of control led to oscillations when a constant reference signal different from maximum or minimum value is imposed. This oscillation vibrates with a frequency equal to the frequency of the PWM signal. To overcome this problem, it has been decided to use pure proportional pneumatic solenoid valve. This type of pneumatic valve can output an airflow proportionally to the current input signal. The proportional valve is shown in figure 14.

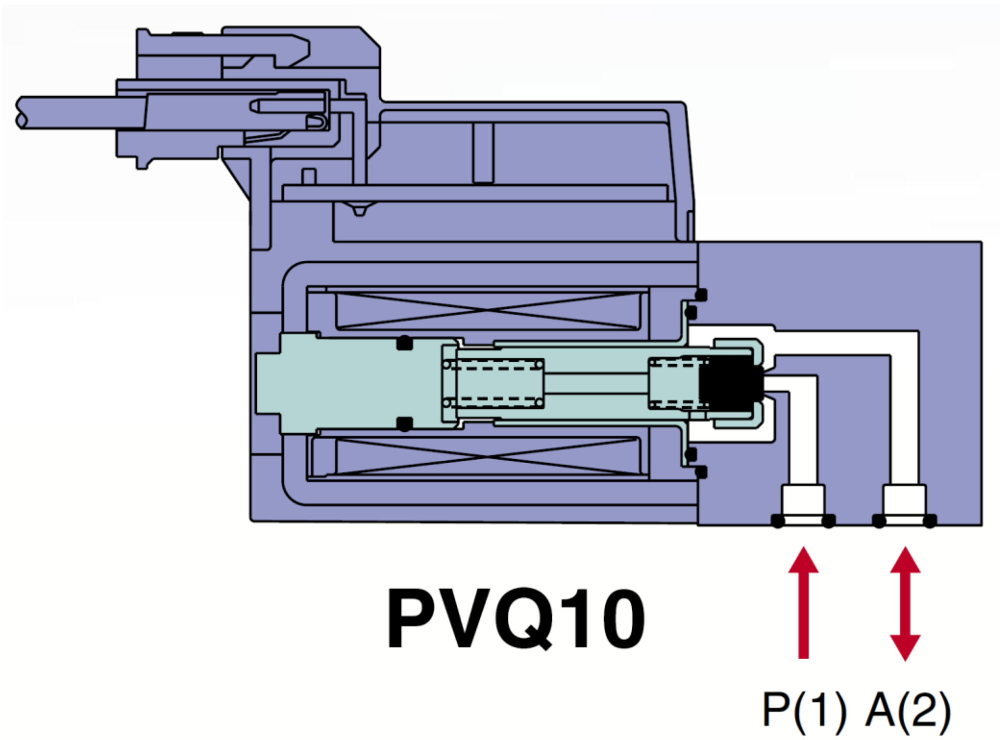


Figure 14: draft of the PVQ10 proportional valve

The valve is current controlled through a current driver not given by the SMC but designed in the laboratory. It is a normally closed valve and the armature, the component in green, is kept in position with the use of a spring. When the valve is energized, the current flows through the solenoid which creates a magnetic force on the armature and, when this force overcomes the spring force, lifts the armature allowing the air to flow through. The higher the current flowing through the coil, the greater will be the stroke of the armature and more air is able to flow. The flow rate can be controlled smoothly with a current control managing the valve. With this kind of valve, it is possible to have a more constant airflow without the oscillation due to the PWM control. The only drawback with respect to a digital electrovalve is that the dynamic response will be slower. This can lead to longer time response of the system when the airflow imposed is changing. The particular valve chosen for this work of thesis is the one with the orifice size of 0,3mm able to let an airflow up to 5L/min [ANR] operating at a maximum pressure of 0,7MPa. The flow characteristic of the valve is shown in figure 15.

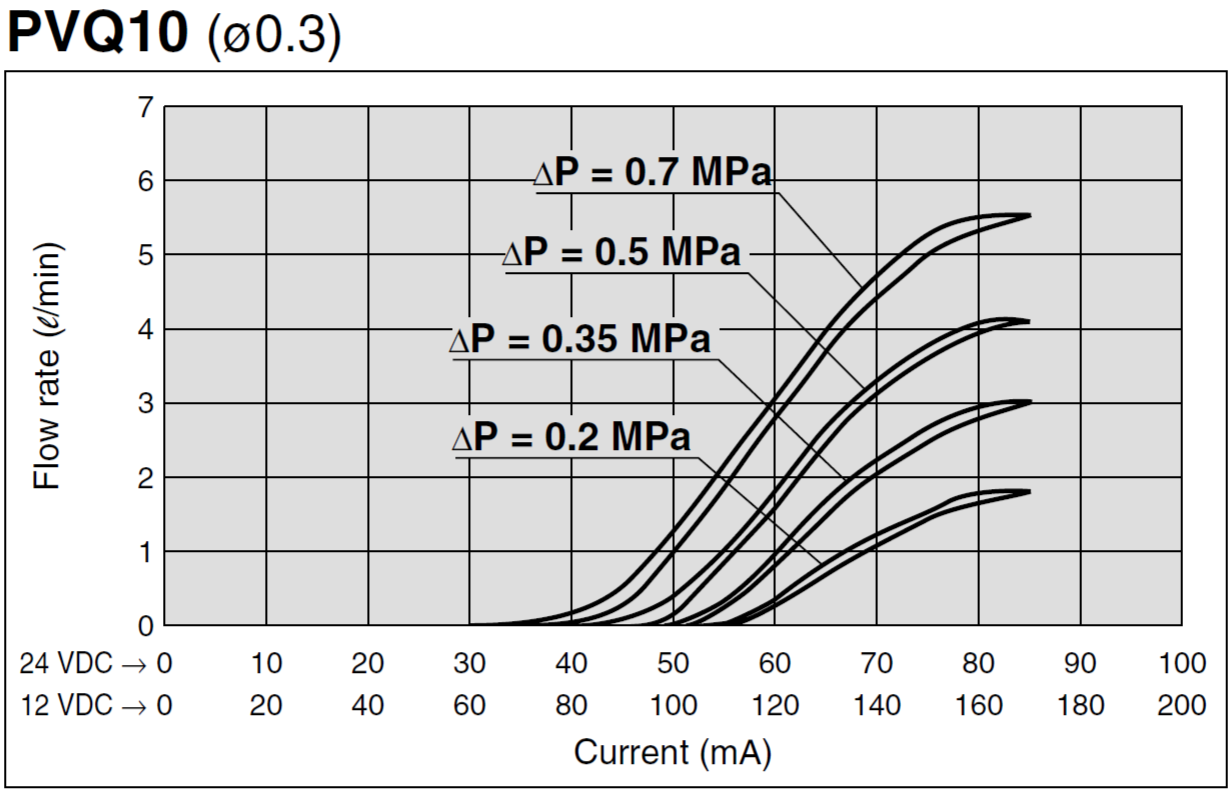


Figure 15: flow characteristic of the PVQ10 valve with the orifice of 0,3mm

The valve needs to be current controlled from 0 to 85mA with up to a voltage of 24VDC. In order to do so, a current drive circuit has been designed and made which converts a proportional voltage coming from the electronic board into a proportional current flowing through the solenoid of the valve

Acquisition system

The signals coming from the capacitive sensors, the digital flowmeter and the load cell are sent to a multifunction data acquisition system, BNC-2120 made by National Instruments, which is connected to the PC. With the use of LabView all the signal coming from the sensors are analyzed and plotted in the graph diagram. The signals are also saved into a text file for a better graph generation on MATLAB.

Control circuit design

Electronic board

In order to deliver the current signal to the proportional pneumatic valve and to evaluate the measure of the air film under the bearing, an electronic board is needed. The command signal, that is to be delivered to the control circuit, must be a pure proportional signal because, as explained before, it will be not used the PWM method as it will bring oscillation on the system. With these considerations, the electronic board used for this system must have a digital-to-analog converter integrated (DAC) so that it can creates a pure proportional voltage. The electronic board chosen is the Whatsnext Orange and is shown in figure 16.

Figure N: Whatsnext Orange electronic board

The Whatsnext Orange board is the analog of the Arduino Due and run on the same software. It can be programmed with the C/C++ language by using the Arduino software and the sketch deployed on the board is divided into two section: the *void set up*, run at first execution of the program, which contains the basic settings to be configured, and the *void loop*, where there is the code to be executed in loop after the void set up has finished. Alternatively to writing the code by hands, on the Mathworks website there are two tools that makes the generation of the code for Arduino boards take less time, which are *MATLAB support package for Arduino hardware* and *Simulink support package for Arduino hardware*. By using these two tools, it is possible to create a MATLAB script or a Simulink block scheme and converts it into the files needed for the Arduino hardware to run.

The choice for the use of this board is justified by the presence of two DAC analog output pins. These pins are able to provide a true analog output ranging from 0.55 to 2.75V with a 12-bit resolution (4096 levels corresponding to a resolution of 0.54mV). With these pins it is possible to have a proportional voltage signal able to command the opening of the pneumatic valve.

Current driver circuit

Since the proportional valve need to be current controlled, it must be designed a control circuit which can deliver current proportionally to the control signal from the What's Next board. Any signal coming from the electronic board is a voltage signal which must be turned into a current and fed to the valve. Then a transconductance circuit must be designed.

A transconductance amplifier, also called VCCS (voltage-controlled current source), is a circuit where to an input voltage corresponds an output current. Only few components are needed: an operational amplifier and two resistors, one of which is the load. As shown in figure 17, the input voltage is fed directly into the non-inverting pin of the amplifier, the resistor R1 is connected in series with the load resistor R2 and its voltage is fed back to the amplifier. With a circuit like this the amplifier output is independent from the load, as long as it has enough power to deliver, but depends only on the input voltage and the resistor R1.

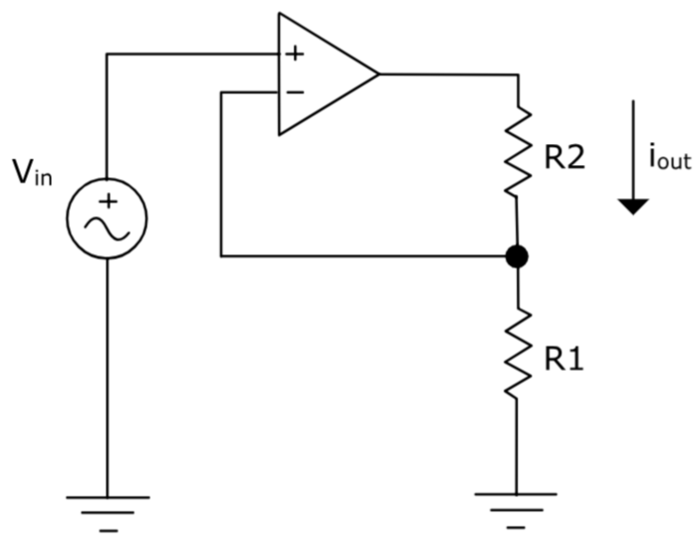


Figure 17: transconductance circuit

Considering an ideal operational amplifier, the current flowing through the R1 resistor will be

$$I_{R1} = \frac{V_{in}}{R1}$$

and, considering that no current flows through inverting and non-inverting pin in ideal operations, the current flowing through R1 is the same as the one flowing through R2

$$I_{R1} = I_{R2}$$

Therefore, the current imposed to be flowing through the load depends only on the input voltage and the resistor R1

$$I_{out} = \frac{V_{in}}{I_{R1}}$$

The electrical conductance of an object, which can be an electrical component or a circuit, is a measure of the ease with which an electric current flow and it is measured in siemens (S). So this circuit is a transconductance amplifier because the ratio between the output, I_{out} , and the input, V_{in} , is the inverse of a resistance, a conductance. It can also be considered as an independent current source. This circuit is very similar to the non-inverting amplifier circuit. The only difference is that, instead of having the load connected between the operational amplifier output and ground, is placed between the amplifier output and its non-inverting pin. Also, since that the output of the circuit is a current, the load is necessary for the circuit to work properly. These considerations shows how versatile are these components: in a more complex circuit, despite they just work as simple comparators, the behavior is dependent on the components connected to them and where they are placed.

This circuit, despite its simplicity, it's not good for a current drive. The valve needs to be supplied up to with 24Vdc and 85mA. Most operational amplifier can supply 24V voltage, but few can deliver such a current, and comes with higher cost. Also, the load itself is a solenoid, which is an inductor, and when a varying current flows through it, a voltage is induced across it. This is not a problem during the normal operation, but becomes critical when the system is turned off. If 100mA is flowing through the solenoid and the supply is turned off, a very large negative voltage is induced across the solenoid which could probably damage the circuit. But most important is that when designing control circuits, the signal and the power part of the circuit are usually separated. This is to prevent that any high signal, voltage or current, could damage the device used to deliver control signals.

The first modification to the circuit proposed before is to detach the power part from the control part. With this consideration, the signal coming from the operational amplifier must not be the power signal fed to the valve. It must be a control signal that, with a proper electrical component, commands the current flowing through the solenoid. In order to do so a transistor must be used, as shown in figure 18. As the previous circuit, the signal V_{IN} coming from the electronic board is fed directly to the amplifier and the feedback resistor, connected to the non-inverting pin, is placed between the valve solenoid and ground. The difference is that the amplifier output is fed to the base gate of the transistor which, if considered as a proportional switch, regulates the current flowing in between the other two gates, collector and emitter.

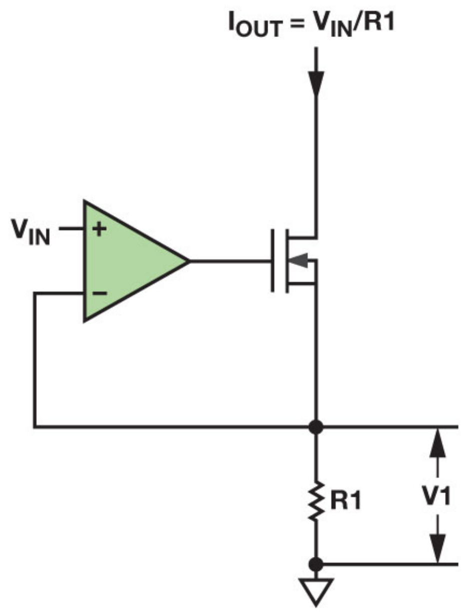


Figure 18: first modification to initial circuit. The control part, the input signal, is detached from the power part, managed by the NPN transistor, and interfaced with the operational amplifier. Modify image

This first modification to the control circuit let the amplifier work with lower values of voltage and current on its output. This let possible to supply it with a weaker power supply. However other possible problems could occur. A fault in the internal components of the operational amplifier could bring a large voltage or current to the pins of the electronic board burning them. Also, the problem of the switch off of the valve is still not resolved.

Then a more complex circuit is designed to drive the current through the load, shown in figure 19. More components are needed to improve performance and prevent troubles. Here the signal and the power part of the circuit are separated and possible fault to electrical components are taken into account.

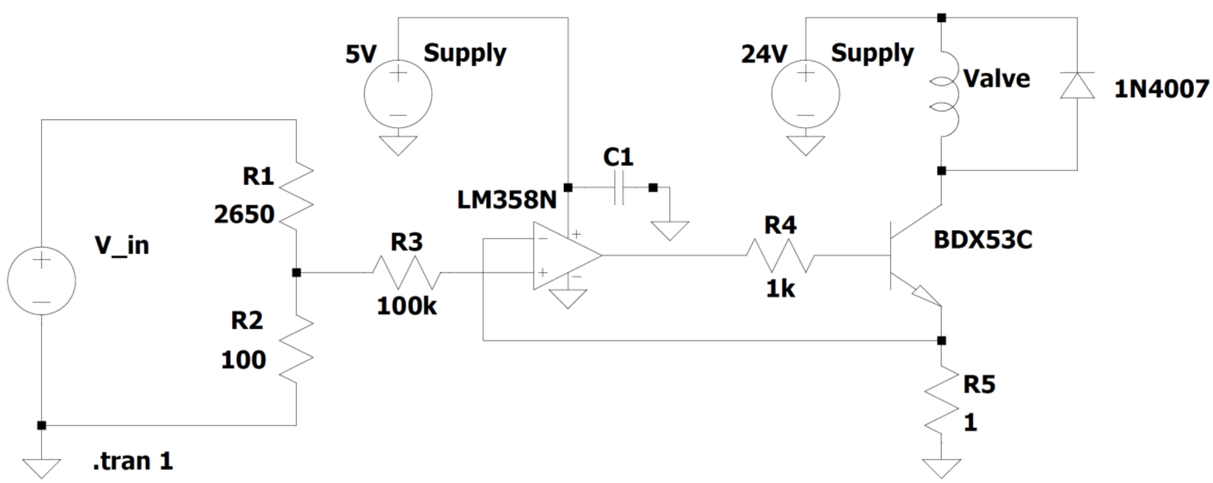


Figure 19: control circuit

The signal coming from the board is driven into a voltage divider which converts it into a smaller signal with a very small current needed from the board. The highest voltage given from the DAC pin is 2.75V which corresponds to 1mA flowing into the voltage divider and 100mV across the R2 resistor. The voltage across R2 is fed into the non-inverting pin of the operational amplifier through a 100KΩ resistor. Since a very little current flows through the input pins of the amplifier, the voltage drop across the 100KΩ resistor is negligible. The purpose of this resistor is to prevent that a fault in the amplifier could bring an high voltage at the non-inverting pin, corresponding to an high current flowing through the board and possible damages to it.

Considering ideal components, in the voltage divider the current flowing is

$$I = \frac{V_{in}}{R_1 + R_2}$$

With the assumption of ideal components, no current flows into the non-inverting pin of the operational amplifier and the voltage input to the op-amp is the voltage across R_2

$$V_+ = V_{R_2} = I * R_2$$

The operational amplifier compares the voltage from the voltage divider with the voltage coming from the R5 resistor, where the valve current flows through, and deliver the output at the base terminal of the transistor through a 1kΩ resistor. This resistor is used to reduce the current delivered by the amplifier. With a circuit like this the operational amplifier doesn't have to deliver the 24V requested by the valve, so it's been supplied with 5V. A bypass capacitor is connected in parallel with the supply to prevent that any oscillation on the supply line. In fact, the cable used to connect the amplifier with its supply is long enough to let possible voltage oscillation over its length, thus modifying the amplifier output and compromising the circuit behavior. A capacitor of 0.1µF is used and has been placed as close as possible to the amplifier to improve its function as more as possible.

The operational amplifier output is driven into the base terminal of the transistor thus controlling the current flowing through the emitter and collector terminals. The transistor works as a proportional switch and the more current flows through its base, the more current is allowed to flow through the other two terminals. The same current, using the R5 resistor, is fed back to the amplifier in order to have a good control over it. Another possible configuration is to put the transistor between the 24V supply and the valve and diode subcircuit. The behavior is unaffected, but in this way the operational amplifier has to deliver an output voltage up to the voltage needed for the nominal value of the valve, approximately 24V, thus requesting more power to work. Placing the transistor under the valve and diode subcircuit allows to supply the operational amplifier with a lower voltage without a change in the circuit behavior.

Eventually a flyback diode is placed in parallel with the valve. In normal operations, it acts as an open circuit and doesn't affect the behavior of the circuit. But when the system is turned off, while for example all the 24V are supplied to the valve (transistor fully open), the valve, acting as an inductor, will generate an high negative voltage with the risk of damaging the transistor. When such a situation happens, the flyback diode becomes a short circuit thus discharging the high voltage.

Electrical components

Operational Amplifier

An operational amplifier is an electronic amplifier where a differential input is amplified through its output. An op-amp can output a voltage even hundreds of thousands of times higher than the differential voltage imposed at its inputs, thus allowing to control a high-power signal with a very low one. They are widely used in analog electronics due to their versatility. In fact, the operational amplifier characteristics, like gain, output impedance, input impedance, bandwidth etc., are determined not only by the op-amp itself, but also by the external components connected to it with the use of the negative feedback.

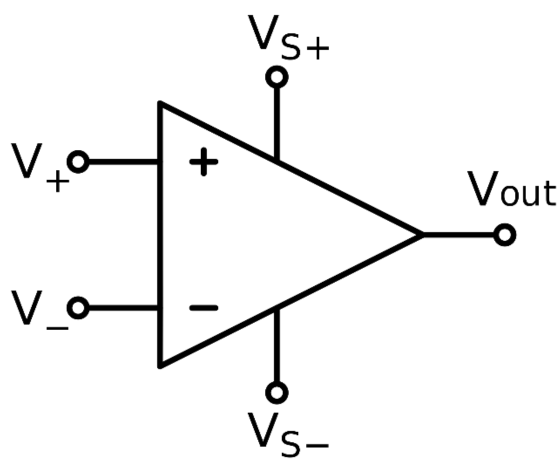


Figure 20: operational amplifier and its terminal: V+ non-inverting input, V- inverting input, Vs+ positive supply, Vs- negative supply, Vout, amplifier output.

The operational amplifier compares the differential voltage between its inputs and amplifies through its output according to its gain. The output voltage is given by the equation

$$V_{out} = A_{OL}(V_+ - V_-)$$

where A_{OL} is the open-loop gain of the amplifier.

The value of A_{OL} is usually very high and it is used when the op-amp is used in open-loop. In this way it works as a simple comparator, in example when it is needed to evaluate if a signal is present on the non-inverting pin. Using feedback element, the closed-loop gain value is much lower and depends on the value of the components used. Thank to these elements, the operational amplifier output value is automatically set in order to balance the voltage on its input pins. In ideal op-amps the voltage difference between the inverting pin and the non-inverting pin must be zero. In real op-amp a differential voltage offset is always present, as specified in the datasheet of the amplifier, and depends on the internal components and how they are placed.

The operational amplifier used in this work of thesis is the LM358N. it is a very common amplifier, commonly used for standard circuit. It can be power supplied up to a voltage of 32V (±16V) with a consume of very low current, about 500µA. It can be single-supplied, which is required in this work. In fact, the valve opens proportionally according to the current flowing through the solenoid and closes when the current value is above the start-up current, thus it does not need to be inverted.

Bipolar junction transistor

A bipolar junction transistor (BJT) is a transistor widely used in analog electronic as amplifier or switch. It is made of three layer of doped semiconductor material, usually silicon, forming two p-n junctions. In a PNP transistor, two layers are positively doped and one negatively, in an NPN the opposite. Each layer is a terminal of the transistor and they are called emitter, collector and base, which is located in between. The working principle of BJTs is that a small change in voltage, or current, between the base and the emitter terminals produces a great variation of current between the emitter and the collector. Thus, they can be thought as voltage-controlled current source or current-controlled current source.

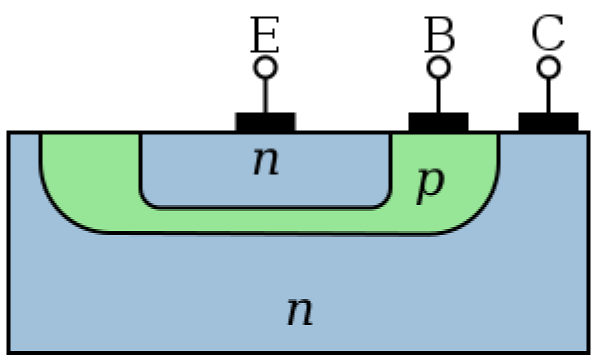


Figure 21: simple transistor scheme evidencing the three N-P layer which is made of

In normal operation, in an NPN transistor the junction between base and emitter is forward-biased (the positively doped terminal is at a higher positive potential than the negatively doped one), while the junction between base and collector is reverse-biased. In this way, when a positive voltage is applied at the base-emitter junction, electrons will flow from the emitter to the base and consequentially to the collector. That means a small current flowing into the base is amplified into a large current flowing from emitter to collector. Transistor's base layer is made very thin to minimize the recombination of charge carriers before they reach the collector-base junction. To let a current flow from the emitter to the collector, V_{BE} must be higher than a minimum value called cut-in voltage. The current flowing from the emitter will be the sum of the currents flowing into the base and the collector.

$$I_E = I_B + I_C$$

The ratio of current flowing to the collector from the emitter is called common base current gain, α_F, which value is very close to unity, and the ratio of DC collector current to the DC base current is called DC current gain, h_{FE}, which is usually very high.

$$\alpha_F = \frac{I_C}{I_E}$$

$$h_{FE} = \frac{I_C}{I_B}$$

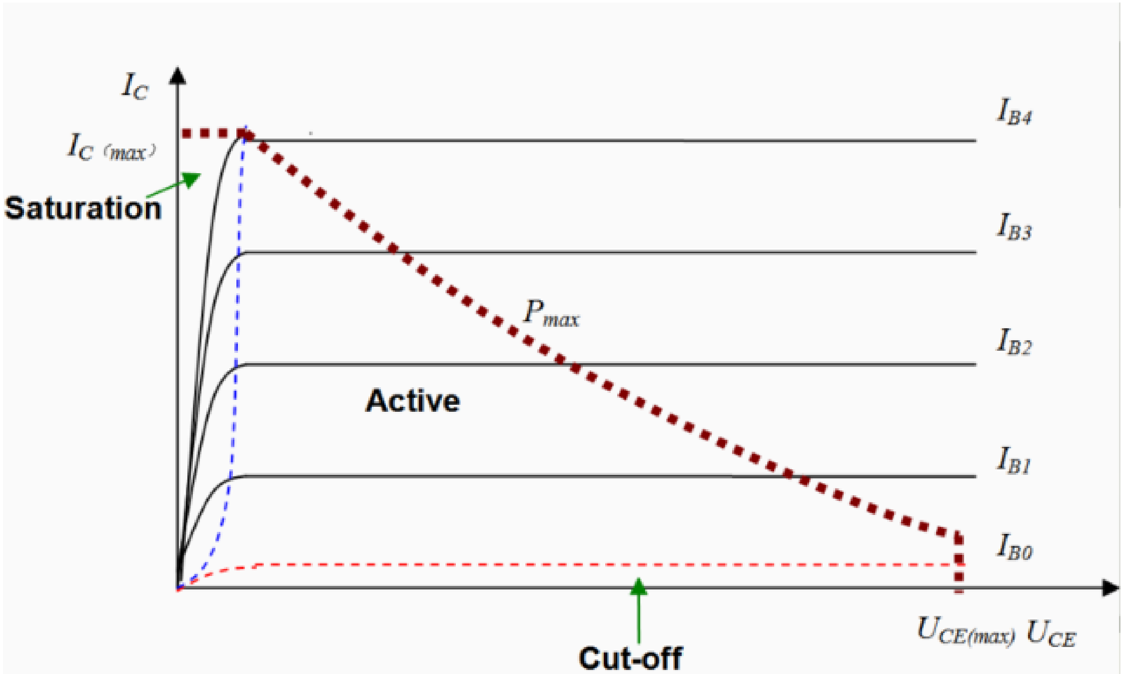
Depending on BJT junction biases, there are four working regions:

-Forward-active: the base-emitter junction is forward biased and the base-collector junction is reverse biased. The current flowing from the emitter to the collector is proportional to the base current and amplified by the DC current gain, which is made very high by design.

-Reverse-active: inverting the biasing of the forward-active mode, the emitter acts as the collector and the collector act as the emitter. Because of the BJT design, in this condition the current gain is lower than in forward mode.

-Saturation: when both junctions are forward biased the transistor is in saturation and it acts like a closed switch.

-Cutoff: when both junctions are reverse biased and acts like an open switch.



Junction type	Applied voltages	Junction bias		Mode
		B-E	B-C	
NPN	E < B < C	Forward	Reverse	Forward-active
	E < B > C	Forward	Forward	Saturation
	E > B < C	Reverse	Reverse	Cut-off
	E > B > C	Reverse	Forward	Reverse-active
PNP	E < B < C	Reverse	Forward	Reverse-active
	E < B > C	Reverse	Reverse	Cut-off
	E > B < C	Forward	Forward	Saturation
	E > B > C	Forward	Reverse	Forward-active

Figure 22: the graph showing the dependence of the collector current and the voltage across the collector-emitter junction with different values of base current (above) and the behavior of the NPN or PNP transistor dependent on the voltage present on its three junction (below)

The transistor used in this work of thesis is the BDX53C. It's a complementary power Darlington transistor with a good DC current gain, h_{FE}, and an high cutting frequency, f_t. It can bear a maximum collector current, I_C, up to 8A and a collector-emitter voltage, V_{CE}, up to 100V. For these components, usually a safe coefficient of two is considered for the maximum nominal voltage and current. It can be seen that, with this particular transistor, a much higher safe coefficient makes these components adapt for its use and even over-designed.

Diode

A diode is a two-terminal electrical component that allows the current flow in one direction and blocks in the opposite direction. An ideal diode can be considered as a variable resistor: in one direction, it has an ideally zero resistance and acts as a short-circuit, not influencing the current flow; in the opposite direction, it has an ideally infinite resistance and acts as an open circuit, thus not allowing the current to flow. The electrical symbol and an example of a diode are shown in figure 23.

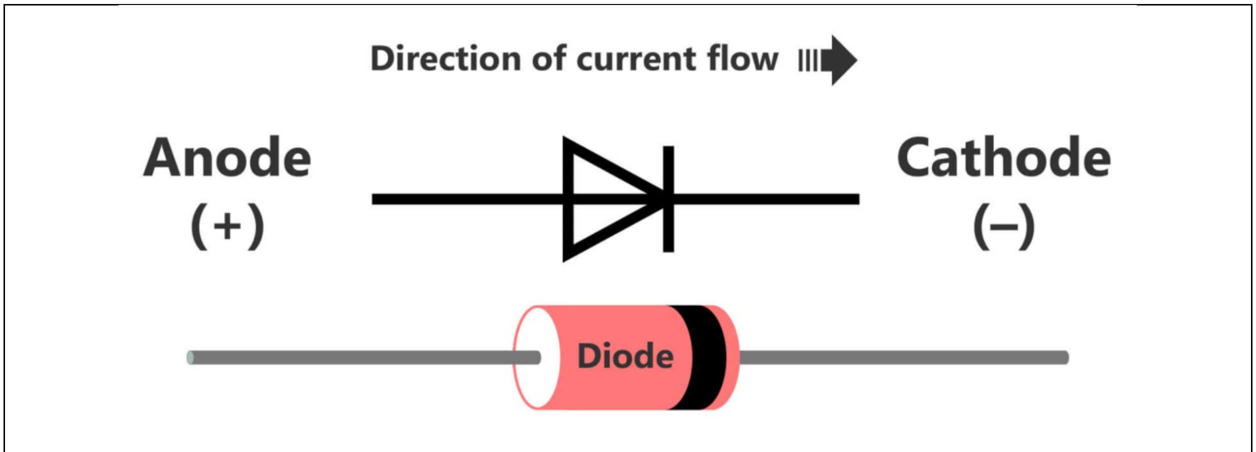


Figure 23: the electrical symbol of a diode (above) and a representation of a real one (below)

As shown in the figure, the current is allowed to flow only in one direction, the direction of the arrow of the electrical symbol. If the current would flow in the opposite direction, the diode prevents the current flow. Considering a real diode, the current is not able to flow in the opposite direction until the voltage across the diode reaches the diode reverse voltage given in the datasheet. When this voltage value is reached, the diode is not anymore able to prevent the current flow and it is likely to be damaged.

A flyback diode, also known as kickback diode, is a diode connected in parallel with an inductive load as shown in figure 24, and it is used to mitigate the phenomenon of the flyback: when the supply current is rapidly interrupted or reduced, a voltage spike rises across the inductor in the opposite direction of the voltage supply, which can cause damages to the other element of the circuit.

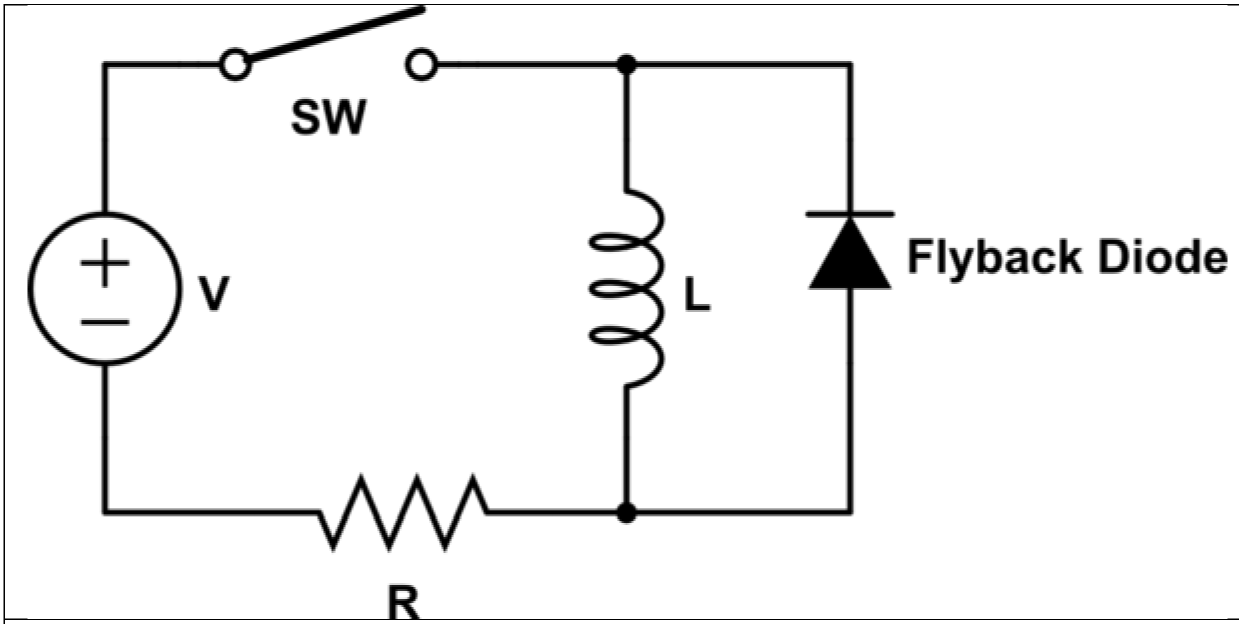


Figure 24: correct connection of a flyback diode with an inductive load

If a diode is connected in parallel with the inductor, the behavior of the circuit is unaffected when the voltage is applied to the inductive load since the diode does not conduct current because it is reverse-biased and acts as an open circuit. When the supply is switched off, the inductor counters the drop of the current by generating an induced voltage with an opposite polarity with respect to the voltage supply as long as the energy stored in the inductor is dissipated. If a flyback diode is present, the induced voltage generated by the inductor forward biases the diode which starts conducting current. A temporary circuit loop is formed powered by the energy stored in the inductor, and the current flows until all the magnetic energy of the inductor is dissipated in this circuit.

The diode chosen for this particular circuit is the 1N4007, a general purpose diode. For the design of a flyback diode, the parameters to be taken into account are the current flowing in the inductive load and the voltage across. In this case, the diode must be able to sustain a current of 85mA and a voltage up to 24V. The 1N4007 can tolerate currents up to 1A and has a revere voltage of 1000V and it can be seen that its absolute maximum ratings are far higher than the ones handled in this circuit, so it is able to do its function as it is overdesigned.

Simulation results

The final circuit has been tested using Simulink considering all the components as ideal components to evaluate that the behavior is as it has been thought from design. The block scheme is represented in figure 25.

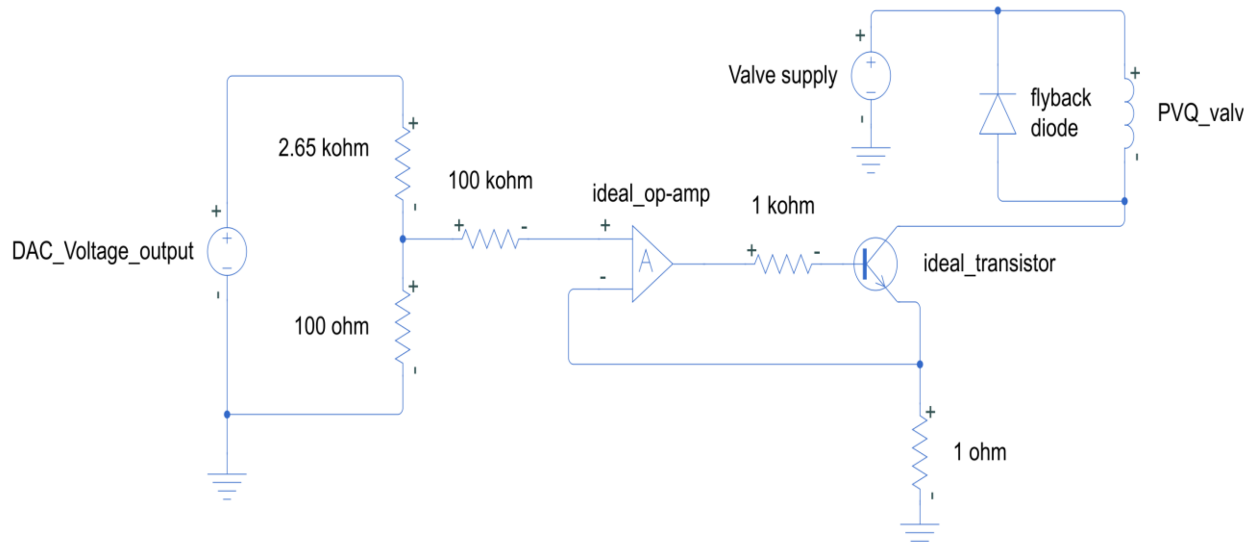
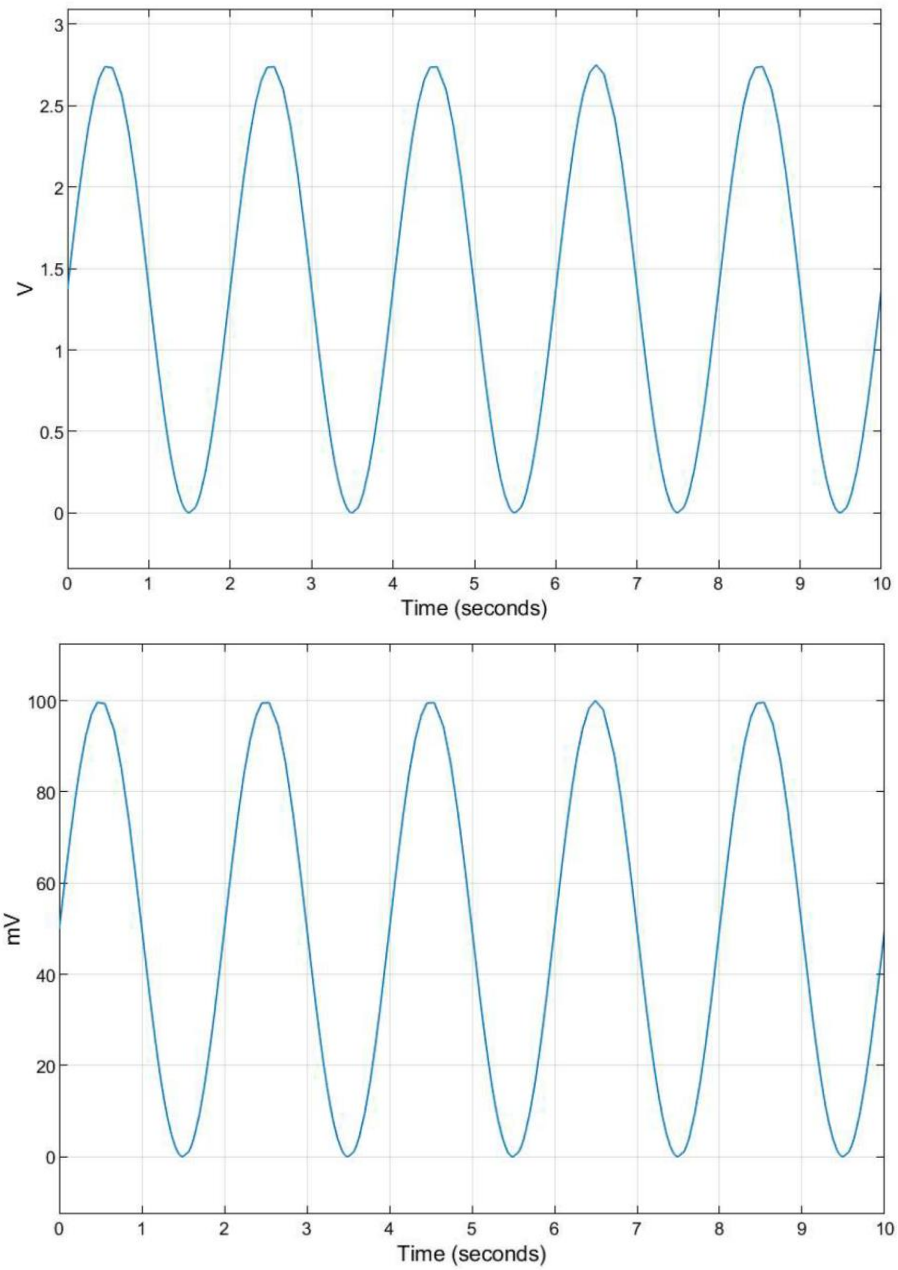


Figure 25: block scheme of the final circuit on Simulink

From the electronic board digital to analog converter pin, a voltage up to 2.75V can be fed into the voltage divider circuit. Across the 100Ω resistor, which is the resistor from the voltage divider able to command the operational amplifier input pin, a voltage up to 100mV can be generated. The 100kΩ resistor, used only for practical purposes which are basically the prevention of damage to the electronic board pin, is of no use under the assumption of ideal components. The operational amplifier output delivers a voltage (and a current) proportional to the voltage difference between the non-inverting pin voltage, given by the voltage divider, and the feedback resistor voltage, which coverts the current flowing through the valve coil, represented by a solenoid, into a voltage. The output of the operational amplifier is then delivered into the base gate of the transistor after flowing through a 1kΩ resistor, also used for practical purposes. According to the current flowing through the base of the transistor, which is a very small one, the transistor acts as a proportional switch and closes proportionally to it. When completely closed it acts as a short circuit, then the valve external supply feeds all the voltage to the valve coil and the feedback resistor. At full saturation of the transistor 100mA flows into the feedback resistor and 100mV are fed back into the inverting pin of the operational amplifier. A current of 100mA is above the maximum current nominal value according to the datasheet of the proportional valve, but it has been chosen in order to see how the valve behave when the absolute current limit is exceeded.

The ideal results obtained by the simulation are proposed in Figure 26. It is shown how the voltage of the non-inverting pin of the operational amplifier and the current through the coil values vary when a sinusoidal voltage signal is given by the digital to analog converter from the electronic board. As expected when the DAC voltage value reaches the maximum value of 2.75V, 100mV are generated across the 1Ω resistor and a current of 100mA flows through the valve coil.



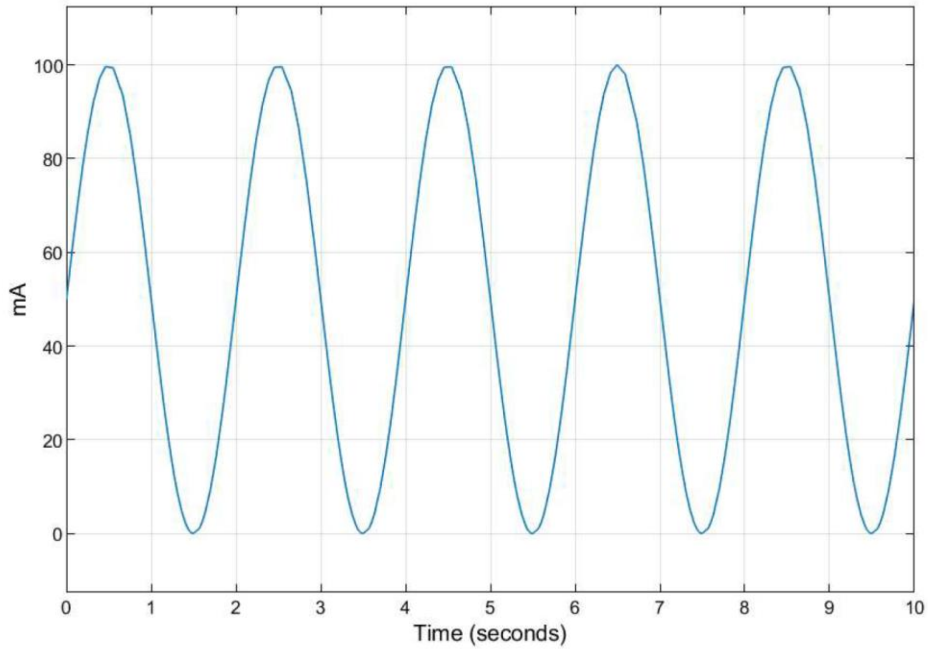


Figure 26: results obtained by the simulation of the system block scheme in Simulink. Starting from the top there are the voltage from the electronic board, the voltage fed into the non-inverting pin of the operational amplifier and the current flowing through the valve coil

In figure 27 it is shown the control block scheme used for the testing of the pneumatic bearing at fixed current.

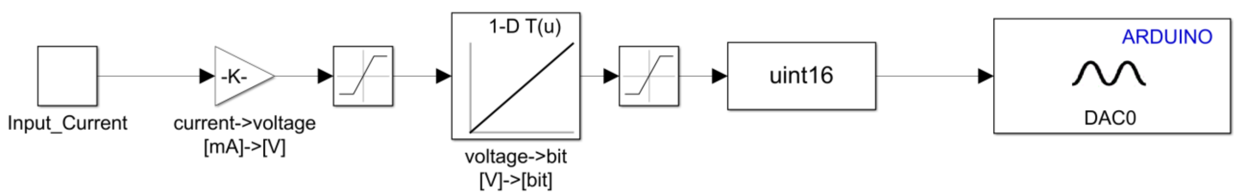


Figure 27: block scheme to be built and programmed into the Orange board

In this simple block scheme, a constant current is desired to flow through the coil of the pneumatic valve, 65mA in this specific one, which corresponds to a 50% opening of the valve. The current value is at first translated into a voltage value by a coefficient determined by the control circuit used, exposed later in this work. The voltage computed is the voltage value the digital-to-analog converter pin must set in order to generate the proper current. This value is bounded so that it does not exceed the voltage limits of the electronic board pin, which is from 0,55V to 2,75V. Then it is translated into a proper bit value through a look-up table designed for a 12-bit resolution. After being bounded by the limits of the 12-bit resolution, from 0 to 4095, the bit value is translated into a uint16 data type and fed to the electronic board DAC zero pin. This last block determines at which pin the analog voltage has to be set.

After being tested with the use of a breadboard, the circuit has been welded together and put in a box for an easier use during the successive tests. As shown in figure 28, it has two supply connection on its sides, one connection with the valve and one cable which takes the signal from the electronic board. The ground connection for the electronic beard, needed in order to have a precise voltage value command signal without oscillation due to electrical noise, is taken from one of the ground connections of the two supply cables.

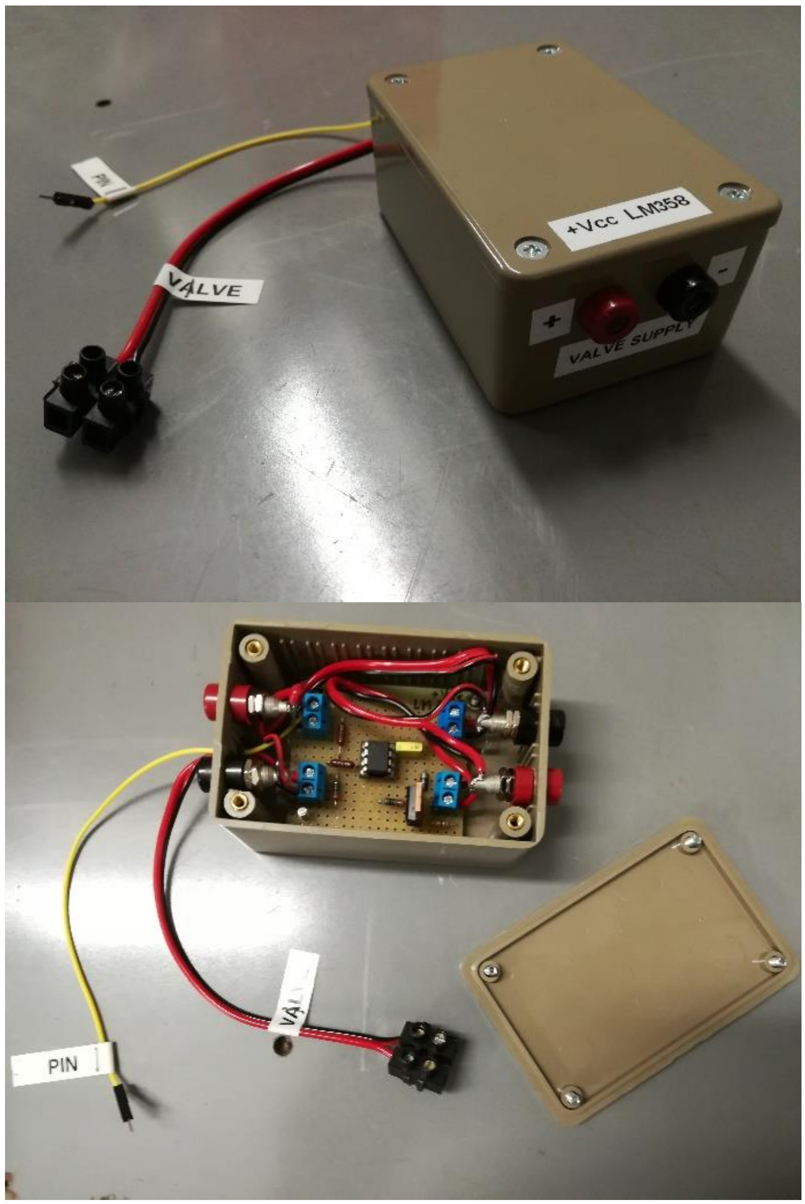


Figure 28: the control box where it is possible to see the electrical components needed to current-control the valve

Experimental tests

Some tests have been executed on the valve alone and mounted with the pneumatic bearing in order to see if its behavior is comparable with the one exposed on the valve datasheet and how it changes when it is mounted on the bearing. Open loop tests on the valve alone and mounted on the bearing have been executed. With different values of pressure supply, the valve has been fed with a very slow sinusoidal current in order to evaluate the start-up current and the hysteresis cycle of the valve. On the valve alone, a step test has been executed, making it possible to compute its dynamic parameters, natural frequency and damping. With different values of pressure supply, fixed values of current have been made flowing into the valve mounted on the bearing, corresponding to an opening of 50%, 70% and 100%. These tests show the load capacity of the system, the air consumption and the thickness of the air film under the bearing related to the force applied above it.

Valve tests

With two different values of pressure supply, 5 and 7 relative bar, a very slow triangular wave current has been fed into the valve with and without the pneumatic bearing. The current signal is a triangular wave centered at the value of 60mA and with an amplitude of 30mA. In this way the current value ranges from 30mA to 90mA, thus covering all the current input range of the valve and exceeding the maximum value by 5mA in order to see if the air flow saturates at the value given in the datasheet. The triangular wave current signal has a frequency of 0,1Hz, corresponding to a period of 10 seconds. Such a low frequency value has been chosen so that the value acquired can be considered as static values, not influenced by the dynamic behavior of the valve. The results of these tests are proposed in figure 29 and 30.

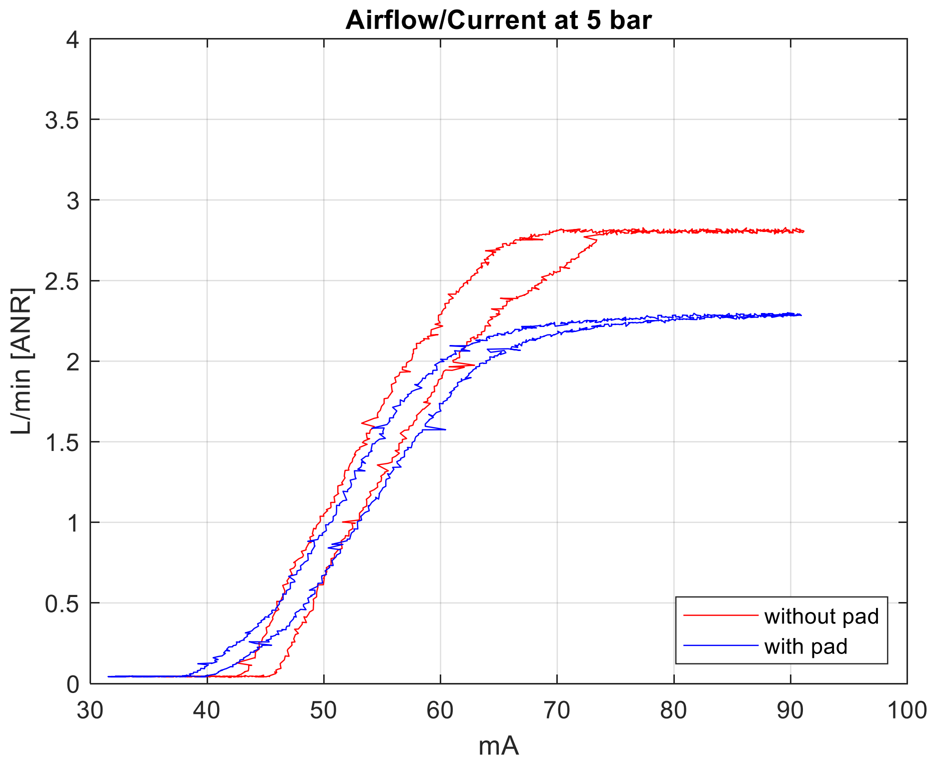


Figure 29: hysteresis cycle of the valve at 5 bar supply

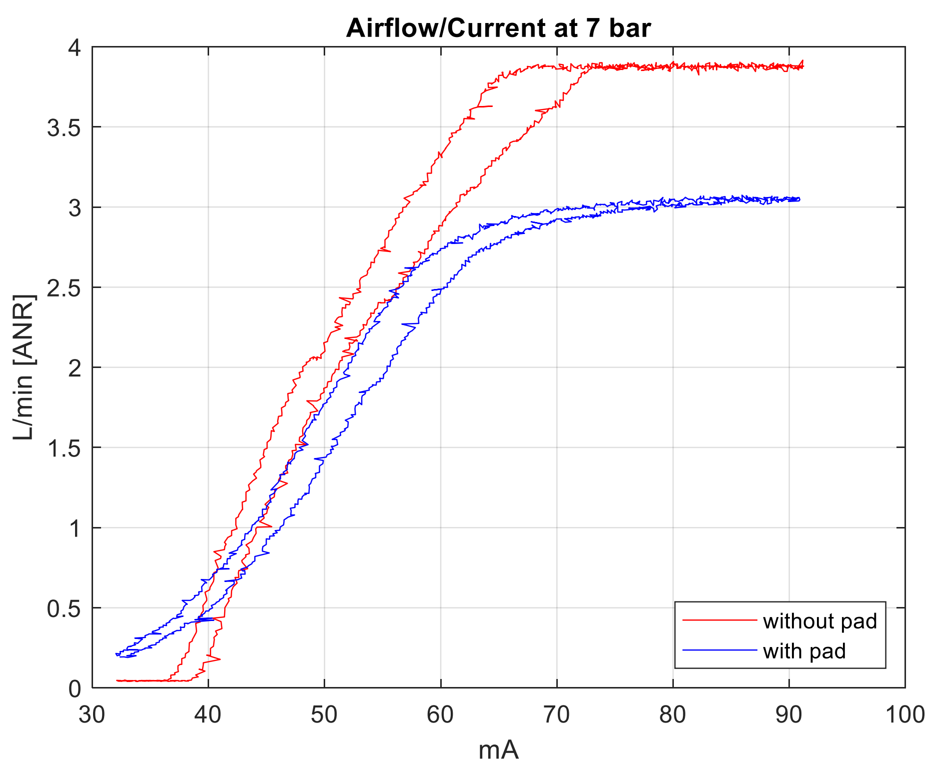


Figure 30: hysteresis cycle of the valve at 7 bar supply

As most of mechanical components, the valve is affected by the phenomenon of hysteresis. Depending on the gradient of the current signal, the air flow consumption is lower when the current is increasing with respect to when the current is decreasing. This is mostly due to the internal friction of the armature of the valve. The moving armature of the valve has a prismatic coupling with the rest of the valve and a gasket is present between them to avoid flow leakage. The gasket creates friction between the two components making it possible that, with the same value of current flowing, different values of air consumptions are delivered by the valve.

It can be noted that the maximum air flow exhausted by the proportional valve is lower than the value given by the datasheet. This lower air flow is caused by the two interface blocks used to mount the valve on the bearing. These two blocks, visible in figure 31, introduce a pneumatic resistance and cause the supply pressure not to be the pressure measured with the manometer. So the pressure supplied to the valve is lower and cause a lower air flow.

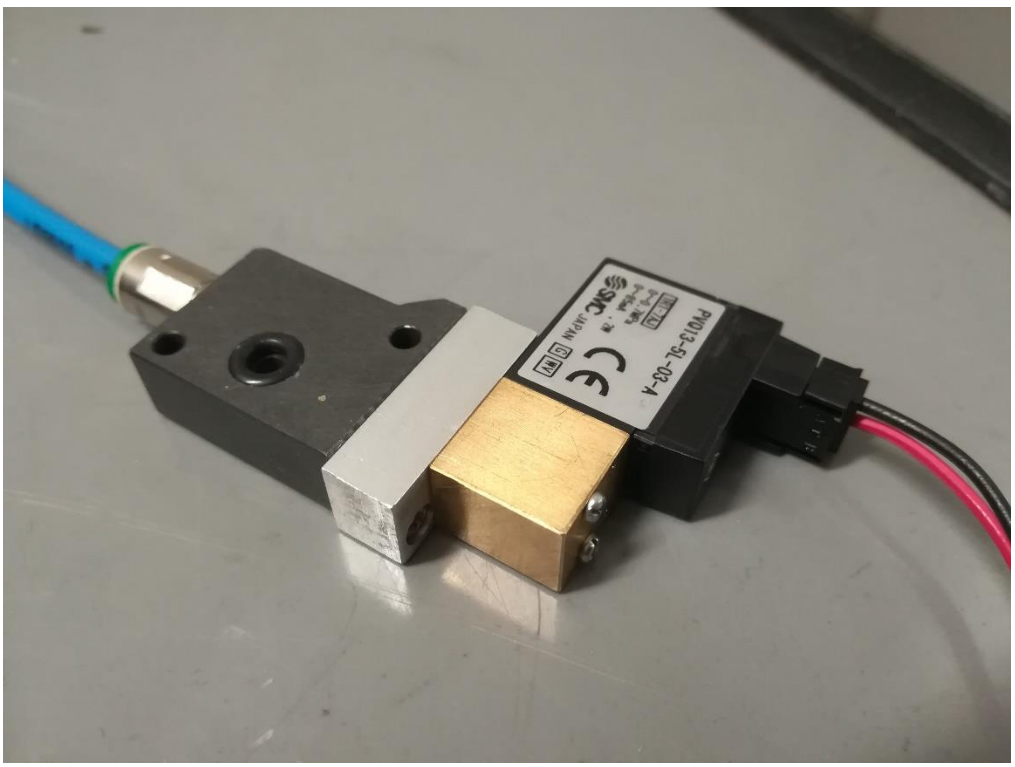


Figure 31: the valve with the two interface blocks

It can be seen that the current value at which the pneumatic valve is completely open is lower with respect to the one written on the datasheet. When the valve is being tested alone without the bearing, the saturation is reached at about 75mA of current flowing and about 80mA when it's mounted on the bearing. The existence of two different saturation current values is due to the fact that the pneumatic bearing introduces a pneumatic resistance to the air flow. Thus an higher current is needed to reach the maximum airflow. The bearing as a pneumatic resistance also explains the lower values of air flow with respect to the ones obtained with the valve alone.

From the graph it can be also seen that the start-up current values are different. This is dependent on the pressure supply and the bearing too. In fact, according to the working principle of the pneumatic valve, the opening to let the air flows through the valve is controlled by the equilibrium of the moving armature between the spring and the magnetic force generated by the coil, but depends also on the pressure values at the inlet and outlet port of the valve. The higher the pressure supply fed to the valve is, the lower will be the current needed to have a minimum airflow through the valve, as shown also on the graph given on the datasheet. The outlet pressure helps the opening of the valve too. This explains why the start-up current values are different for the valve with and without the bearing when the same pressure supply is present. As explained before, the bearing introduces a pneumatic resistance between the valve and the ambient pressure at its outlet hole. When the valve is tested alone, at its outlet there is ambient pressure, but when it is tested mounted on the bearing, the pressure at its outlet is higher than the ambient pressure and facilitates the opening of the valve.

After these tests, it has been analyzed the dynamic behavior of the valve in order to compute its dynamic parameters. The valve has been analyzed without the bearing and sinusoidal current signals with increasing frequency have been made flowing through the valve coil. The amplitude of the current signal is 10mA thus ranging from 65mA to 75mA. The frequency of the current signal fed to the valve ranges from 1Hz to 100Hz. The sinusoidal airflow outputs have been compared with the one gained from the static tests. In the analysis of these tests the amplitude of the output has been related with the airflow amplitude from the hysteresis test and it was computed the delay of the output with respect to the current input. In this way it was possible to draw the Bode plot of the pneumatic valve from the frequency of 1Hz to 100Hz. The Bode plot is shown in Figure 32.

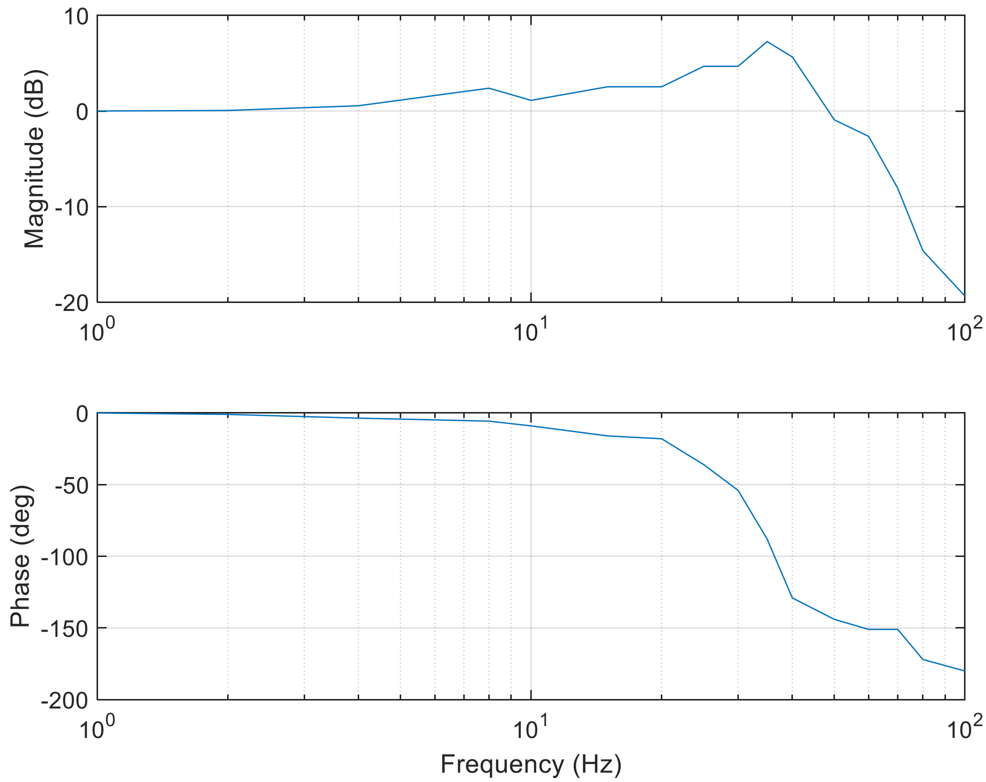


Figure 32: Bode plot of the pneumatic valve

From the bode plot of the pneumatic valve it can be seen that it has a peak in the amplitude when the frequency is around 35Hz, which is the natural frequency of the valve. When the frequency is greater than 50Hz the amplitude of the oscillations of the output starts decreasing under the value of 0dB and with frequency higher than 70Hz the oscillations hardly follow the sinusoidal input.

After these tests, it was executed a step test in order to validate the natural frequency obtained before and find the damping if the pneumatic valve. With a pressure supply of 5 bar, it has been fed to the valve a step current signal from 0mA to 60mA and it has been plotted together with the airflow consumption. As explained before, since the minimum output of the DAC of the electronic board is 0,55V, the true step current signal ranges from 20mA to 60mA, but the lower value does not affect the test because with this low current there is no opening of the pneumatic valve. The results are shown in Figure 33.

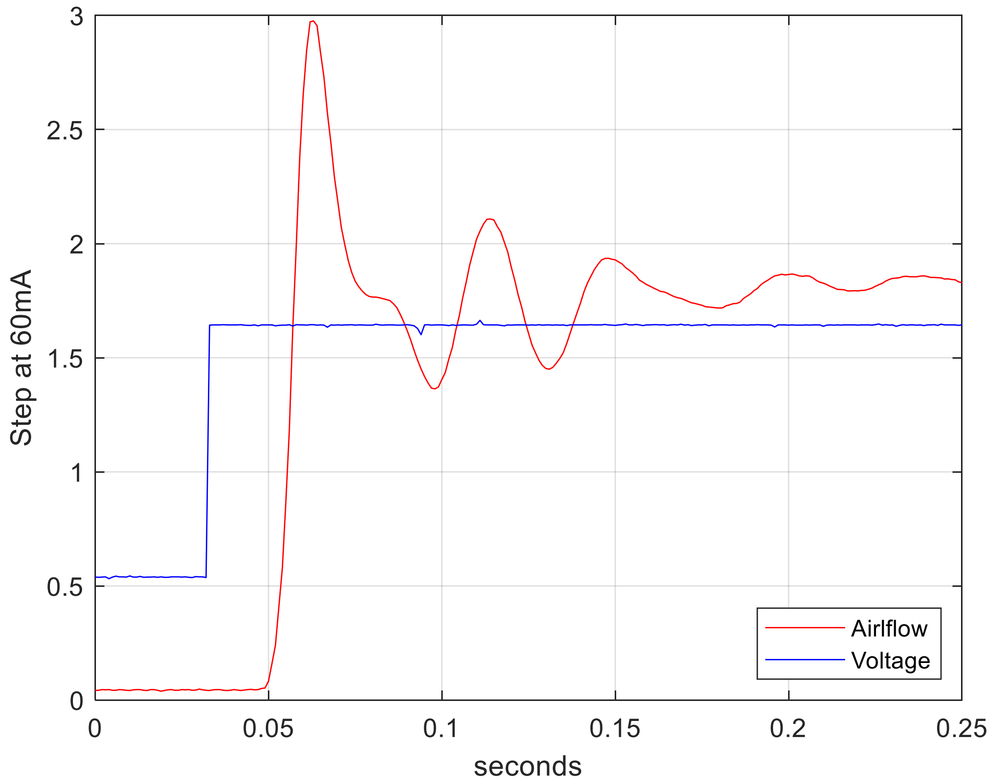


Figure 33: step test on the valve

From this graph it is possible to see a great overshoot of the airflow consumption when the current signal commands the opening of the pneumatic valve and, after that, some oscillations occur on the valve output. This might be due to a low value of the damping factor, explaining the great overshoot and the subsequent oscillations. Also it can be noted that there is a time delay from the input signal to the opening of the pneumatic valve, which is about 20 milliseconds. This value has been taken into account when computing the phase shift in the Bode plot shown previously on this paragraph.

The pneumatic valve can be considered as a system of the second order with natural frequency ω_n and damping factor ζ. The transfer function of the pneumatic valve *H(s)* with an input of current and an output of air flow is given by

$$H(s) = \frac{K_Q * \omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

where Q is the airflow output of the valve, I is the current fed into the valve, ω_n is the valve natural frequency, ζ is the valve damping factor and K_Q is the static airflow gain for a given current.

Then it was made a graph with the experimental result compared with a simulated step of a second order system. The value of ζ has been chosen in order to match as possible the experimental result with the simulated one and it was chosen a value of 0,2. The graph is shown in figure 34.

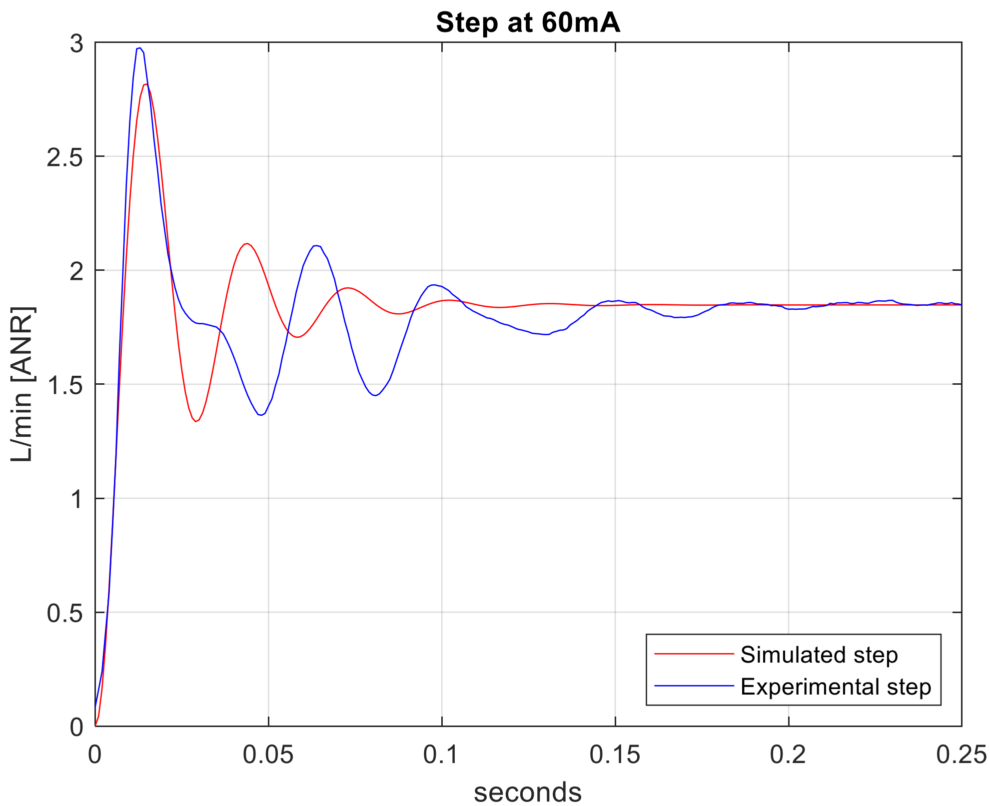


Figure 34: comparison between the experimental step with the simulated one

It can be seen from the graph above that a simulated second order step with $\omega_n = 35Hz$ and $\zeta = 0{,}2$ approximates the results from the experimental test on the pneumatic valve. The first peak is followed with a response time and overshoot very similar to the ones obtained from the step test. After the first peak the two curves becomes a little out of phase, which may be due to the internal friction caused by the gasket placed on the moving armature of the valve, which is not taken into account in the simulated second order system.

Then the Bode plot of the simulated second order system has been drawn and compared with the one obtained from the experimental tests. The Bode plot is shown in figure 35.

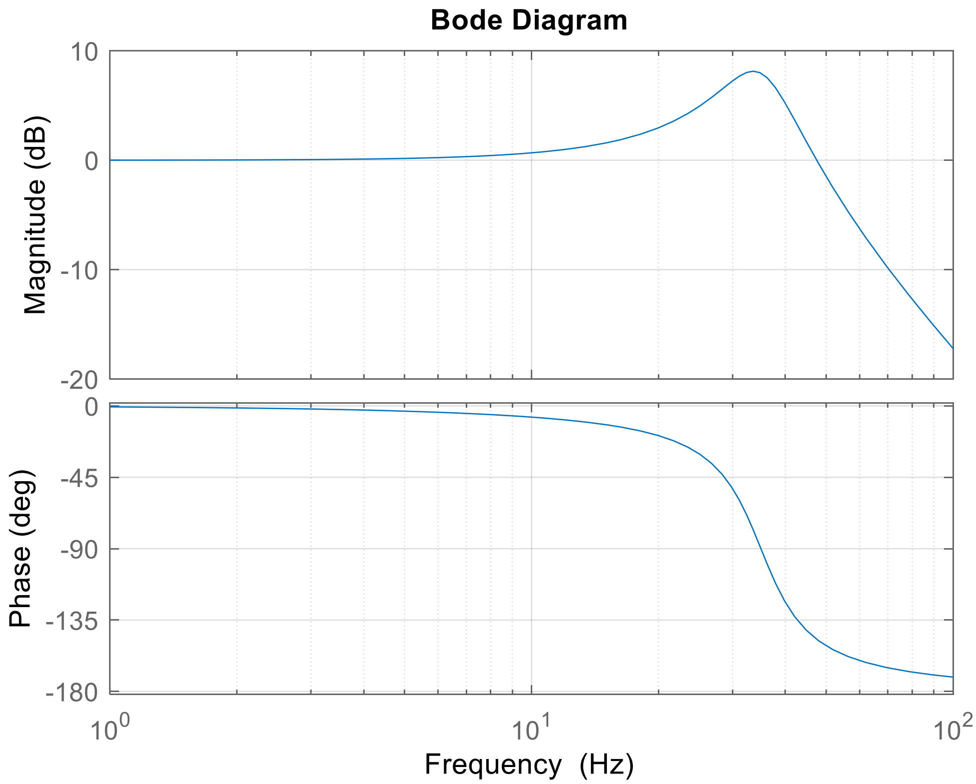


Figure 35: Bode plot of the second order system with $\omega_n = 35Hz$ and $\zeta = 0{,}2$

The two Bode plots are similar and validates the tests and the second order system design, which values have been used in the design of the Simulink Model.

Backpressure sensors test and calibration

In order to close the control loop, it has been analyzed the output given by the backpressure sensors so that the voltage coming from them respect the height of the air film under the bearing. Before that, it is necessary to validate the backpressure sensors themselves to be sure that they are working correctly. In order to validate the sensor, they have been connected with determined pressure supply, whose value is measured through a manometer, and it was obtained the voltage value output. The results are shown in figure 36.

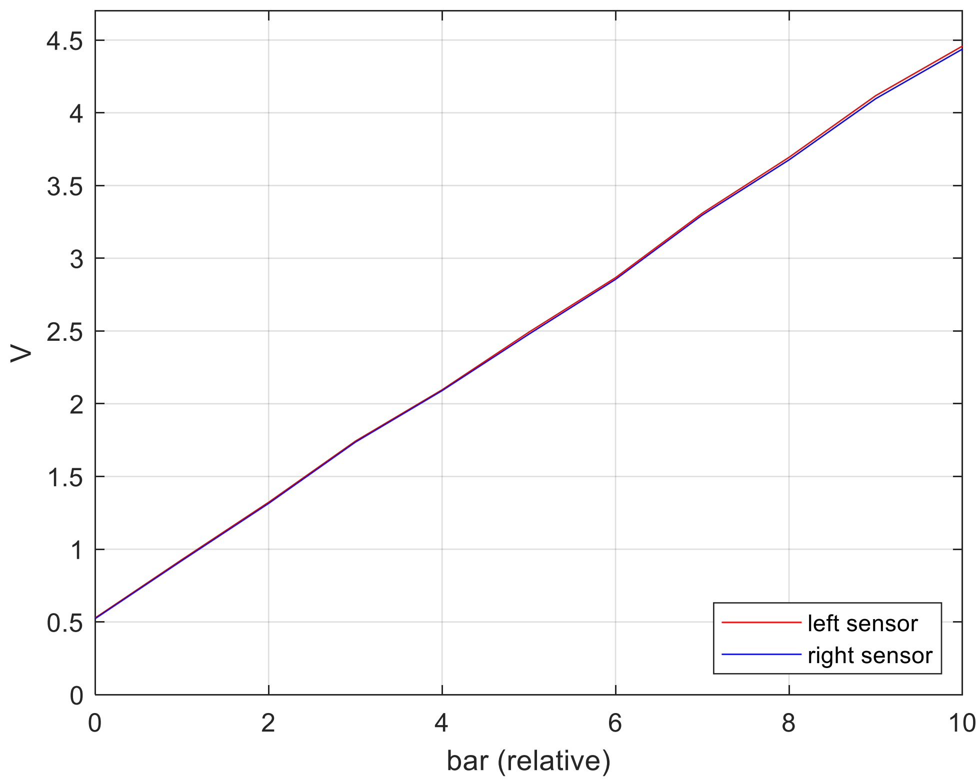


Figure 36: output characteristic of the counterpressure sensors

The sensors have been connected with a pressure supply ranging from 0 to 10 relative bar and the voltage output is obtained. The graph above shows that the sensors work fine since their output is very similar between them and the slope is constant.

After the validation of the correct functioning of the sensors, they have been mounted on the bearing. In order to acquire an output as similar as possible between them, it is necessary that they are mounted with the same height with respect to the bottom surface of the bearing. The higher they are mounted the less sensible their measure is. Then, to get the most sensible output from them, it was decided to mount them with no offset with respect to the bearing. To do so, the bearing was put on a flat surface as the sensors and they were mounted together. In this way, when the air film under the bearing is null, the pneumatic resistance seen from the sensors, which reflects the distance from the bench surface, is maximum and so is their output. As the bearing rises, the pneumatic resistance decreases and so does the voltage output from the sensor.

Once the sensors are mounted on the bearing, it has been obtained their output with respect to the air film under the bearing. In order to do so, a ramp current input has been fed to the pneumatic valve so that its air flow increases from zero to the maximum value. During the test, the value of the air film has been acquired through the capacitive sensors and it has been related with the voltage given by the backpressure sensors. Then an interpolation curve has been designed which can relate the voltage output with the air film gap. The interpolation curve obtained is the curve that need to be implemented on the electronic board so that it is able to read the air film gap from the voltage output of the sensors and, once closed the control loop, manage the current to be fed to the valve in order to keep the reference gap value. The results of the test are shown in figure 37.

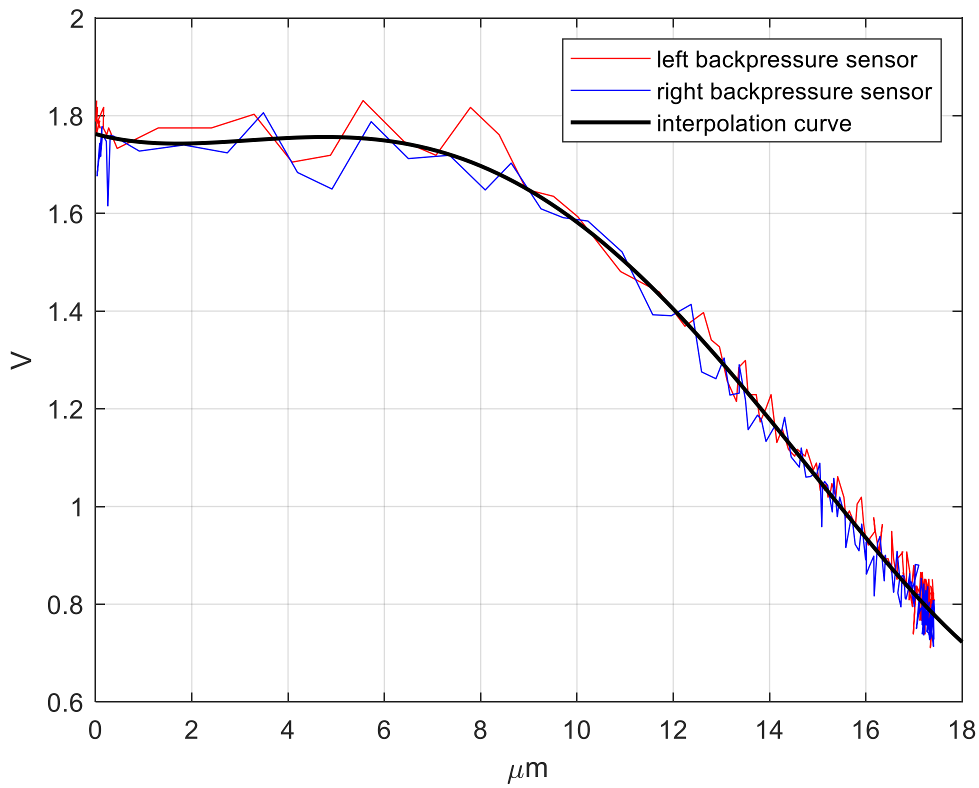


Figure 37: output voltage given from the backpressure sensors with respect to the air film under the bearing

From the graph above it can be seen that the output given by the backpressure sensor is not linear with respect to the air film gap. The output is not much sensitive in the range from 0 to 6μm, while it reads the air gap pretty well for higher values. This is acceptable since the bearing in normal working conditions does not operate with such low value of air film. It can be also noted that the values obtained from the sensors is very similar between them so one interpolation curve can be designed for both.

Open Loop tests

With the following tests it has been analyzed the system in open loop, that is to validate the functioning of the pneumatic pressure valve together with the bearing. During these tests the pressure supply has been kept fixed at 5 and 7 relative bar and the values of the air film have been acquired with different opening of the proportional valve. in this way it is possible to draw the lift-air film graph and the air flow-air film graph. The test have been executed for different value of current flowing through the pneumatic valve corresponding to an opening of 50%, 75% and 100%. The algorithm followed for the execution of the tests is:

1) Start with the proportional valve completely closed and maximum force (about 500N for each test);
2) Open the valve with a fixed current equivalent to the opening of the valve of 50%, 70% or 100%;
3) Slowly decrease the applied force so that the air film under the bearing increases;
4) Close the valve so that no air flow pass through it;
5) Increase the force to the starting value and close the test loop.

During the execution of the test, it has been acquired the load applied to the bearing, the air flow consumed by the bearing and the air film generated. In figure 38 it is shown the load/air film graph with the proportional valve supplied with 7 bar opened at 50%.

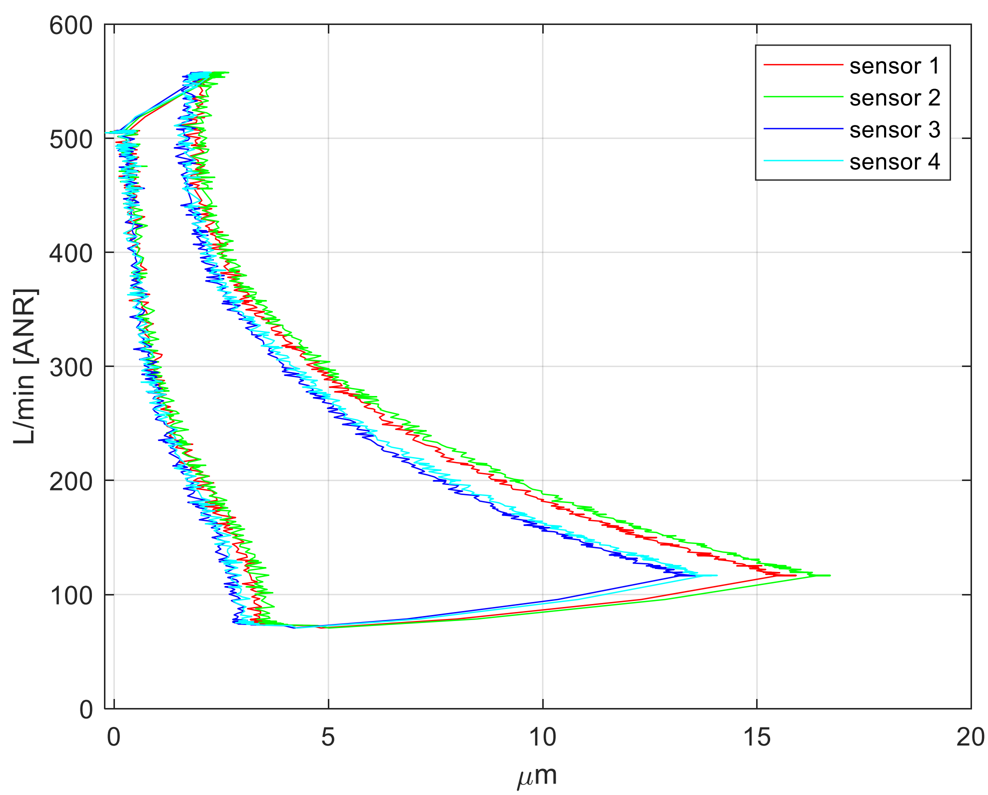


Figure 38: load/air film at 7 bar with the valve open at 50%

From the graph above it can be noted that the bearing tilt along one direction. In fact the measure from the sensors on the left, sensor 1 and 2, is slightly higher than the measure of the sensors on the right, sensor 3 and 4. It can be also noted that in the part of the loop with the valve close and the load applied increasing the measure of the sensor is not constant, even if there is no air flowing and no air film under the bearing. This can be explained by a compression of the test bench, which increases proportionally to the load applied. Then the measure of the capacitive sensors must be correct eliminating the compression of the bench. To do this, a polynomial curve has been designed to fit as accurately as possible the part of the curve with valve closed and load increasing. Then, using the polynomial curve, the measure of the sensors has been corrected by the compression of the bench for the given load applied. The designed polynomial curve has been used for all the tests since the compression of the bench does not depend on the opening of the valve, but only by the bench itself and the load applied to the bearing.

In the following graphs there are shown all the tests executed, with the opening of the valve of 50%, 75% and 100% with a pressure supply of 5 and 7 bar.

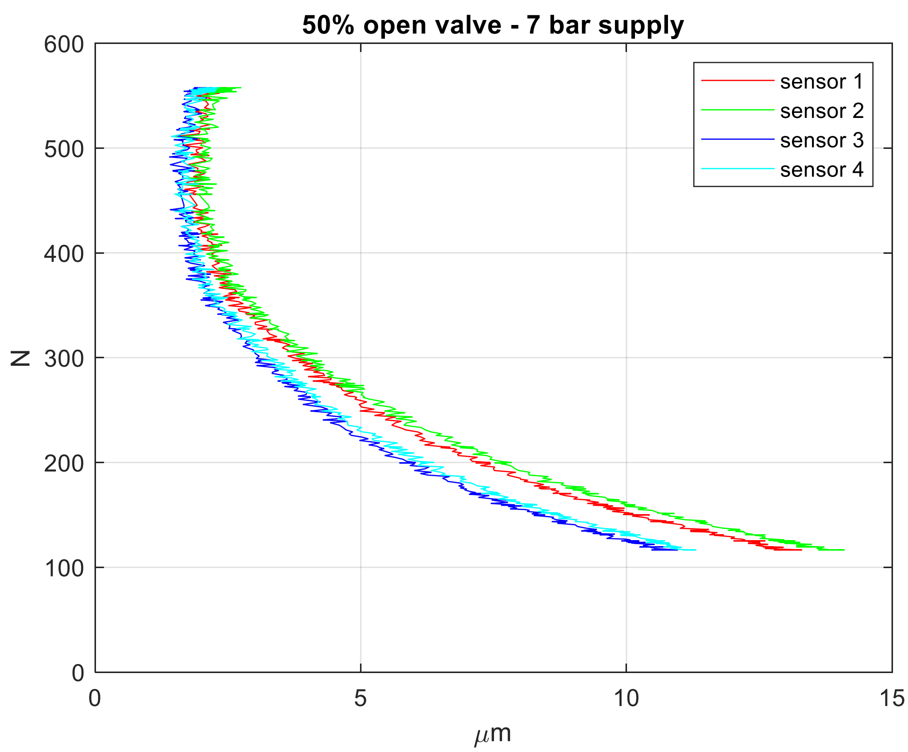


Figure 39: lift-air film graph at 7 bar supply and opening of the valve at 50%

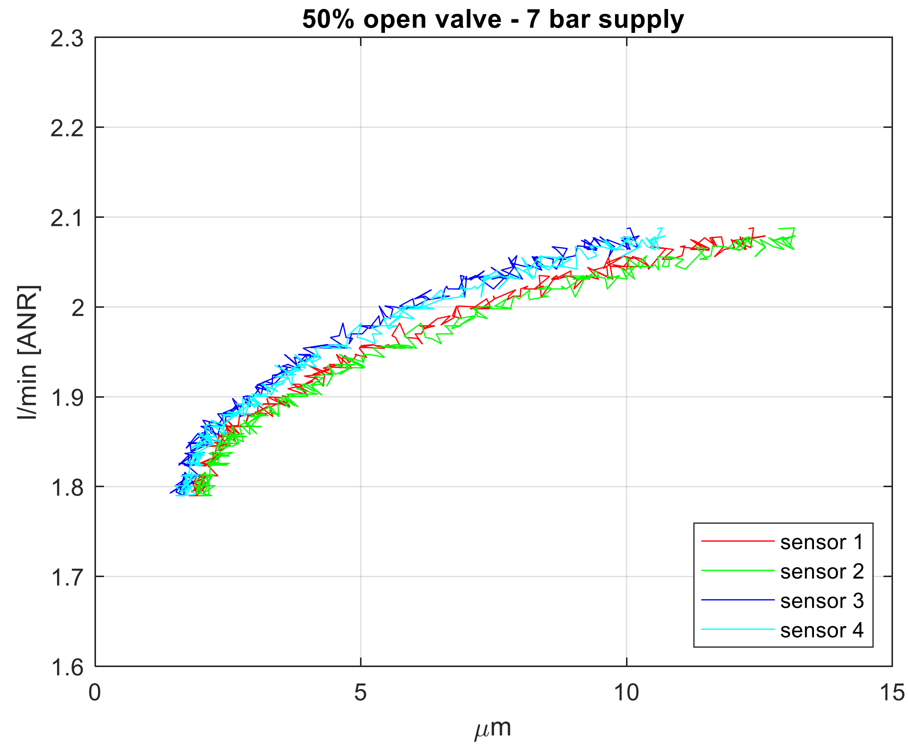


Figure 40: air flow-air film graph at 7 bar supply and opening of the valve at 50%

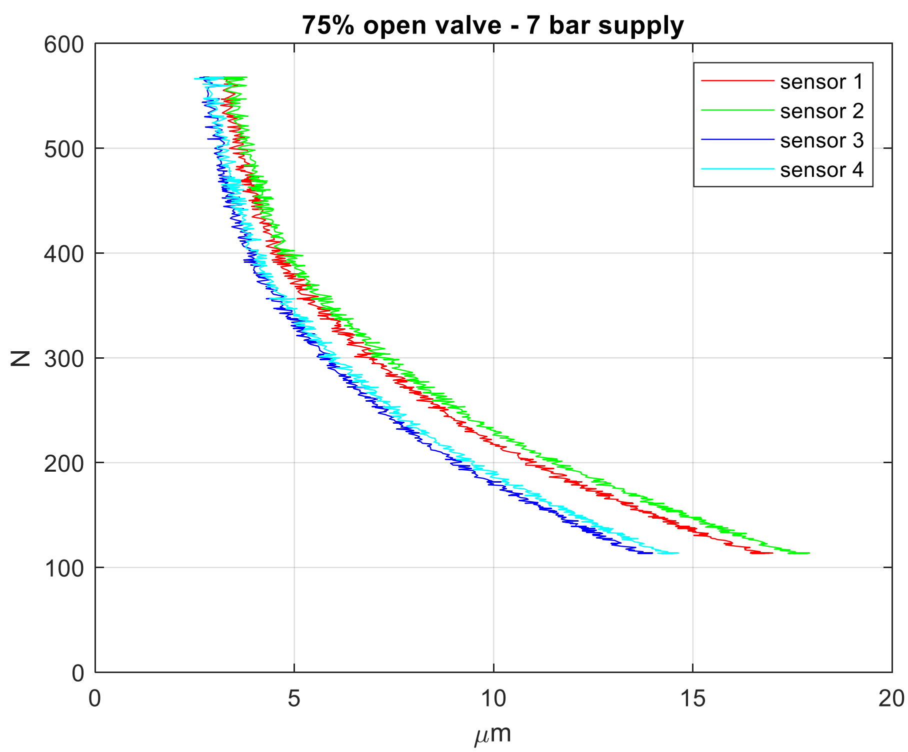


Figure 41: lift-air film graph at 7 bar supply and opening of the valve at 75%

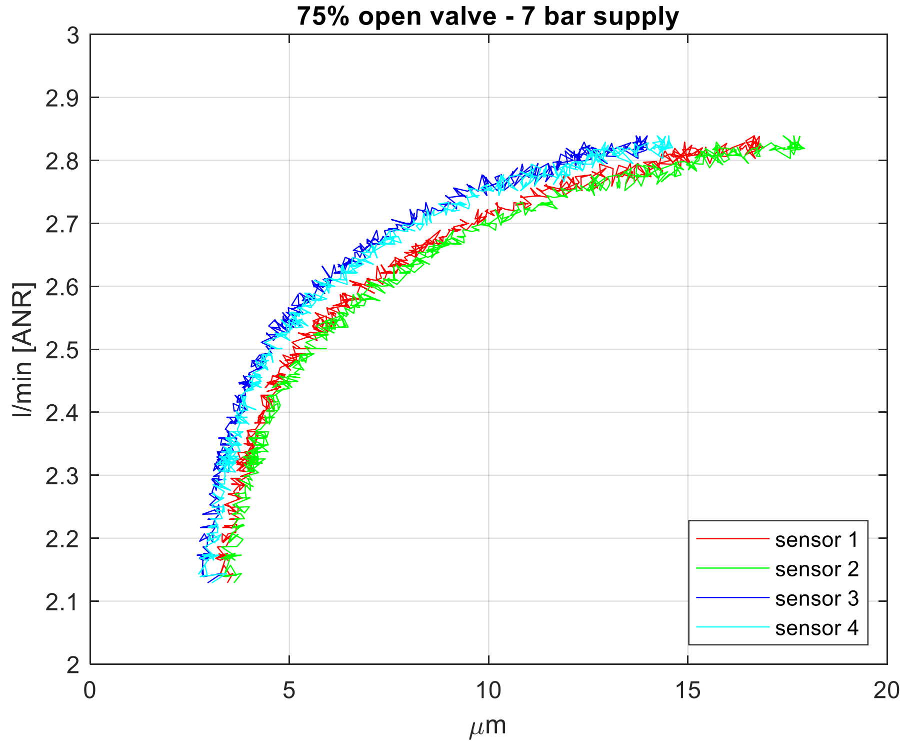


Figure 42: air flow-air film graph at 7 bar supply and opening of the valve at 75%

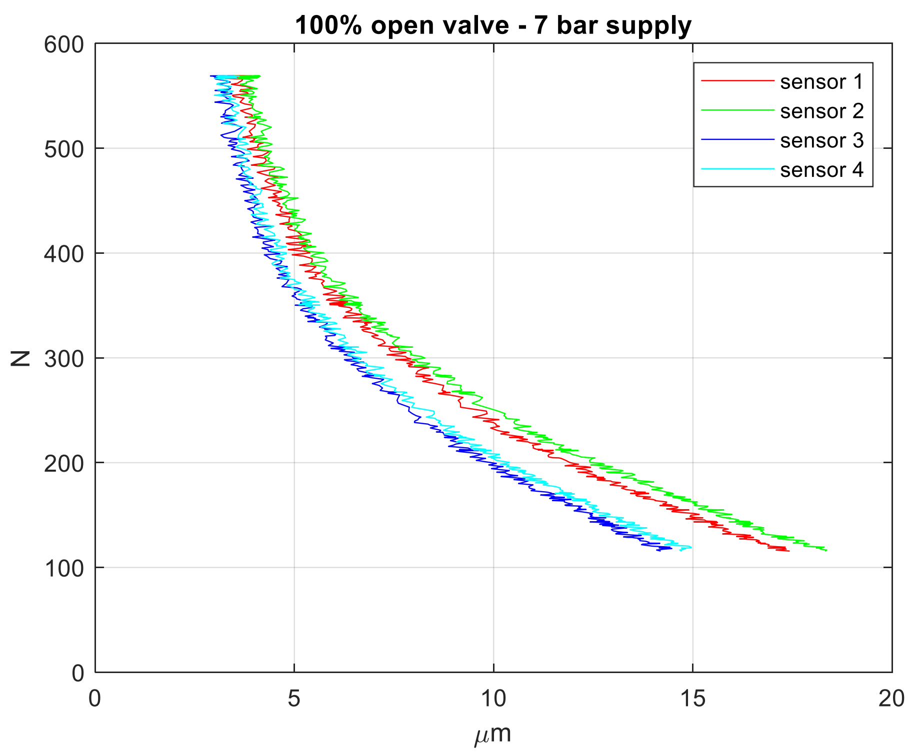


Figure 43: lift-air film graph at 7 bar supply and opening of the valve at 100%

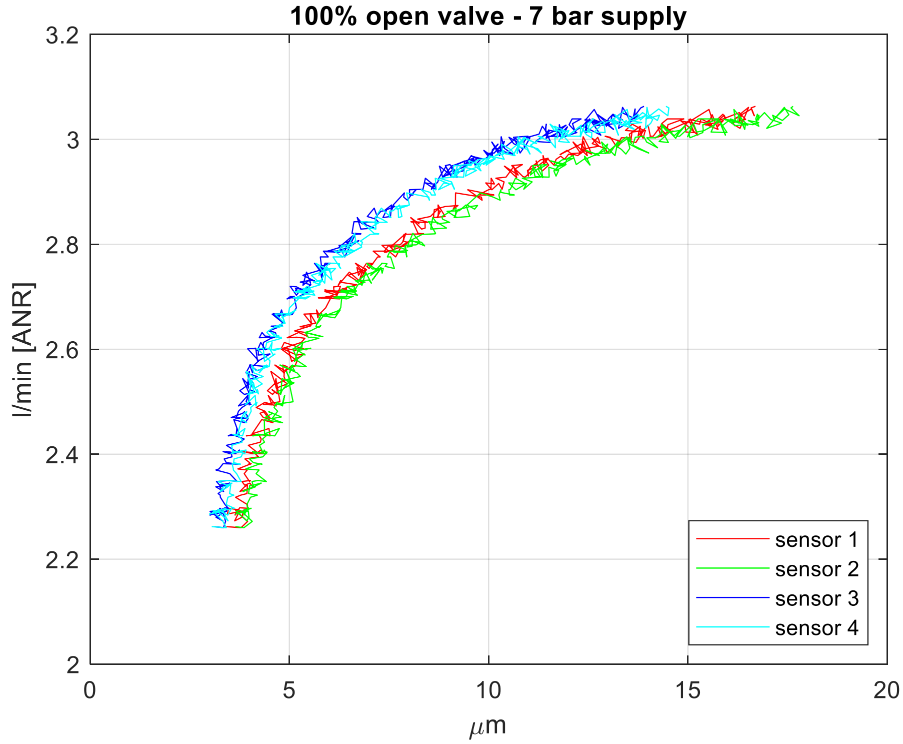


Figure 44: air flow-air film graph at 7 bar supply and opening of the valve at 100%

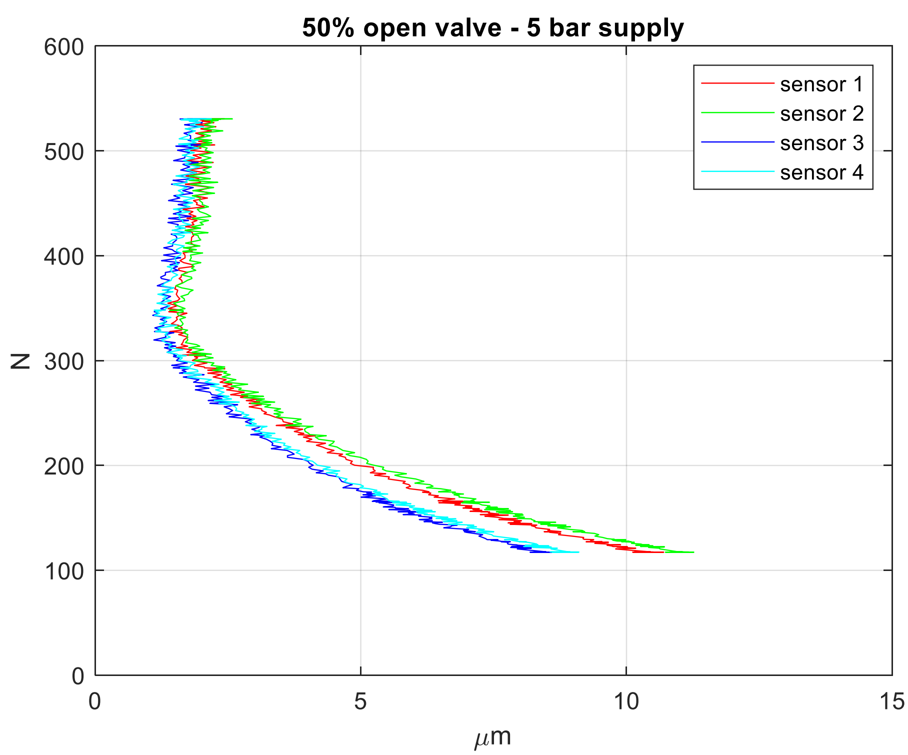


Figure 39: lift-air film graph at 5 bar supply and opening of the valve at 50%

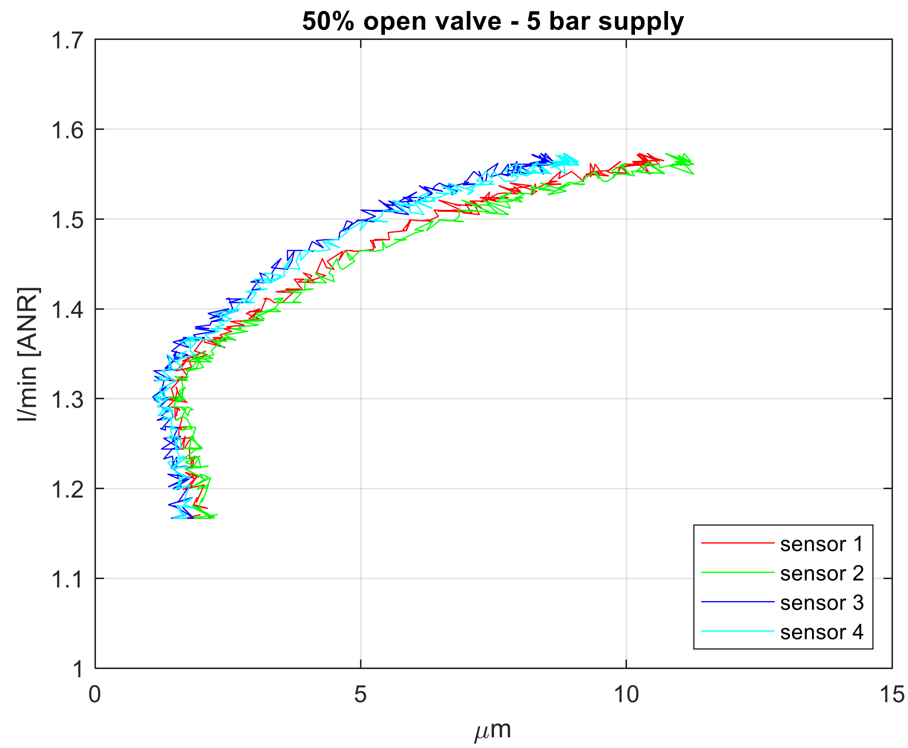


Figure 40: air flow-air film graph at 5 bar supply and opening of the valve at 50%

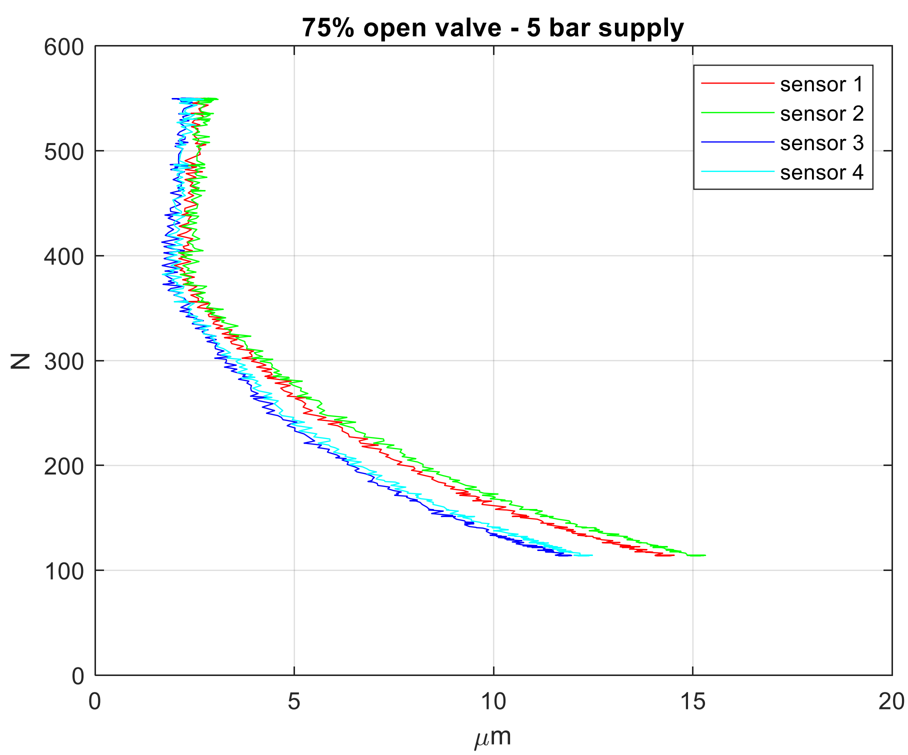


Figure 41: lift-air film graph at 5 bar supply and opening of the valve at 75%

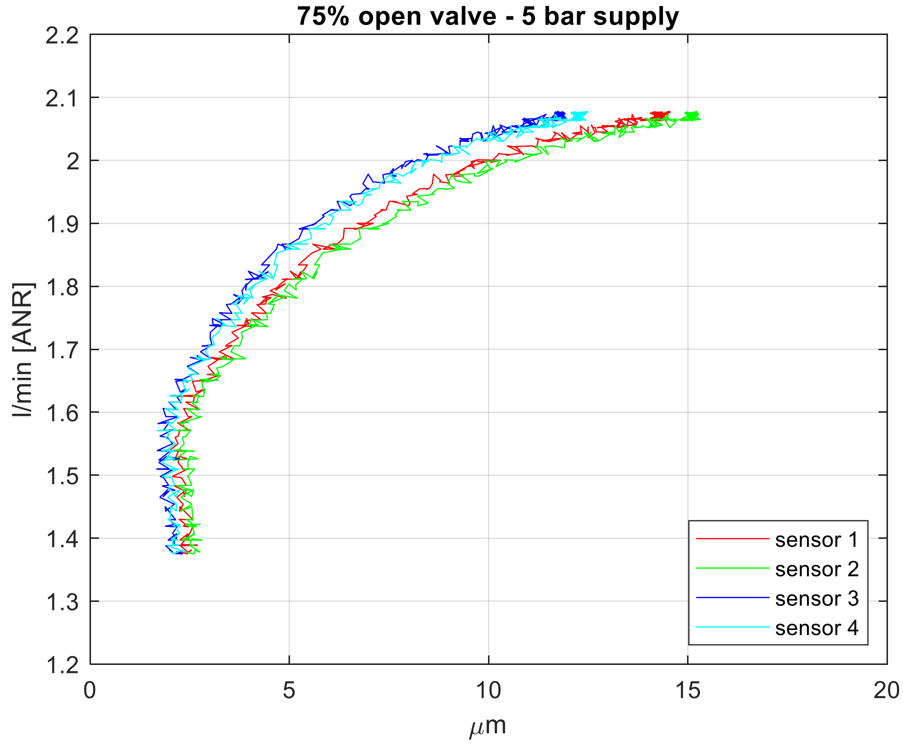


Figure 42: air flow-air film graph at 5 bar supply and opening of the valve at 75%

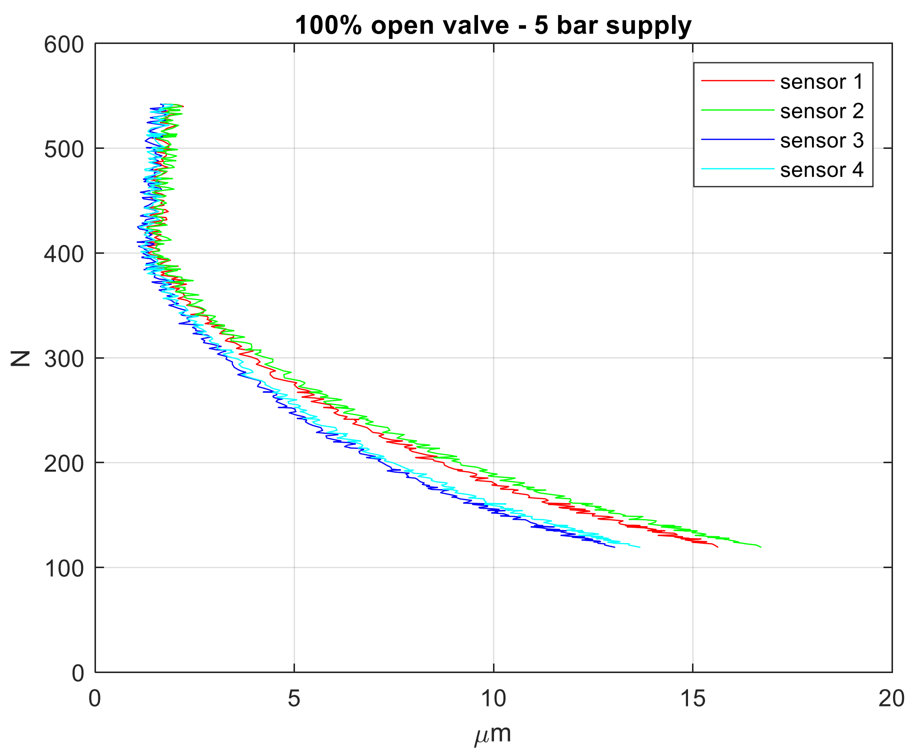


Figure 43: lift-air film graph at 5 bar supply and opening of the valve at 100%

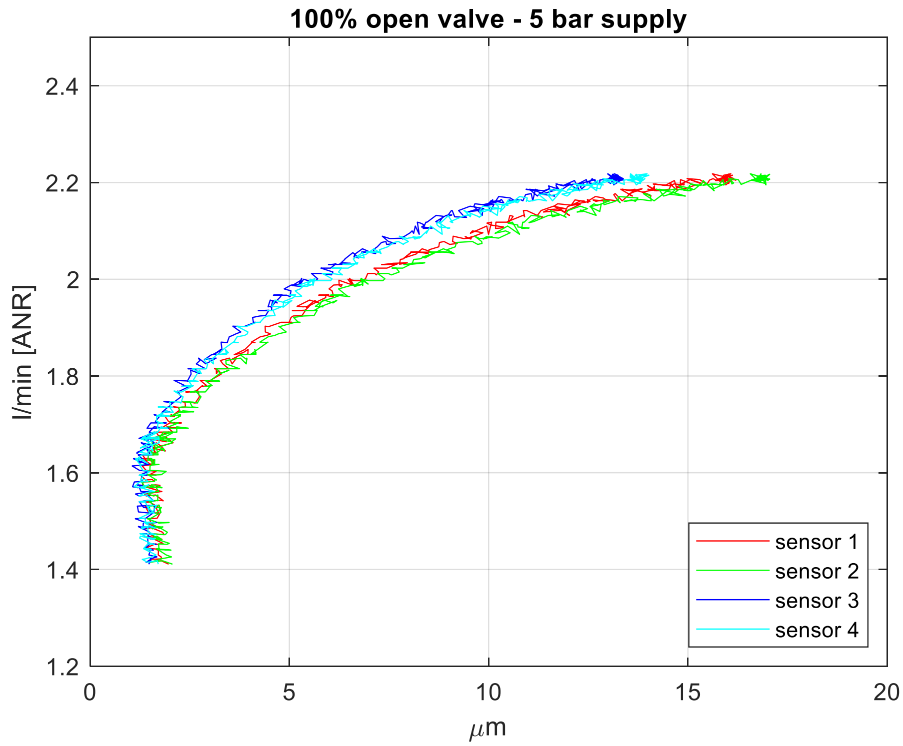


Figure 44: air flow-air film graph at 5 bar supply and opening of the valve at 100%

Simulation Model Design

Proportional valve model

The pneumatic proportional valve PVQ13 has been modeled as a variable pneumatic resistance. In order to calculate the air flow rate G [$\frac{l}{min*bar}$] through the pneumatic resistance, the formulas used for this calculation are shown below:

- Sonic flow, $0 < \frac{P_2}{P_1} < b$: $G = P_1 C$
- Subsonic flow, $b < \frac{P_2}{P_1} < 1$: $G = P_A C \sqrt{1 - \left(\frac{\frac{P_2}{P_1} - b}{1-b}\right)^2}$

where P_1 is the valve supply pressure [bar], P_2 is the valve exhaust pressure [bar], C is the valve conductance [$\frac{l}{min*bar}$] and b the air critical ratio with a constant value of 0.528.

As exposed before, the pneumatic valve has been considered as a system of the second order type and for the calculation of the conductance of the valve a second order system commanded by the reference current signal I_{ref} has been modeled. The differential equation used for the calculation of the opening of the passage aperture A_v is:

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

where ζ is the damping factor, ω_n is the valve natural frequency and K_s is its area static gain.

It has been assumed that the relation between the opening A_v of the valve and the conductance C is linear and therefore the valve conductance is:

$$C = K_C A_v = K_C K_S I_{ref} = K_v I_{ref}$$

where K_v is the flow static gain of the valve, which is function of the conductance C and the reference current signal I_{ref}.

The values used for the flow static coefficient have been computed from the hysteresis test executed on the valve. A lookup table has been designed from the values of the air flow exhausted by the valve with the respective current values in order to use the proper flow static coefficient. The final differential equation that calculates the valve conductance with the reference current signal I_ref is:

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

From the valve tests, the values for the valve natural frequency, damping factor and conductance have been computed and it was then possible to design the final valve dynamic model. The model is composed by two parts, one computing the conductance value and the other recognizing whether the valve is working under sonic or subsonic condition. In figure 45 it is shown the model for the proportional pneumatic valve.

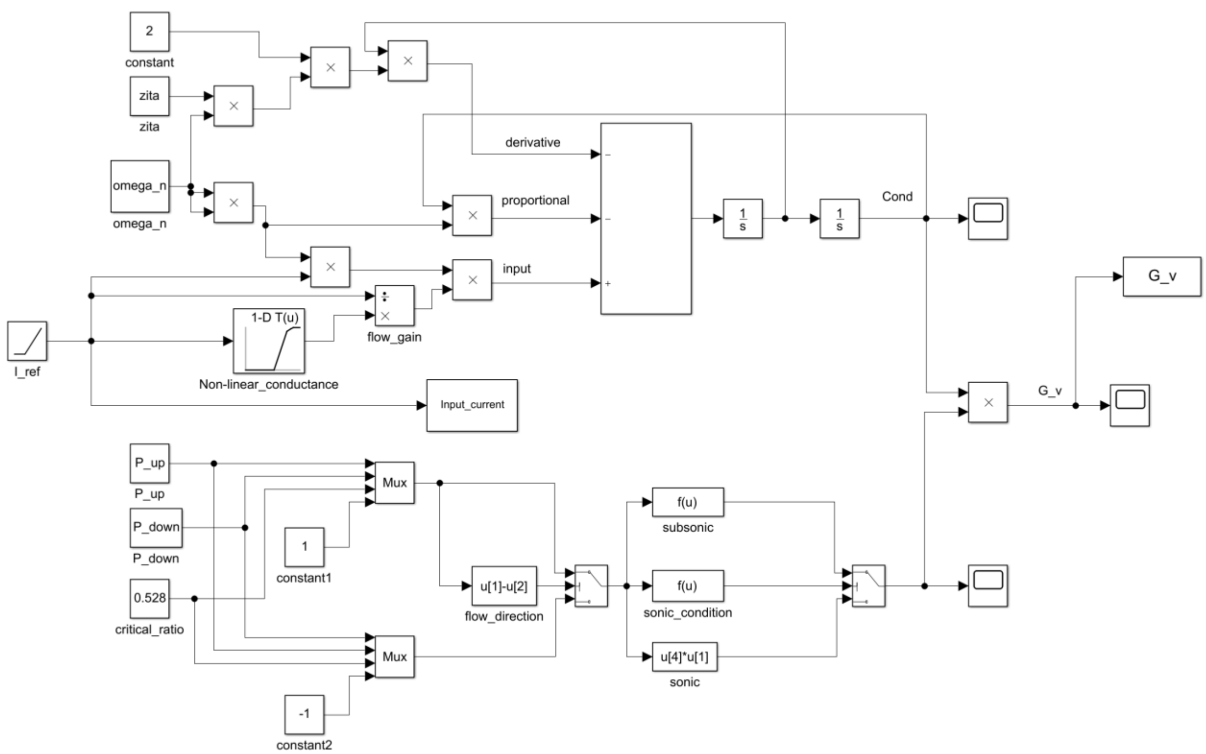


Figure 45: model of the proportional pneumatic valve

The upper part of the model is responsible for the computation of the conductance of the valve. It models a second order system characterized by a damping factor of 0.2 and a natural frequency of 35Hz. The command signal is the reference current I_{ref} , from which it is also computed the flow static gain through a lookup table. In fact, from the experimental tests executed on the valve, it was possible to see that the valve conductance is not constant and depends on the input current. In order to have a model with a behavior as similar as possible to the one shown in the experimental tests, it was decided to use the obtained air flow consumption for different values of current to compute the flow static gain. In this way, according to the reference signal, the flow static gain is computed, and the model results are more similar to the experimental ones.

The lower part of the model implements the formulas for the calculation of the air flow through a nozzle discerning whether it is in sonic or subsonic condition. Assumed a constant critical ration, which value is 0.528, this part is able to understand the flow direction, given from the difference between the pressure from the supply and the exhaust, and the condition of the air flow. The values obtained from the two part of the model are eventually multiplied together to get the amount of air flowing through the valve in *l/min* [ANR].

Air bearing model

After the model of the pneumatic proportional valve, the air bearing has been modeled considering it divided into4 different pneumatic subparts:

- the internal chamber capacity;
- the bearing nozzle, which can be considered as a pneumatic resistance;
- the air film capacity;
- the air film pneumatic resistance.

A generic pneumatic scheme of the air bearing is shown in figure 46.

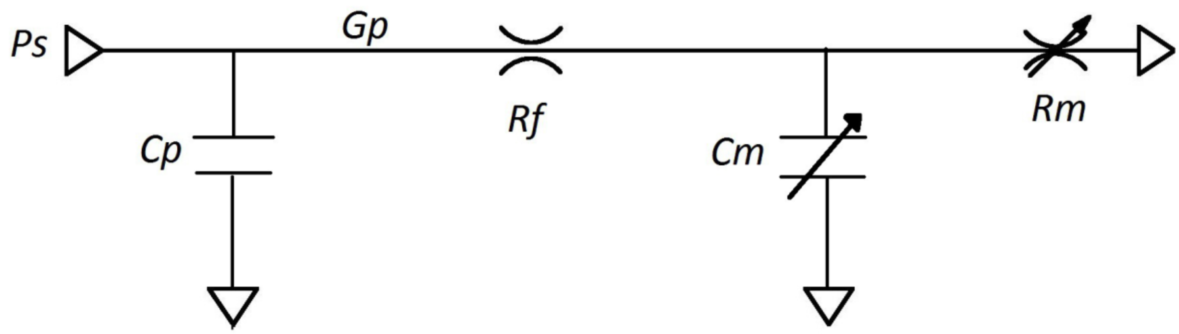


Figure 46: equivalent pneumatic scheme of the air bearing

where P_s is the supply pressure of the bearing, C_p is the pneumatic capacity of the internal chamber, G_p is the air flowing through the exhaust hole of the bearing, R_f is the pneumatic resistance given by the bearing exhaust hole, C_m is the variable pneumatic capacity of the air film under the bearing and R_m is the variable resistance of the air film under the bearing.

The model of the internal chamber capacity has been considered starting from the definition of capacity:

$$C = \frac{G}{\frac{dP}{dt}}$$

where G is the flow through the considered volume, which is the difference between entering flow and exiting flow, C is the volume pneumatic capacity and P is the mean pressure inside the volume.

Considering that in this particular case the volume of the internal chamber can be considered constant, which corresponds to an infinite elastic stiffness of the chamber walls, the equation for the calculation of the pneumatic capacity becomes

$$\frac{dP}{dt} = G\frac{nRT}{V}\left(\frac{P}{P_i}\right)^{1-1/n}$$

where P_i is the initial pressure inside the capacity, n is the polytropic exponent, R is the ideal gas constant (287J/kgK), V is the volume of the internal chamber.

From the precedent work of thesis, the value of the volume of the internal chamber has been measured $V = 739{,}2 * 10^{-9}\, m^3$ with the use of SolidWorks and, since the process inside the chamber can be considered an isothermal one, the polytropic exponent is $n = 1$. The Simulink block model for the internal chamber capacity is shown in figure 47.

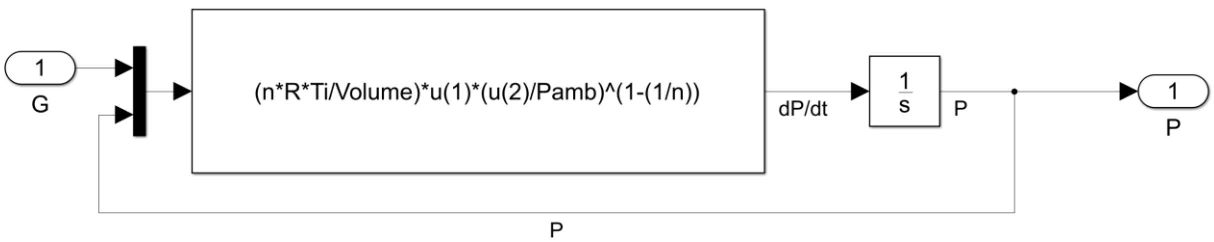


Figure 47: model of the internal chamber of the bearing

Then it was modeled the exhaust hole of the bearing considering the classic equation of the airflow through a nozzle, in which it must distinguish whether it is flowing in sonic or subsonic condition

- subsonic flow $\frac{P_2}{P_1} > b$

$$G_{in} = \frac{\pi d_s^2}{4}\psi P_s c_d \sqrt{1 - \left(\frac{\frac{P_c}{P_s} - b}{1 - b}\right)^2}$$

- sonic flow $\frac{P_2}{P_1} \leq b$

$$G_{in} = \frac{\pi d_s^2}{4}\psi P_s c_d$$

with:

- G_{in} air flowing from the exhaust hole;
- d_s hole diameter ($d_s = 0{,}26 * 10^{-3} m$);
- P_s absolute inlet pressure [Pa];
- P_c absolute outlet pressure [Pa];
- $\psi = \frac{0{,}685}{\sqrt{RT}}$ with $R = 287 J/kgK$ and $T = 288K$

- b air critical ratio ($b = 0{,}528$)
- c_d hole flow coefficient:

$$c_d = 0{,}85\left(1 - \left(e^{-8{,}2\frac{h}{d}}\right)\right)$$

where h is the sum of the air film under the bearing and the distance between the hole and the bench surface. From the detail exposed in figure 48, it can be seen that the distance between the hole and the bench surface depends on the characteristic of the bearing and is equal to $550\mu m$.

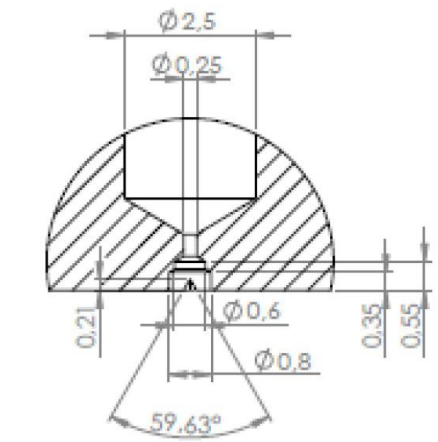


Figure 48: detail of the bearing exhaust hole

Since the value of the air film gap is much lower with respect to the distance between the hole and the bench surface, for easier calculation the flow coefficient has been kept constant with a value of 0,85. The model of the exhaust hole under the bearing is shown in figure 49.

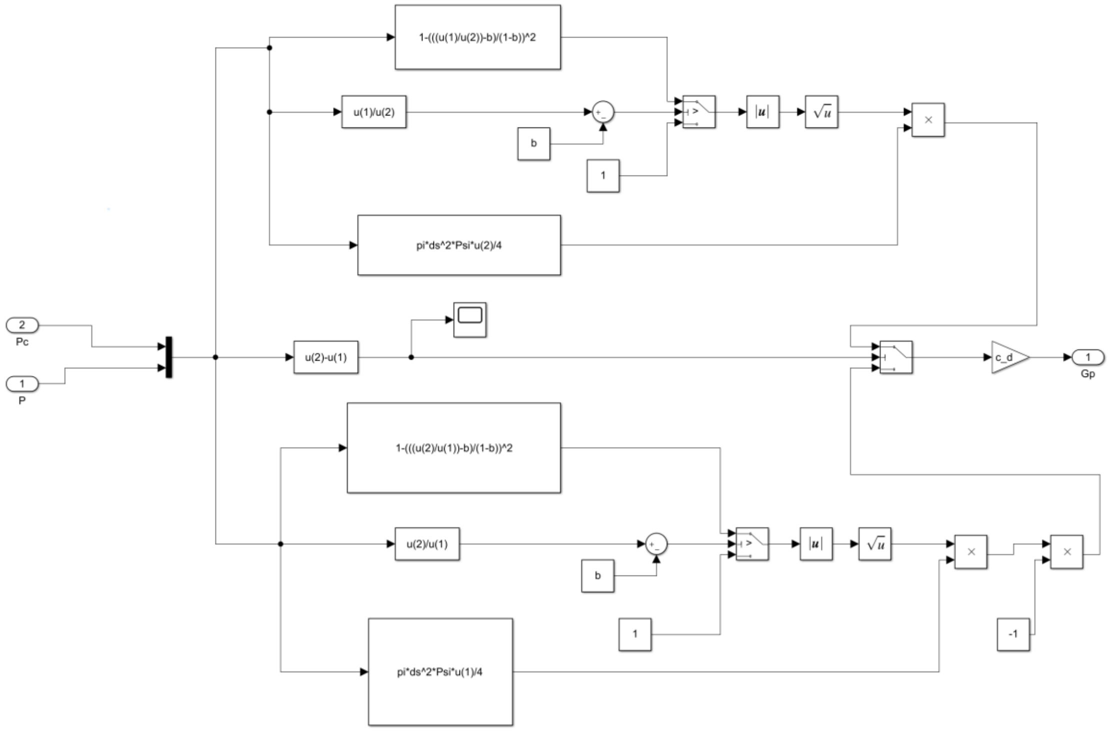


Figure 49: model of the exhaust hole of the bearing

Regarding the model of the capacity of the air film under the bearing, it must be considered that is not a constant volume like the internal chamber, but it is variable according to the measure of the air gap

$$V = L_1 L_2 h$$

where L_1 and L_2 are the length and width of the bearing, h the thickness of the air film and V the variable volume of air.

Moreover, it has to be considered that the pressure used for the calculation is the mean one, P_m, which is different from the pressure at the center of the lower surface of the bearing. Considering an isothermal process (n=1), like the process for the internal chamber, the equation for the calculation of the variable capacity is

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

Since the tests executed are static ones, with a constant air film gap, the first component of the equation is null and the equation becomes exactly as the equation used for the calculation of the internal chamber capacity and the Simulink model used is the same.

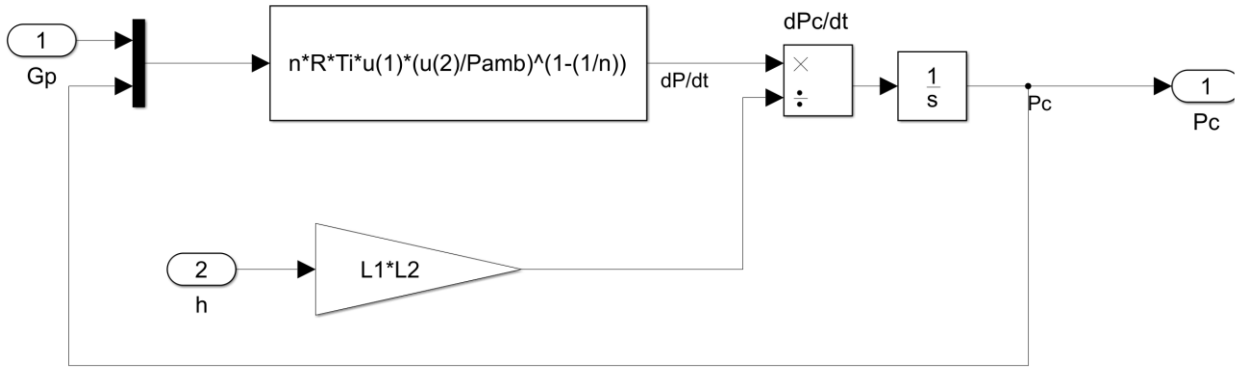


Figure 50: model of the pneumatic capacity of the air film gap

Before starting the modeling of the air film pneumatic resistance, it must be noted that for the calculation of the air film capacity it has been used the mean pressure, not the maximum. Considering a pyramidal distribution of the pressure under the bearing, with the maximum value at the center and the minimum value along its lower surface perimeter, it is possible to compute the pressure at the center of the bearing knowing that

$$P_m = \frac{P_C - P_a}{3} + P_a$$

with P_m mean pressure, P_a ambient pressure and P_c pressure at the center of the bearing. Rearranging the equation, it is possible to compute the maximum pressure

$$P_c = 3P_m - 2P_a$$

The formula for the calculation of the pneumatic resistance of the air film is

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

with

- G_{out} air flowing out of the bearing [*kg/s*]
- c_h bearing coefficient equal to 0,8 [s/m^2]
- h height of the air film
- P_{amb} ambient pressure [*Pa*]
- P_c pressure at the center of the bearing [*Pa].*

The model of the pneumatic resistance of the air film is shown in figure 51.

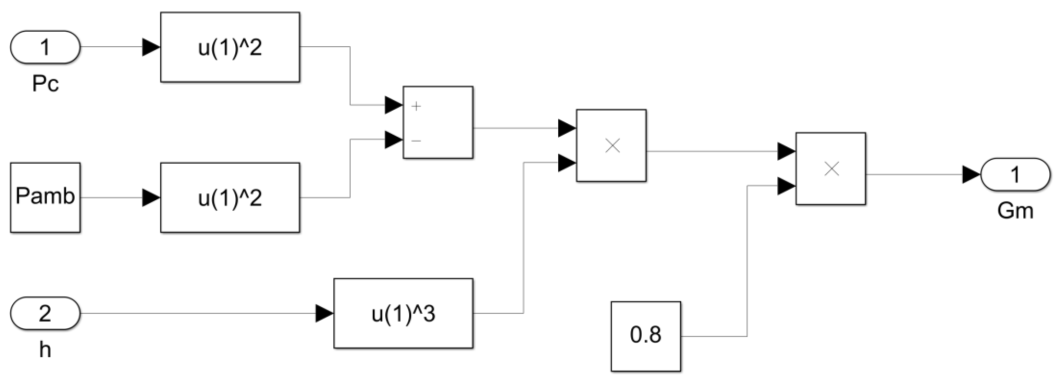


Figure 51: model of the pneumatic resistance of the air film

The last subsystem of the model is responsible for the calculation of the lift produced by the bearing starting from the pressure generated in the air film. The equation used is

$$F = (P_c - P_{amb})\frac{L_1 L_2}{3}$$

The model for this equation is shown in figure 52.

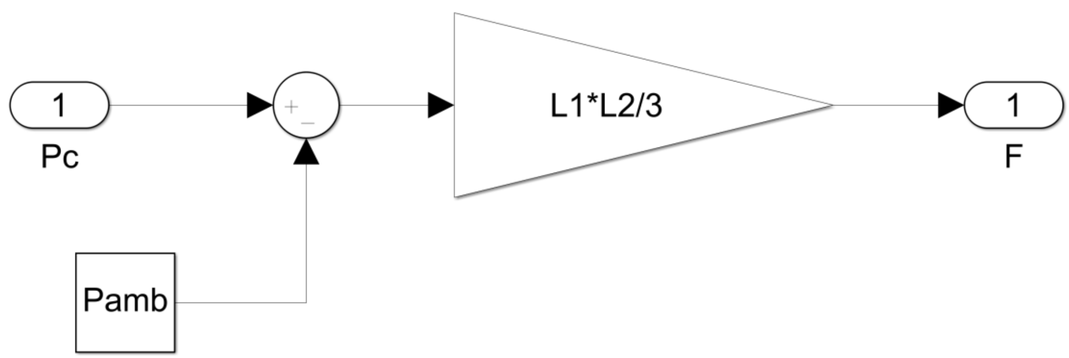


Figure 52: model for the calculation of the force produced by the bearing

Open Loop model

After all the pneumatic components of the system, from the proportional valve to the air bearing, have been modelled, it is possible to assemble them together and obtain the open loop model of the system, which is shown in figure 53.

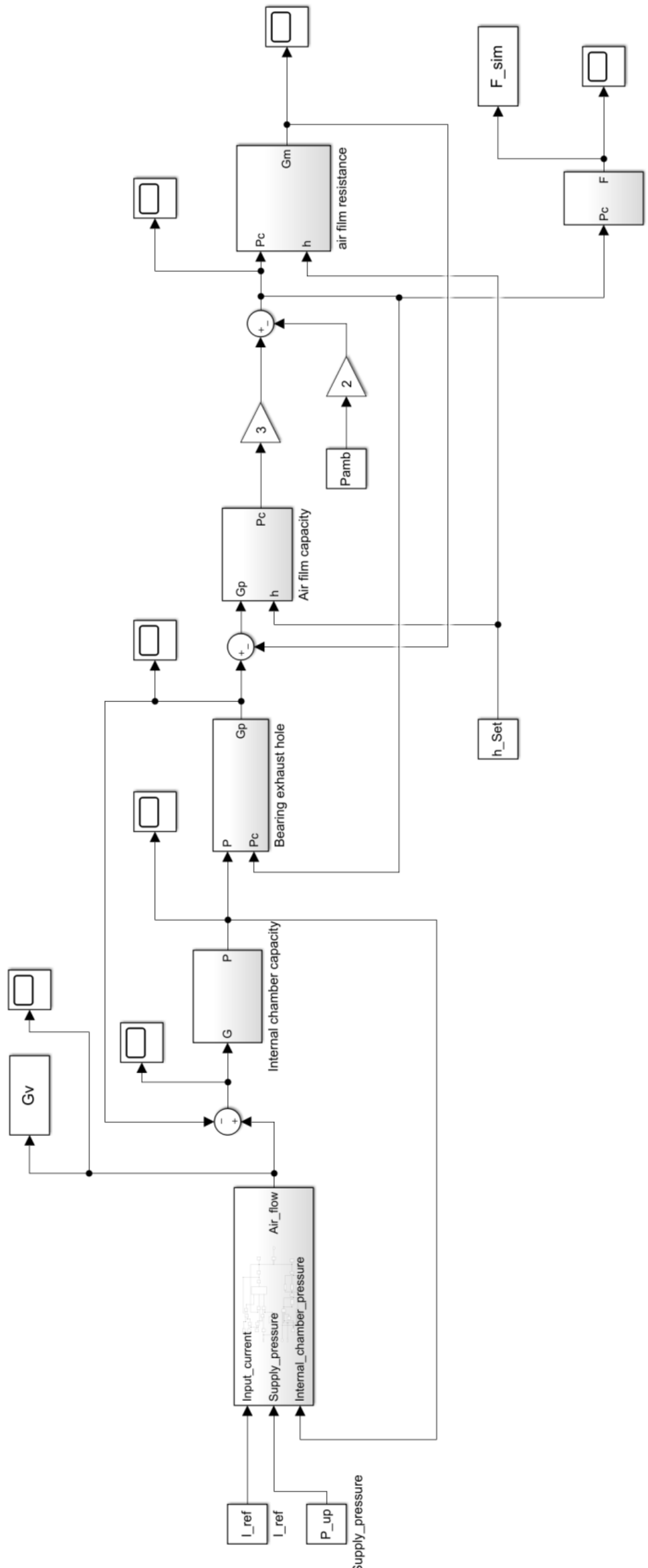


Figure 53: model of the open loop system

Open loop simulation results

After having designed the open loop Simulink block model, it has been simulated in order to see if the results given are comparable to the results obtained through the experimental tests. In the following figures there are shown the simulated values with the values obtained through the experimental tests. For different pressure supplies and different opening of the proportional valve, the values obtained from the model has been confronted with the mean value of the sensors on the left and on the right.

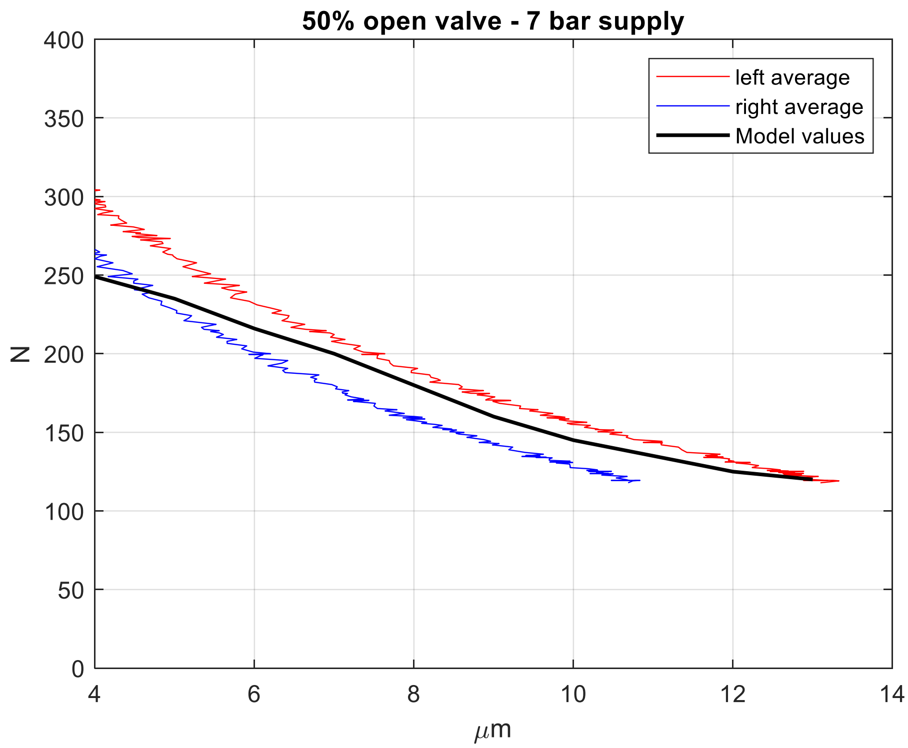


Figure 54: simulated and experimental force at 7 bar supply and 50% opened valve

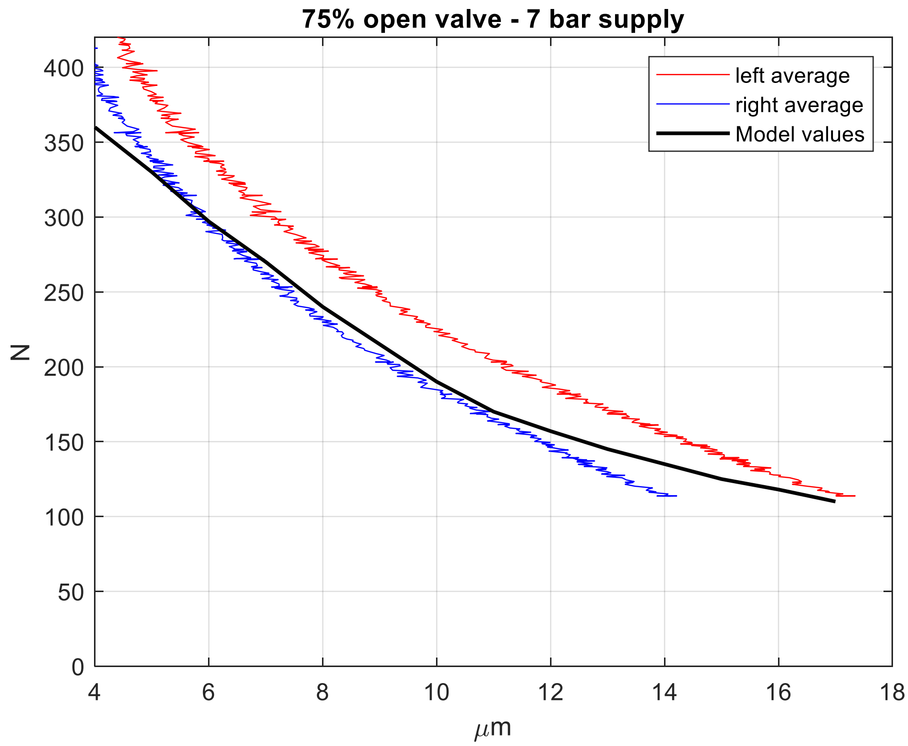


Figure 55: simulated and experimental force at 7 bar supply and 75% opened valve

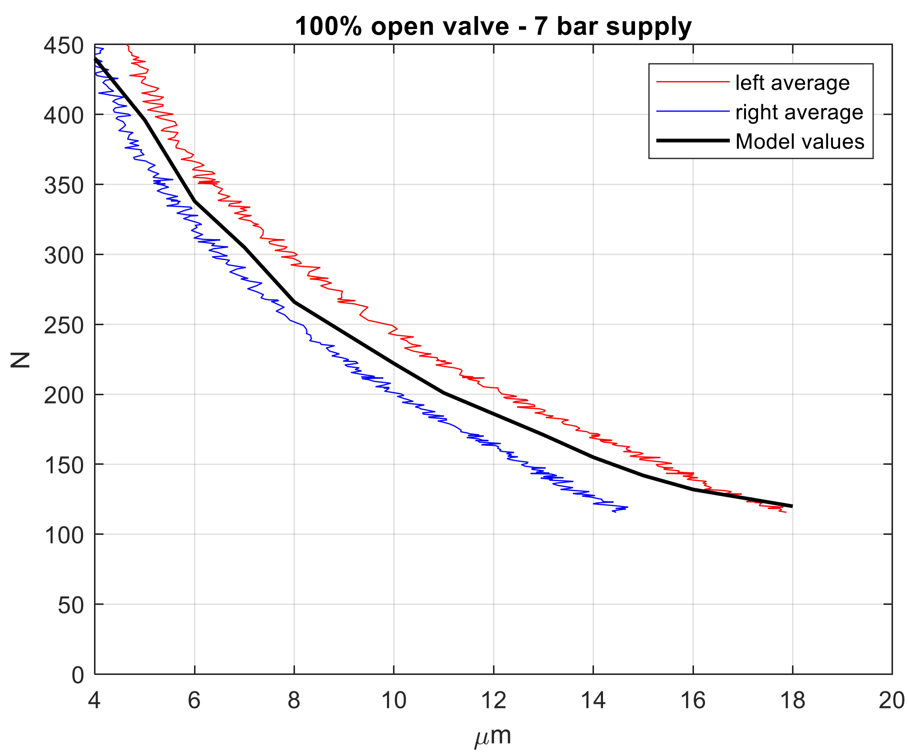


Figure 56: simulated and experimental force at 7 bar supply and 100% opened valve

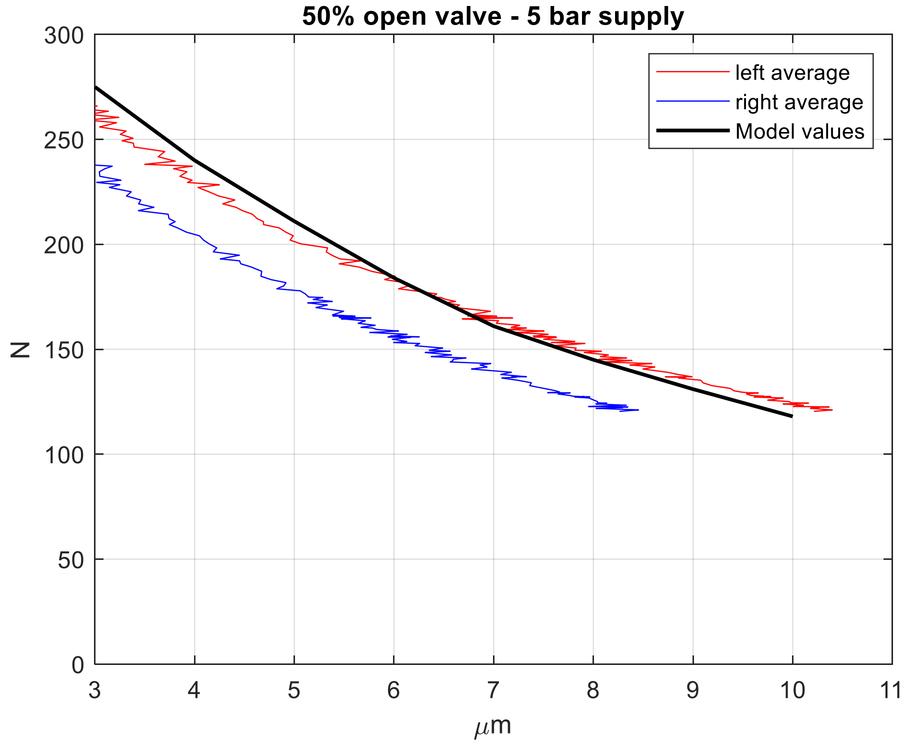


Figure 57: simulated and experimental force at 5 bar supply and 50% opened valve

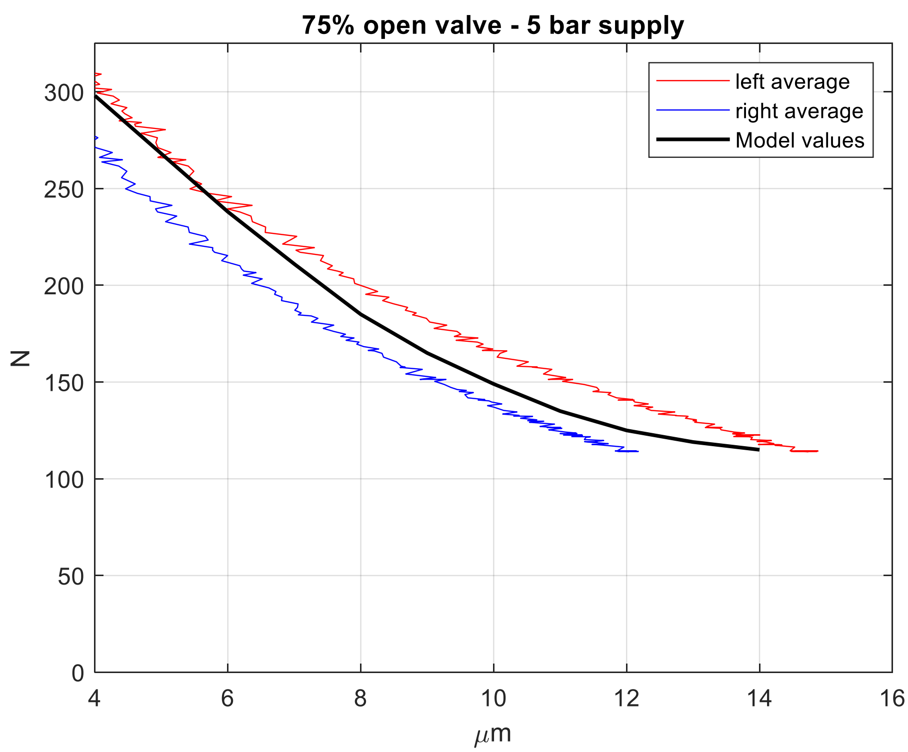


Figure 58: simulated and experimental force at 5 bar supply and 75% opened valve

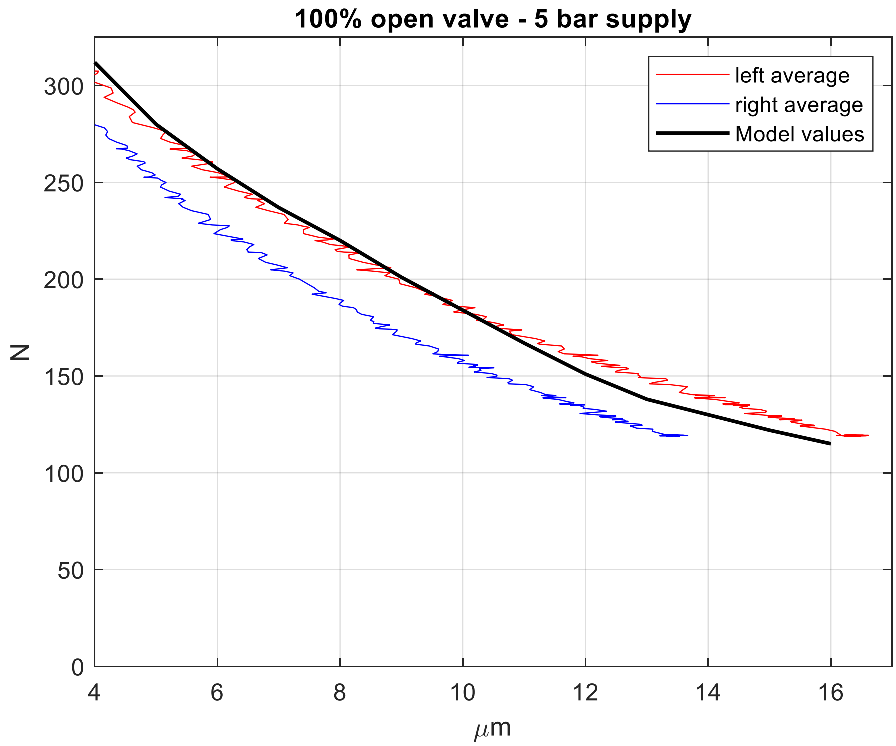


Figure 59: simulated and experimental force at 5 bar supply and 100% opened valve

From the graphs presented above it can be seen that the model is quite accurate because the values obtained fall almost always in the gap between the two means of the sensors, especially in the range of working of the bearing. In fact, pneumatic bearings usually work with an air film thickness around the value of 10µm. Then the model represents quite accurately the mechanical system analyzed in this work and it is possible to design the closed loop model by closing the control loop.

Closed Loop Model

The closed loop model of the pneumatic system has been modeled starting from the open loop model and connecting the feedback of the air film with the current signal using a PID technique. It must be taken into account that the next tests are dynamic and not static like the previous ones. Then the equation used for the calculation of the pneumatic variable capacity of the air film under the bearing is the more general one

$$G = \frac{dP_m}{dt}\left[\frac{P_m}{RT}L_1L_2\frac{dh}{dt}\frac{dt}{dP_m} + L_1L_2\frac{h}{RT}\right]$$

In the static tests the first term of the equation was null because the air film gap was constant. In these tests the air film gap can change and so does the capacity relative to it, which can be calculated rearranging the previous equation

$$\frac{dP_m}{dt} = G\frac{RT}{L_1L_2h} - \frac{P_m}{h}\frac{dh}{dt}$$

In figure 60 it is shown the Simulink model for the air film capacity used for the dynamic tests. It can be seen that there is a saturation block for the height of the air film. The saturation block is necessary since it is not possible to have a negative value for this measure because, in the real test, it is limited inferiorly by the presence of the test bench surface.

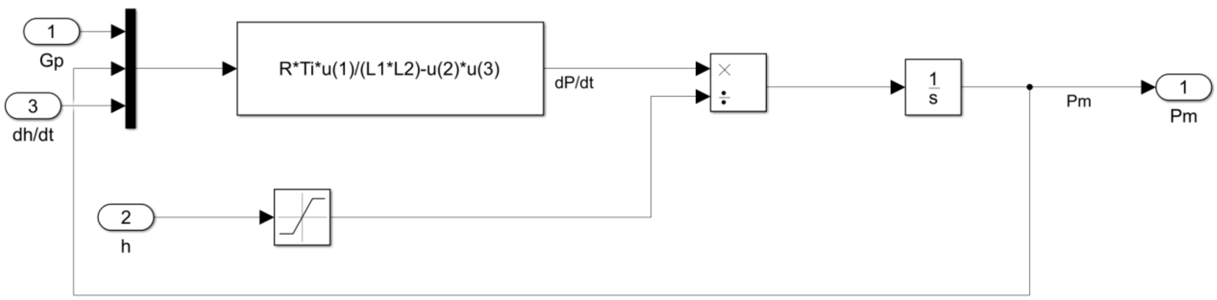


Figure 60: model of the air film capacity for dynamic test

For what concern the dynamic tests, from the vertical equilibrium equation it is possible to compute the air film generated under the bearing, which was not needed in static tests. The equation for the vertical equilibrium of the bearing is

$$(P_c - P_{amb})L_1L_2 - (F + mg) - \left(m + \frac{F}{g}\right)\ddot{h} = 0$$

with

- P_c is pressure at the center of the bearing
- P_{amb} is the ambient pressure (1 bar)
- L_1 and L_2 are the length and width of the bearing
- F is the external force applied above the bearing
- m is the mass of the bearing (0,3kg)
- g is the gravitational acceleration
- $\ddot{h}$ is the vertical acceleration of the bearing

In figure 61 it is shown the block model for the computation of the vertical acceleration of the bearing during the dynamic tests.

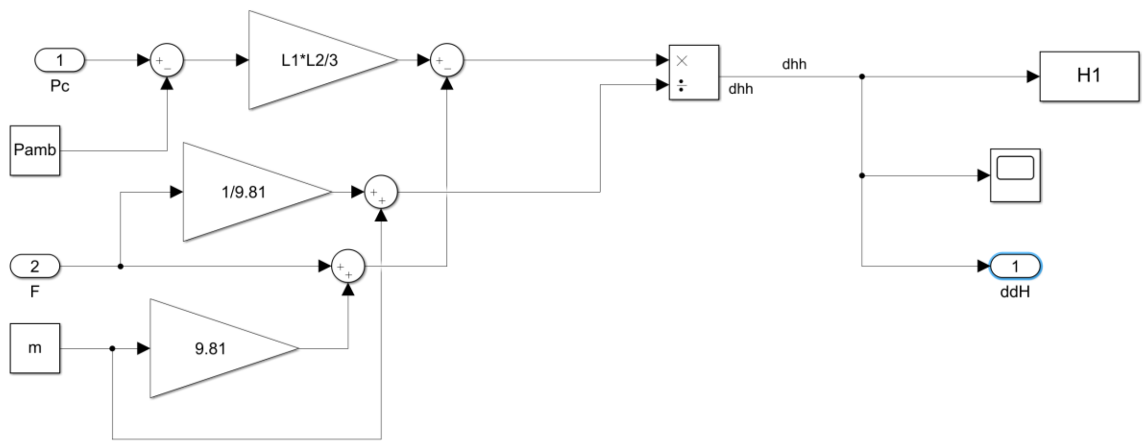


Figure 61: Simulink model for the computation of the vertical acceleration of the bearing

At this point it is possible to construct the complete model for the closed loop system. The model is shown in figure 62.

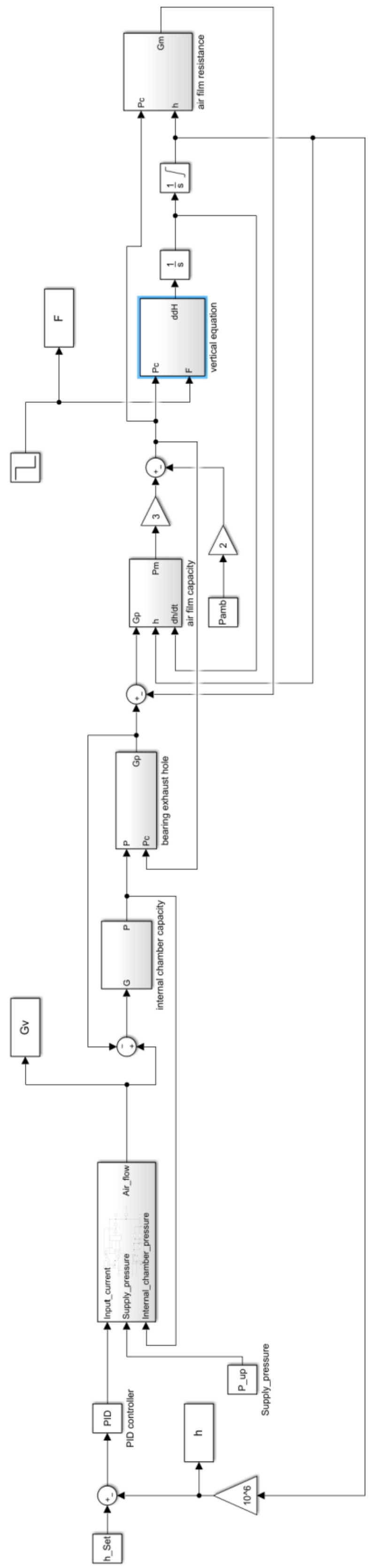


Figure 62: closed loop model of the complete system

Closed loop simulation results

The Simulink model of the closed loop system has been executed imposing a reference value for the air film under the bearing. The values of the PID controller block have been modified in order to have the best resulting response of the system. The tests have been simulated with the block of the proportional valve supplied at 5 bar. Starting from a value of zero, which represents the thickness of the air film under the bearing, the system firstly reacts to reach the reference value imposed. After the system is stable at the reference value, the force applied changes and the system is forced to react against the variation of load. In the following graphs it is exposed how the system reacts to a step variation of the force applied.

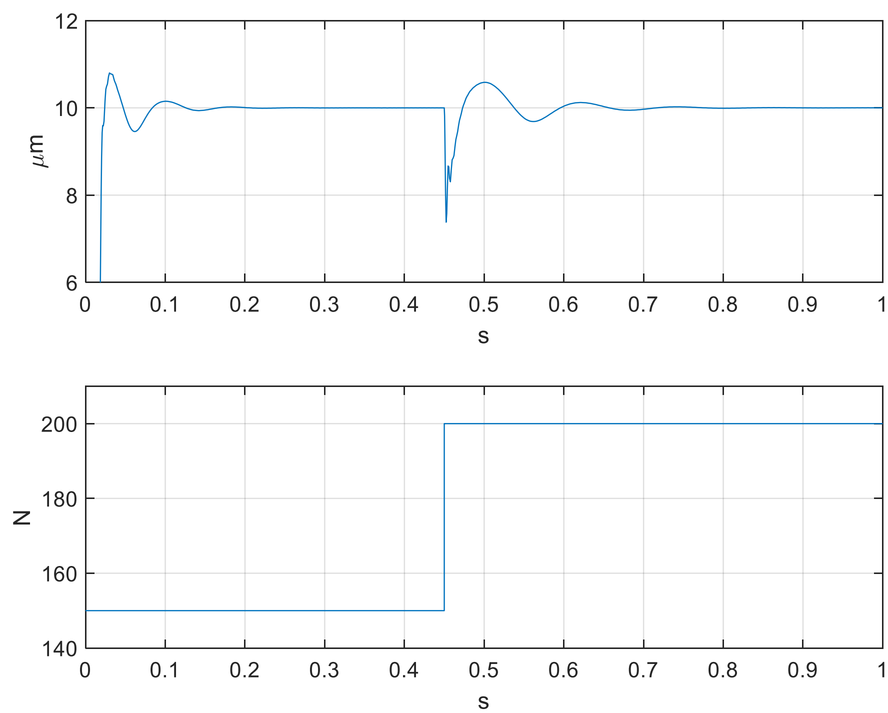


Figure 63: step response with 10µm reference

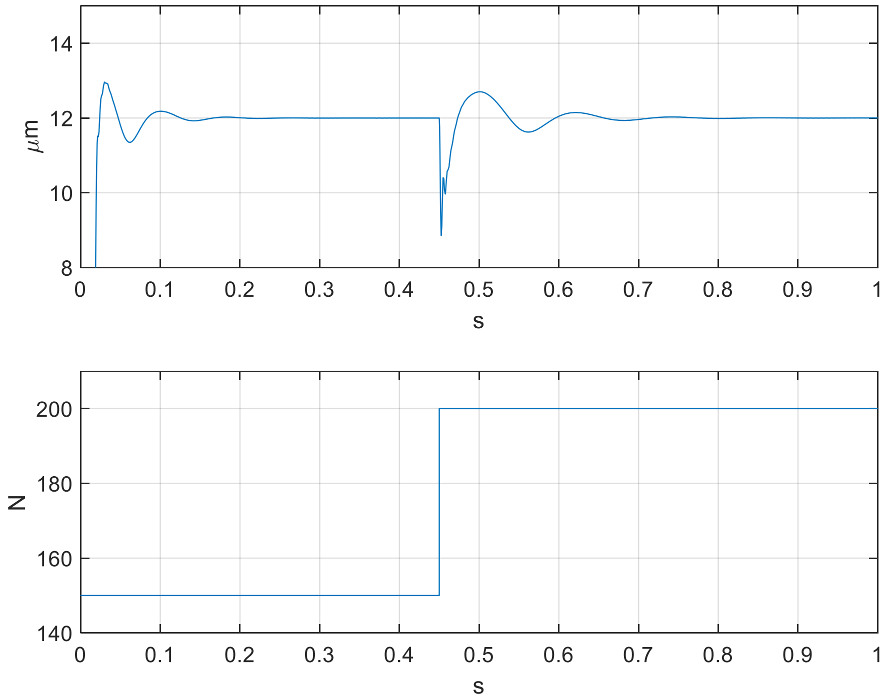


Figure 64: step response with 12μm reference

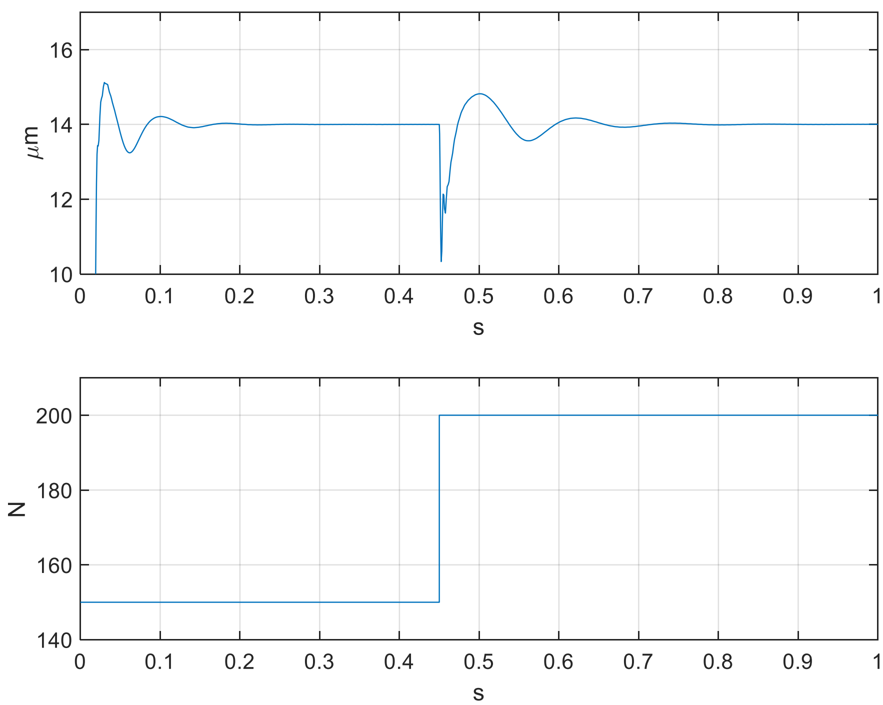


Figure 65: step response with 14μm reference

The reference values imposed to the system are 10, 12 and 14 µm, and it is imposed a step load, which increases from 150N to 200N.

From the graphs above it can be seen that the simulated system response has some oscillation before stabilizing to the reference value. This is due to the behavior of the pneumatic proportional valve. In fact, in the chapter where the valve was analyzed, the damping factor obtained through the experimental tests was quite a low value. Such a low value of damping creates oscillation in the airflow that are reflected in oscillation of the bearing before reaching the steady reference value.

The step variation of the lift applied increases from 150N to 200N, thus requiring the proportional valve to be more open and let a greater quantity of air to flow. Before reaching again the reference value, the value of the air film decreases. This decrease is not constant for all the simulated result. It can be noted that the higher the reference value, the higher is the decrease of the air film when the load increases. This is due to the fact that with higher values of the air film under the bearing, the stiffness of the system decreases which causes to have a wider oscillation.

Conclusions

The aim of this work of thesis is to design and model an active air thrust bearing controlled via a proportional valve. The purpose of this system is to keep a constant air film under the bearing when the load applied changes.

At first it was designed the control circuit needed to drive the valve, in order to have the desired value of current flowing through the solenoid corresponding to a proportional opening of it. With the use of an electronic board capable to deliver a proportional voltage signal, it was possible to have a proportional current given by the circuit. Before making the current drive circuit, it was designed an analogous one with the use of Simulink in order to check if thee behavior is the one to be expected.

Subsequently, many experimental tests have been executed. It was analyzed the behavior of thee proportional pneumatic valve in static and dynamic domain. In this way it was possible to have a correlation between the current fed to the valve with the air flow output related to the supply pressure of the valve.

Then it was checked the behavior of the backpressure sensors. They have been tested alone and mounted on the pneumatic bearing. The sensors are needed in order to close the control loop of the system.

Open loop tests have been executed on the complete system. With different pressure supplies, it was analyzed the lift capacity of the system for different values of opening of the pneumatic proportional valve. These tests helped to understand how much load the bearing can lift.

Then it was designed a Simulink model of the complete system. At first it was designed the model of the proportional valve, considering it a second order system where the parameters are the one obtained through the experimental tests. After that, it was modeled the bearing itself considering it as a constant pneumatic resistance and capacity associated to the bearing characteristics and a variable pneumatic resistance and capacity associated to the air film under it. The complete model was then simulated in open loop to check if the values obtained are comparable to the values of the experimental tests. It was also simulated the system in closed loop, by adding a PID controller. The parameter of the PID controller have been tuned in order to have the best response of the system. By setting a reference value of air film under the bearing, it was simulated how the system responds to a change in the load applied above it.

Bibliography

Matteo Troiano, “Srudio del controllo di un pattino ad aria con valvole pneumatiche integrate” Tesi di laurea, Politecnico di Torino (2016)

Robert H. Bishop, Mechatronic Systems, Sensors, and Actuators: Fundamentals and Modeling, CRC Press

Attachments