UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

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Ultra-fast Sensor for Pressure Measurements in Shock Waves

Tesis en torno a una hipótesis o problema de investigación y su contrastación

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Ultra-fast Sensor for Pressure Measurements in Shock Waves

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DEDICATION

To God for keeping me in good health even in these difficult times we have all had to live.

To my beloved wife from whom I have received so much love and support in this year away from home.

To my dear son who is the reason to be a better professional.

To my parents who made possible my academic studies without which I could not have been here.

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To the teachers of the USFQ and the ENSEEIHT for all the knowledge received.

To my LAAS-CNRS tutors, Patrick and Antony, who accepted my collaboration in their project and from whom I have learned a lot.

To my classmates and friends of the master, in Quito during the M1 and in Toulouse during the M2, they made my days away from home better.

RESUMEN

El presente reporte recapitula el trabajo de la pasantía de fin de estudios para obtener el grado de Master of Science en la USFQ y se llevó a cabo en el laboratorio LAAS-CNRS en Toulouse, Francia.

El proyecto COCNANO tiene como objetivo el diseño y fabricación de un sensor de presión ultra-rápido para ondas de choque, este sensor permite detectar el instante en el que la onda de choque generada por una explosión lo atraviesa obteniendo una señal eléctrica.

El sensor consiste en un puente pasivo de galgas extensiométricas alimentado por una batería de 9 V diseñado y construido en el laboratorio, el cambio en el valor de las resistencias del sensor es registrado y transformado a una señal variable de voltaje que ingresa en un amplificador diferencial, luego, la señal amplificada es medida y se la interpreta como la representación eléctrica de la explosión.

Debido a que la variación medida en el sensor es muy pequeña, es necesario eliminar o al menos reducir todas las fuentes de ruido, también debe tomarse en cuenta que el uso de un amplificador diferencial implica un diseño de circuito tan simétrico como sea posible con el propósito de evitar cualquier desajuste que genere un voltaje no deseado en modo común.

La primera parte de la pasantía consiste en caracterizar eléctricamente el sensor y su acondicionamiento ya fabricados para obtener un modelo virtual usando el programa ADS de Keysight Technologies y así efectuar simulaciones cuyo resultado sea validado con los datos reales obtenidos experimentalmente en un tubo de choque en el laboratorio.

En la segunda parte, el origen del ruido presente en el prototipo fabricado es identificado y se rediseña el modelo utilizado en las simulaciones para reducir el voltaje en modo común para que posteriormente sea posible volverlo a fabricar implementando las mejoras propuestas.

Palabras clave: caracterización, ruido, voltaje en modo común, PCB, simetría, parásitos.

ABSTRACT

This report summarizes all the work of an end-of-studies internship to obtain the USFQ Master of Science diploma and took place at the LAAS-CNRS in Toulouse, France.

The COCNANO project has the objective of design and manufacture an ultra-fast sensor for pressure in shock waves, it allows to detect the moment when the shock wave generated by an explosion passes through a sensor to then understand the electrical signal produced.

The sensor consists of a passive bridge of gauges with a 9 volts battery power supply designed and built in the laboratory, the variation of resistance produced in this sensor is transformed to a signal of variable voltage that goes to a differential amplifier, later, the amplified signal is measured and is the electrical representation of the explosion.

Since the variation in the sensor is very small, it is necessary to eliminate or reduce all sources of noise, it should also be considered that the use of a differential amplifier implies a design as symmetrical as possible in order to avoid any mismatch that may produce an undesirable signal in common mode.

The first part of the internship consisted in characterizing the sensor and the conditioning circuit already manufactured to obtain a model using software ADS by Keysight Technologies and perform simulations whose results are validated with the data obtained in real experiments employing a laboratory shock tube.

In the second part the origin of the noise present in the first model of the project was identified and by modifying the design in the simulations it was possible to reduce the undesirable signal to later manufacture it and implement the changes.

Key words: characterization, noise, common mode voltage, PCB, symmetrical design, parasitics.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

This end-of-studies internship completes the master's degree of Science and Technologies in Nanoelectronics with mention in Embedded Systems and Integration at San Francisco de Quito University (USFQ), which has taken place at the Laboratoire d'Analyse et d'Architecture des Systèmes (LAAS) of the Centre National de la Recherche Scientifique (CNRS) in Toulouse, France.

This internship is part of COCNACO project at Micro and Nano Systems for Wireless Communications team led by Patrick Pons, research director, and Antony Coustou, research engineer.

Before presenting the status of this project certain basic concepts must be explained, that will make it possible to fully understand the activities made.

1.1 Basic concepts

1.1.1 Explosion

An explosion is defined as the sudden release of energy in the form of heat, sound, and light. Usually, an explosion is produced by man either on purpose or not, the amount of energy generated depends on the type and amount of explosive involved in the explosion as Figure 1 shows.

Figure 1: Various stages of the explosion in Beirut on August 4th of 2020.[1]

1.1.2 Supersonic explosion

Immediately afterwards, molecules near the origin of explosion are accelerated when part of the released energy is transformed into kinetic energy. If the amount of energy is high enough, the propagation speed can be lower or higher than the speed of sound in the medium, classifying the explosion as subsonic or supersonic, respectively.

1.1.3 Blast wave

A supersonic explosion can accelerate nearby air molecules causing a strong wind and an overpressure for a very short time but enough to move and break solid objects, the air overpressure propagates from the origin of explosion taking the form of a spherical surface whose radius increases at the speed of propagation, figure 2 shows this spherical surface which is called a blast wave and is one of the destructive effects of the explosion.

Figure 2: Picture of a blast wave with its typical spherical shape.[2]

1.1.4 Blast wave overpressure

When an object makes contact with a blast wave, it is subjected to an overpressure whose magnitude can reach 140 kPa depending on the power of previous explosion.

Due to the supersonic speed at which it travels, the blast wave can move away from the center of the explosion very quickly, then the air pressure around the object increases abruptly to its maximum value and immediately decreases almost as fast until it returns to atmospheric pressure, this is called the positive phase.

After that, the pressure continues decreasing but at a much lower speed compared with the previous phase reaching a relatively low negative value to finally increase its value again more or less at the same speed to reach the atmospheric pressure and stay in that value, this is called negative phase. Figure 3 illustrates this phenomenon:

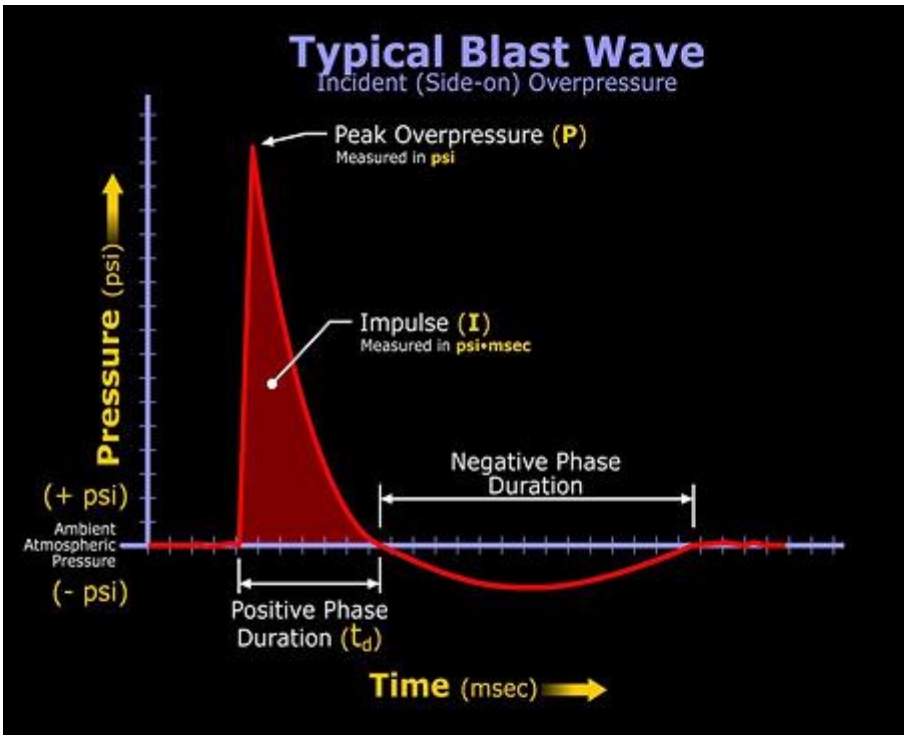

Figure 3: Typical blast wave curve.[3]

1.1.5 Piezo resistive strain gauge for measuring pressure

One of the most used devices to measure environmental pressure is the piezo resistive strain gauge which consists of a membrane containing various embedded resistors. One side of the membrane is in contact with a small vacuum chamber, while the other side is in contact with the surrounding atmosphere so this membrane senses both pressures and deforms itself due to this difference, on figures 4 and 5 we can see the structure of a sensor.

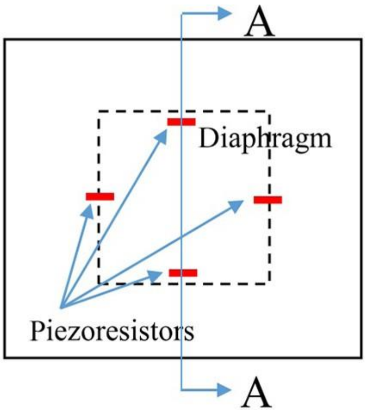

Figure 4: Top view of piezo resistive gauge structure.[4]

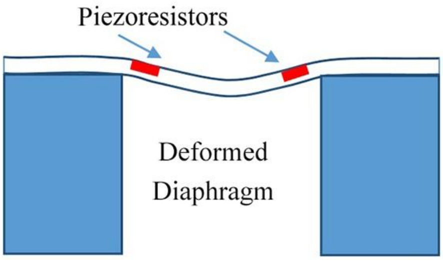

Figure 5: Cross section of piezo resistive gauge structure, the double arrow A-A in top view is the reference line for the cross section.[4]

The deformation causes that resistances in the membrane change their value and can be measured if they are connected to a power supply.

1.2 Status of the project

The COCNANO project develops a system with piezo resistive pressure sensor signal specifically designed for explosions. The main objective is to achieve a much faster measurement than actual commercial sensors. Therefore, the sensor to be developed must operate within a high bandwidth and show low harmonic distortion. Actual sensors have a bandwidth between 100 kHz and 1 MHz.

A simple diagram on figure 6 shows the stages of the project.

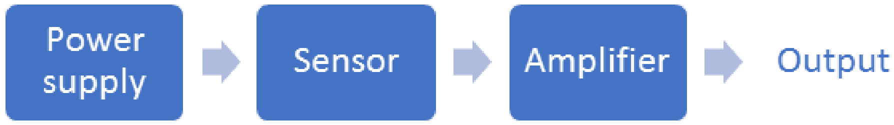

Figure 6: General block diagram of the system.

1.2.1 Sensor

This project uses a piezo resistive sensor that reacts to a stimulus such as pressure variation, the signal generated is too small so it is necessary a conditioning circuit to deliver a more measurable voltage and to be able to relate it to the mechanical stress applied to the sensor membrane. For this sensor and its conditioning circuit, the bandwidth is 40 MHz.

For mechanical and acoustic reasons, the sensor must be as compact as possible, to reduce parasitics caused by the connections, the power supply and the conditioning stage are located as close as possible to the sensor.

For experimental purposes, several tests of the sensor design were made but their components and general shape are the same varying, for example, in their thickness and doping to obtain electrical characteristics of different value.

The top side of the sensitive membrane sens the atmospheric pressure and deforms itself depending on the difference with the vacuum chamber on its bottom side, this chamber is sealed by a glass substrate and finally this device has been mounted on a metal casing connected to the ground of the whole system.

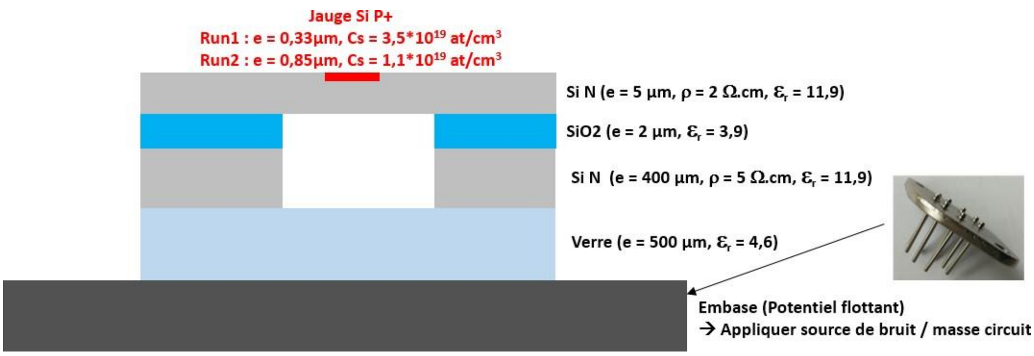

Figure 7: Section of piezo resistive sensor with values of thickness (e), linear resistivity (ρ) and relative permittivity (εr).

Figure 7 illustrates each layer of device. The sensor consists of four resistors arranged in a Wheatstone bridge of piezo resistive strain gages engraved on a deformable silicon membrane. The bridge is supplied by a symmetrical voltage source and provides a differential voltage which is proportional to the deformation of diaphragm generated by an overpressure on the top side of the sensor.

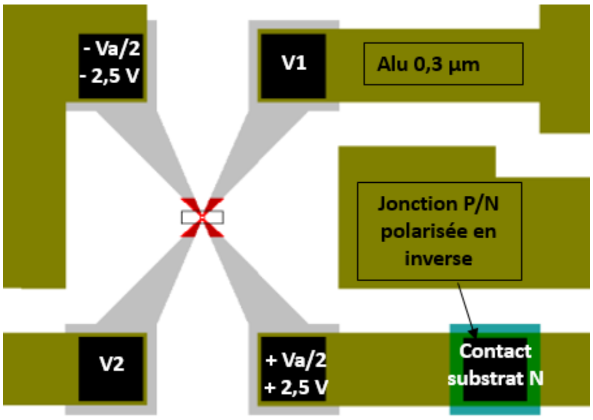

Figure 8: Top view of fabricated sensor.

Figure 8 displays the top view of sensor. Two contacts called V1 and V2, which constitute the sensor output and are connected to the input of the conditioning circuit, and two more contacts called +Va/2 and -Va/2 to which the symmetrical power supply of 2.5V and -2.5V respectively is connected.

An 8-pin TO-3 connector is used for the connection between the sensor and the conditioning system (figure 9), since the piezo resistive sensor located on one of the side of the shock tube has been fabricated with this type of case.

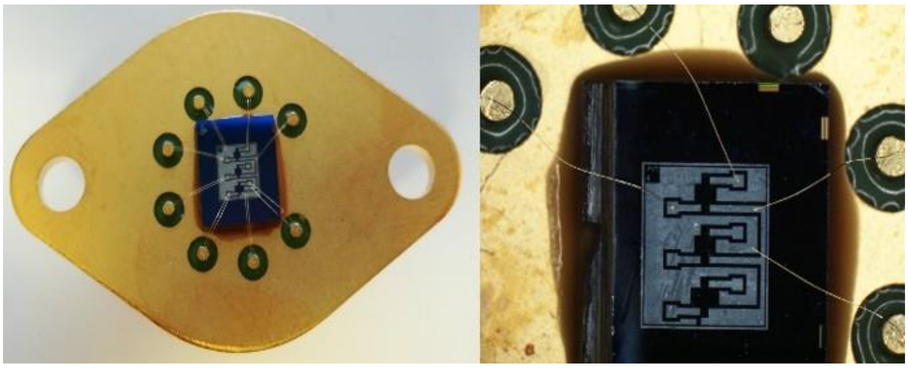

Figure 9: Piezo resistive pressure sensor in TO-3 case mounting.

1.2.2 Power supply and conditioning stage

A THS4520RGTT Texas Instruments differential operational amplifier with a gain bandwidth of 600 MHz is used for the conditioning stage.[5]

This amplifier requires a symmetrical power supply shown on figure 10, the value of +2.5V and -2.5V has been chosen to obtain these voltage levels through a resistive voltage divider from a 5V voltage regulator previously powered by a 9V battery.

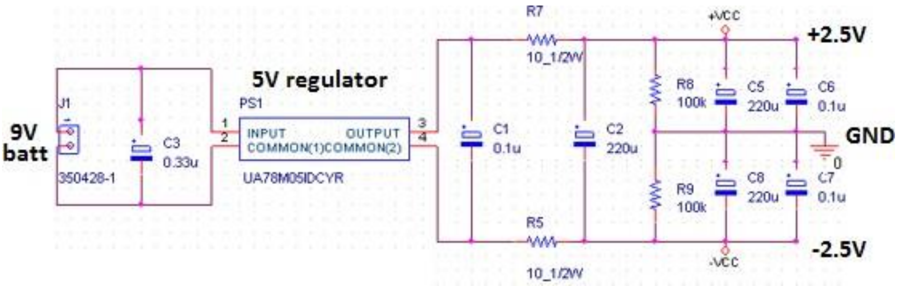

Figure 10: Schematic of power supply stage.

The gain of the amplifier is set at 22 using two 3.3 kohm resistors as negative feedback and two 150 ohm resistors on the differential input lines and finally, two more 50 ohm resistors have been connected to the OpAmp output for coupling with an oscilloscope coaxial cable on each line to measure the individual and differential voltage. The figure 11 shows this part of the project.

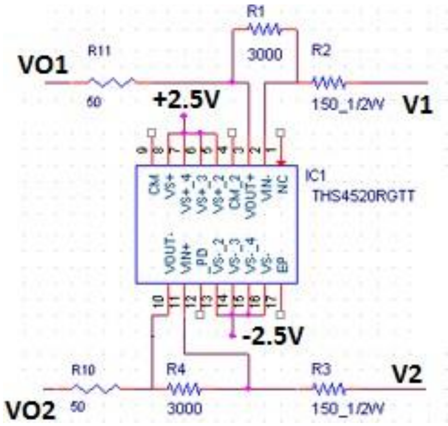

Figure 11: Schematic of conditioning stage, V1 and V2 pins are for sensor outputs, VO1 and VO2 pins are for conditioning outputs.

Both power supply and conditioning stages have been integrated on a PCB (figure 12) with their respective connectors to the sensor, battery, and oscilloscope.

Figure 12: Conditioning and power supply stages on PCB circuit.

Several tests have been made in the laboratory to check the operation of the sensor and its amplification, a shock tube (figures 13 and 14) is used which accumulates pressure thanks to a compressor at the entrance, a membrane is placed in the middle of the length of the tube closing the first half of the tube and which will break when the pressure reaches a desired value, in the second part of the tube the sensor is placed and will measure an abrupt increase in pressure when the seal is broken.

Figure 13: Shock tube from lab.

Figure 14: Connections between sensor and conditioning circuit.

1.3 Statement of the problem

To measure the performance of the whole system, it has been compared with the signal produced by a commercial sensor as a reference, it can be clearly seen that the voltage levels of both sensors detect the overpressure simultaneously, it means that the system works, so for obtain the same voltage values it would be enough to modify the conditioning stage to get a signal at the desired levels, but the system presents noise before, during and even after the overpressure stimulus as shown on figure 15.

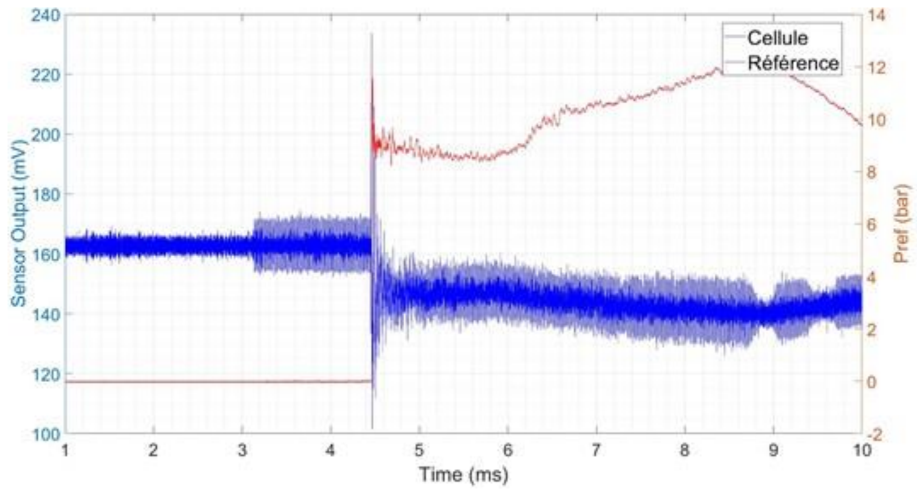

Figure 15: Voltage signal from sensor and conditioner (blue) and pressure measurement from a commercial sensor (red) vs time.

1.4 Objectives of the internship

A noisy signal is undesirable because it makes difficult to analyze properly the mentioned signal, so it is imperative to reduce the noise.

First, it is necessary to perform a characterization of the hardware that includes the sensor, power supply and conditioning stage considering parasitics and coupling elements from the PCB for analyze it in common mode, for that purpose the software ADS by Keysight Technologies will be used.

Once a valid model is obtained, that is, a simulation as similar as possible to the real data got by the system and the connection cables, the origin of the mentioned noise must be identified and consequently confirmed that a symmetrical redesign using the software DesignSpark by RS will be a very simple solution to the problem. At the end, a more efficient PCB for the same system will be generated.

1.5 Research question

In a PCB, can undesirable common mode signal be reduced using characterization for symmetrical redesign instead manufacture it over again?

CHAPTER 2: REVIEW OF THE LITERATURE

Since the problem is an undesirable high common mode voltage, the technique to solve it was discussed by the participants of this project and defined: do an electronic characterization for confirm that the sources of noise signal are mismatches on circuitry due the asymmetrical actual design and then reconfigure the components on the PCB to reduce the noise, what remains to be done is to know the procedure for the characterization using ADS software by Keysight Technologies and redesign the PCB using DesignSpark software by RS. Therefore, the documents are cataloged into 2 groups: data sheets and manuals.

2.1 Data Sheets

Also searched as specifications, their purpose is to get all the electrical parameters of every component in the system before their characterization. It is very important those documents include performance graphics because the system works in a specific frequency range, so it is needed a range of values instead only one.

Since the project had already started before the present internship, several lots of the components to be used had already been purchased, so the search for information was done on known manufacturers' websites.

2.2 Manuals

For a correct characterization, simulations must be performed with specific tools provided by the software selected for this activity, this means there is a lot of different functions but only the useful ones will be considered. This information will be found on a known company website which developed the software is used in the project.

A similar criterion will be employed for the redesign, using the database of the company that owns the design software for the new PCB.

CHAPTER 3: METHODOLOGY AND DESIGN OF RESEARCH

The activities of this internship respond to a quantitative experimental study because the information previously collected (secondary data) and obtained at the end (primary data) are of a numerical nature; if these data meet certain mathematical conditions, it will be possible to conclude whether the research was successful or not.

In the characterization experiment, independent variables are the electrical parameters to be loaded in the simulation of the system with the objective of obtaining a response, which is the dependent variable, as close as possible to real circuit one. All those electrical parameters are in data sheets of devices used in the project; for the other hand, in the simulation it is necessary to get several operation manuals in order to perform an optimal simulation. It is also important to note that the data obtained in the simulations must correspond to the same frequency bandwidth of the prototype.

For the redesign experiment, independent variable is the asymmetry of the configuration defined as the difference between the value of metallic connection parasitic impedance of every paired components in the two branches of the circuit, and the dependent variable is common mode voltage response. In this part, more manuals and guides are collected to redesign more symmetrically the same system and achieve the proposed objective.

The possibility of any other external variable affecting the results is also ruled out, since only the established parameters will be modified to ensure the reliability of the data obtained. Another condition that should also be considered is that the tests performed on the system are in a controlled environment such as a computer simulation, which means that a high internal validity is obtained.

CHAPTER 4: ACTUAL MODEL CHARACTERIZATION

For the electrical characterization will be used as main software ADS from Keysight Technologies and these results will be compared with data obtained from real system.[6]

4.1 DC model

The first part of the characterization was for DC signal, that is, finding a simulation model for the sensor represented by the Wheatstone bridge and all its pressure-dependent variable resistances (figure 16), as well as the amplification reaching the gain value obtained with the real circuit.

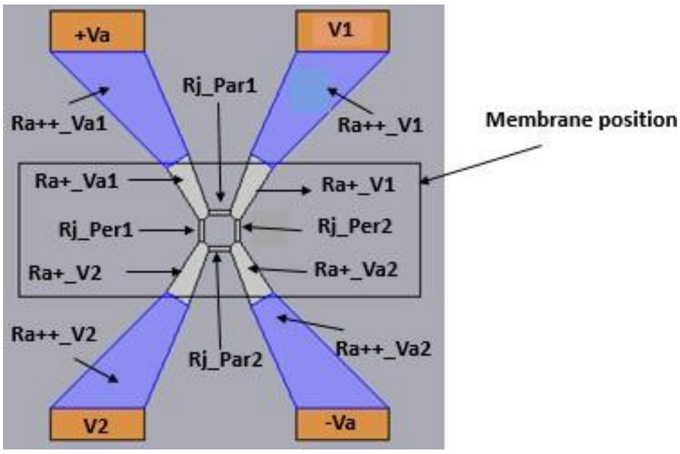

Figure 16: Distribution of all resistors and contacts of sensor with their names.

Resistors	Rj_Par1	Rj_Par2	Rj_Per1	Rj_Per2
Rio (Ω) ΔRi (Ω/bar)	1378 0.698	1378 0.698	1378 -0.801	1378 -0.801
Resistors	Ra+_Va1	Ra+_Va2	Ra+_V1	Ra+_V2
Rio (Ω) ΔRi (Ω/bar)	949 -0.084	949 -0.084	949 -0.084	949 -0.084
Resistors	Ra++_Va1	Ra++_Va2	Ra++_V1	Ra++_V2
Rio (Ω) ΔRi (Ω/bar)	77 0	77 0	77 0	77 0

Table 1: Values of resistors in sensor, Rio is the fixed value and ΔRi is the increment or decrement of resistance per bar.

Using the resistance values of table 1 measured in the sensor, it is possible to elaborate a schematic circuit in ADS and using a simple mathematical equation that varies these resistances according to the value of pressure stimulus we can check that the theoretical gain for the amplifier is practically maintained in the whole overpressure range as shown in table 2.

Pressure [bar]	V1-V2 (sensor)[V]	VO1-VO2 (amplifier)[V]	GAIN
0.0	0.0	0.0	0.0
0.1	0.000009	-0.000193	-21.44
0.2	0.000018	-0.000387	-21.50
0.3	0.000026	-0.000580	-22.30
0.4	0.000035	-0.000773	-22.09
0.5	0.000044	-0.000967	-21.98
0.6	0.000053	-0.001160	-21.89
0.7	0.000062	-0.001353	-21.82
0.8	0.000070	-0.001547	-22.10
0.9	0.000079	-0.001740	-22.03
1.0	0.000088	-0.001933	-21.97

Table 2: Simulated pressure between 0.0 and 1.0 bar, input voltage, output voltage and GAIN calculation.

$$GAIN_{OpAmp} = -\frac{R_{feedback}}{R_{input}} = -\frac{3300\Omega}{150\Omega} = -22$$

4.2 AC model

For the model in AC signal we must correctly characterize the fully differential OpAmp, the parasitics and the coupling with the sensor substrate for the circuit already fabricated to find the cause of noise in common mode and improve it.

4.2.1 OpAmp characterization

The commercial amplifier used in the project is not in the ADS simulation libraries, so it was necessary to edit an OpAmp with all the electrical parameters displayed on figure 17 according to the data sheet to obtain a model whose behavior is as close as possible to the real device. The manufacturer Texas Instruments has available a simple software called Tina-TI to obtain the S parameters of any of its manufactured devices and thus include it in almost any other simulation software.[7]

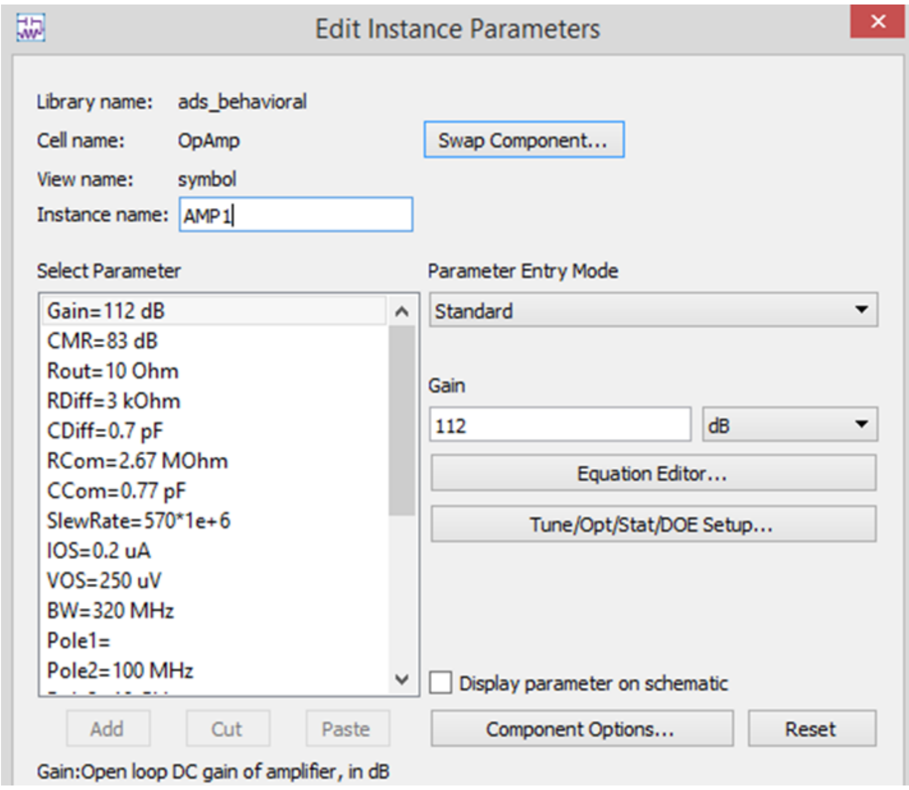

Figure 17: ADS model of OpAmp according to parameters from data sheet.

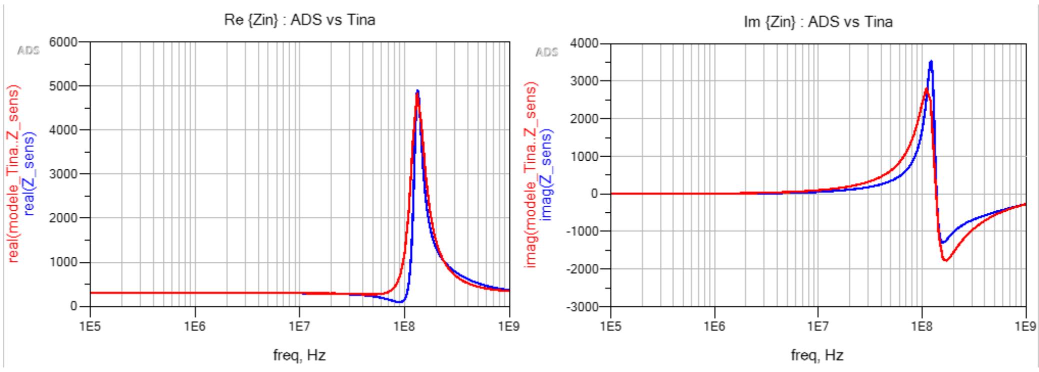

Figure 18: Comparison between input impedance of OpAmp from ADS model in blue and Tina model in red.

Figure 18 shows that two signals are very similar, so the model is validated for use in the rest of the simulations.

4.2.2 Power supply and conditioning PCB parasitics

Using the ADS EM simulation tool (Momentum RF) it is possible to obtain, for example, the S parameters of any section of a PCB in a desired frequency range by assigning a port, then these parameters can be plotted, and the impedance calculated. In the case of the connections shown on figure 19, a negligible resistance was obtained, so only the maximum value of each parasitic inductance was taken into account and registered on table 3.[8]

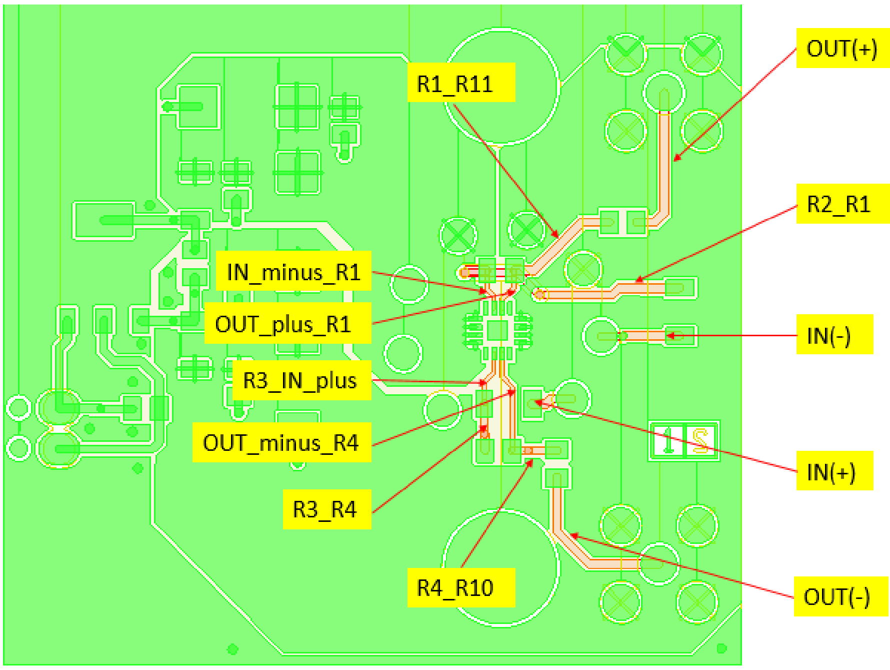

Figure 19: In red, the connections between every component in the power supply and conditioning PCB.

Connection Parasitics [nH]	IN(+) 1.37	R1_R11 5.18	OUT_minus_R4 4.97	R3_IN_plus 2.19
Connection Parasitics [nH]	IN(-) 3.41	R3_R4 1.71	OUT_plus_R1 1.64	OUT(-) 5.6
Connection Parasitics [nH]	R2_R1 11.1	R4_R10 1.69	IN_minus_R1 1.53	OUT(+) 5.23

Table 3: Parasitic inductance equivalent for connections on power supply and conditioning PCB.

With the parasitic inductance values it will be possible include them in the schematic circuit of the system and make the simulation more real, especially considering the mismatches that generate a high common mode signal.

4.2.3 Sensor substrate coupling

In this part of the internship, the EM simulation tool from ADS is again used to obtain the S parameters in the desired frequency range of 4 sensor substrate contacts: V1, V2, +Va and -Va. In this case the equivalent impedance will be a very low resistance that will not be taken into account and a parallel coupling capacitance between the 4 mentioned points and GND.

For a correct simulation it is necessary to consider all the layers (figure 20), materials and dimensions so that the result will be as close as possible to the real behavior of the device.

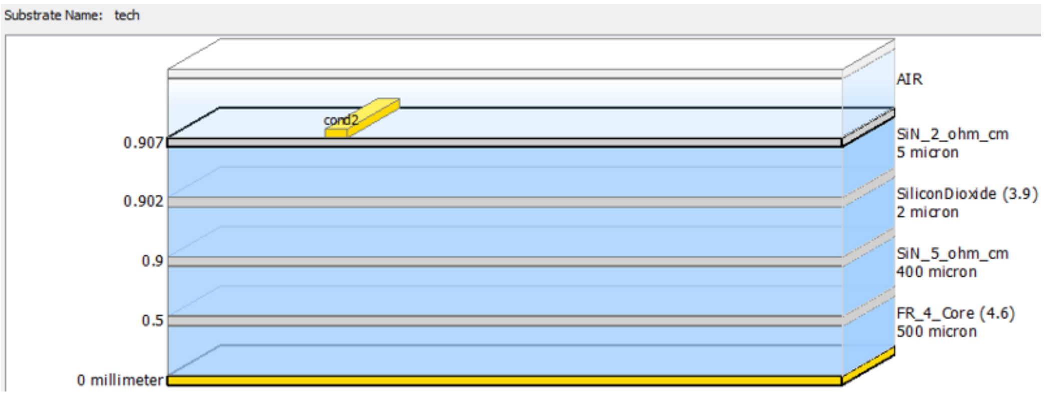

Figure 20: Substrate layers of sensor for simulate its electro magnetics effects.

With the results of the simulation, it is possible to include this parameter in the circuit of the system in two possible ways: the first is using a monopole in ADS to which the file with the data of the S parameters is loaded and the response will be obtained in the same frequency range in which the EM simulation was performed, the second is to consider the highest value of coupling capacitance and include it in the circuit as a fixed capacitance, although the first method is the most exact, the second can also be valid. Table 4 shows all those values.

Contact	V1	V2	+Va	-Va
Coupling capacitance [pF]	165.6	160.4	313.6	383.3

Table 4: Fixed value for coupling capacitance of sensor contacts.

4.3 Validation

After including all the previous stages of characterization such as: DC signal, parasites from the power supply and conditioning PCB, and sensor coupling, a common mode curve is obtained at the system output for GAIN in dB quite close to the data measured in the real circuit as shown on figure 21 so it can be considered as valid model in ADS.

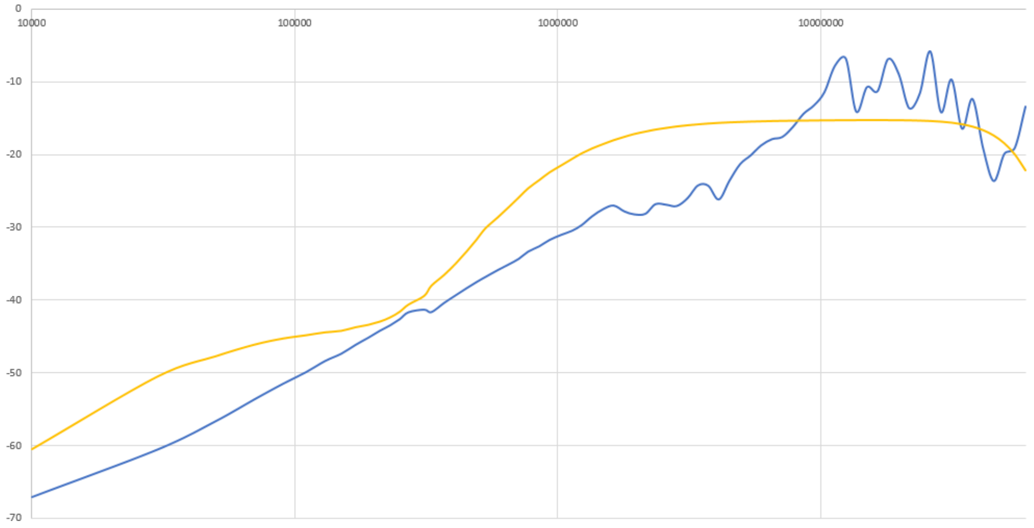

Figure 21: Comparison between GAIN in dB of real data (blue line) and ADS model behavior (yellow line) in a frequency range from 10kHz to 100MHz and common mode.

CHAPTER 5: NEW DESIGN

The main objective of the new design will be to reduce the noise in the signal obtained by the system, to do this the power supply will be changed replacing the resistors by integrated circuits that provide the required voltage levels, also will use connectors that have isolation against interference, because the common mode response is high and produced by the mismatches in the PCB circuit a new one will be developed as symmetrical as possible to avoid these undesired signals.

In addition to the above, a stage will be included to adjust the offset of system output, which will have its own power supply for laboratory tests.

The software DesignSpark PCB by company RS is used and every new or old component for the circuit is checked if it is on stock for its future purchase.[9]

5.1 Power supply

The new power supply includes two integrated circuits: NCP718BSN250T1G and MAX1735EUK30+T, which are two +2.5V and -2.5V voltage regulators respectively to power the sensor and the conditioning.[10][11]

5.2 Connectors

For the new design of the power supply and conditioning PCB, the sensor TO-3 connector is replaced by a shielded RJ45. Since the sensor cannot be removed from the current TO-3 connector, an additional PCB must be made only for the connections between the current and the new sensor connector.

For laboratory tests, new 5 pins for voltage measurements will also included in the circuit: positive power, negative power, two at the sensor output and ground.

5.3 Voltage offset

For laboratory measurement purposes only, a stage for adjusting the DC voltage level at the differential system output is included. This allows the DC value to be completely suppressed and only the AC component to be analyzed if necessary.

5.4 Symmetrical PCB

To reduce the system signal in common mode the main criteria for the new distribution of the components inside the power supply and conditioning PCB is symmetry as illustrated on figure 22, this implies that you will have the same parasites and couplings in the two lines of differential amplification, which in reality are impossible to avoid but their effects can be properly reduced.

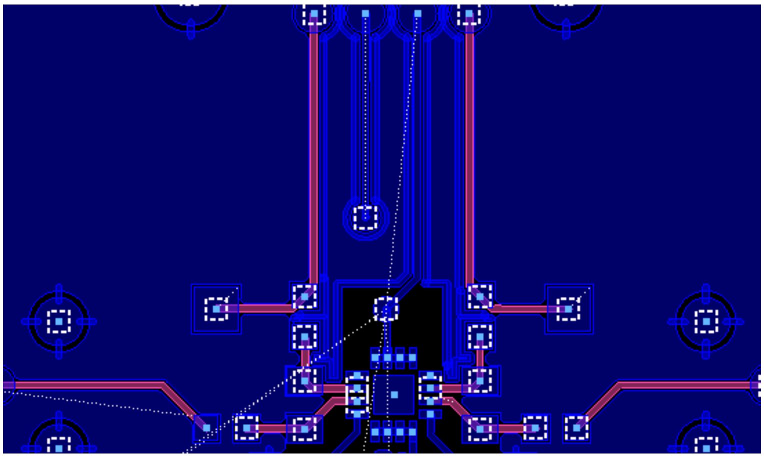

Figure 22: In red, the connections between every component in the conditioning stage on the new PCB which is very symmetrical.

Now as a next check, the common mode signal obtained should be lower than the previous one.

5.5 Results

To check if the common mode signal of the new design is lower than the current one, the parasites on the PCB must be characterized again and the signals of the two versions of the circuit must be compared to measure how much its performance has improved.

5.5.1 Parasitics from new design

The same ADS simulation tool is used to obtain the parameters of each connection between components (figure 24) and the maximum value of inductance in the whole frequency range is chosen and registered on table 5.

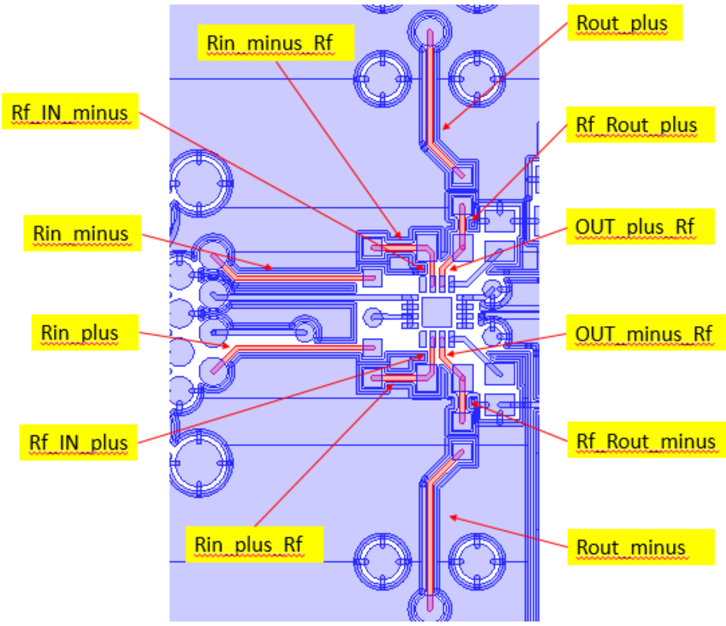

Figure 23: In red, the connections between every component in the conditioning stage on the PCB, it is noticed the symmetry that new design presents.

Connection Parasitics [nH]	Rin_minus 7.78	Rin_plus 7.75	Rf_IN_minus 1.31	Rf_IN_plus 1.28
Connection Parasitics [nH]	Rin_minus_Rf 1.96	Rin_plus_Rf 1.91	OUT_plus_Rf 1.57	OUT_minus_Rf 1.49
Connection Parasitics [nH]	Rf_Rout_plus 1.4	Rf_Rout_minus 1.31	Rout_plus 7.92	Rout_minus 7.16

Table 5: Parasitic inductance equivalent for connections on new power supply and conditioning PCB.

Analyzing the values obtained, the symmetry of new design is again evident since the values are very similar in pairs.

5.5.2 Validation for new PCB

As a final result, the figure 24 shows that common mode signal is reduced by 45 dB so the new PCB is much better than the first version and it will be manufactured with the design specifications already described.

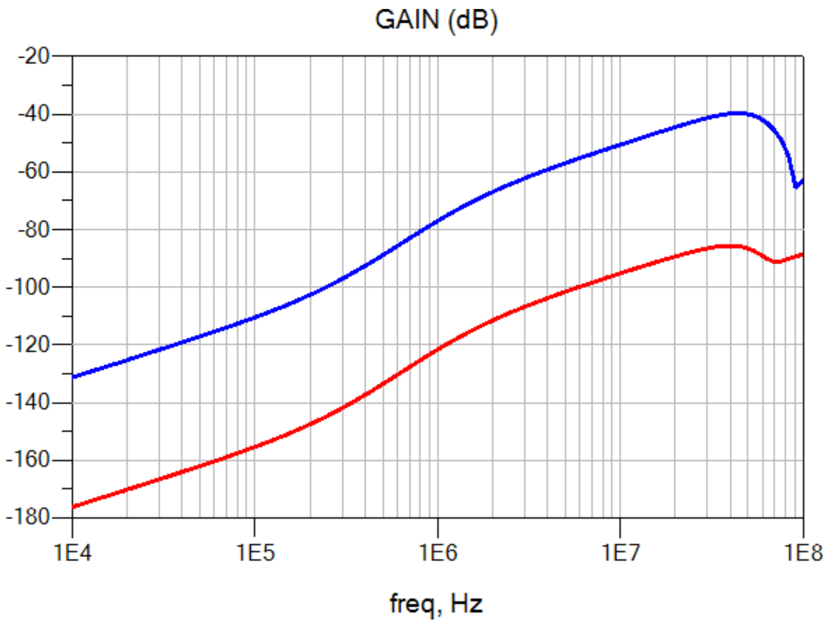

Figure 24: Comparison between both GAIN signals in dB at the output of the actual circuit (in blue) and the new one (in red) for common mode.

CHAPTER 6: CONCLUSIONS

It is known that one of the advantages of reducing the size of sensors is to avoid noise, but at the same time such a small sensor generates a small signal too and it becomes necessary to use an amplification stage to increase the levels of that signal, so now noise can be produced in the conditioning.

To improve the performance of any system the best way is to obtain a mathematical model to modify it and verify if its response can be improved, in the case of this project a valid model in ADS was characterized from actual circuit that can be simulated, modified, and improved.

In reality, it is impossible to eliminate the parasitic inductances of the metallic connections or the capacitive coupling to reduce the signal in common mode, but care must be taken to reduce their length and above all to maintain symmetry.

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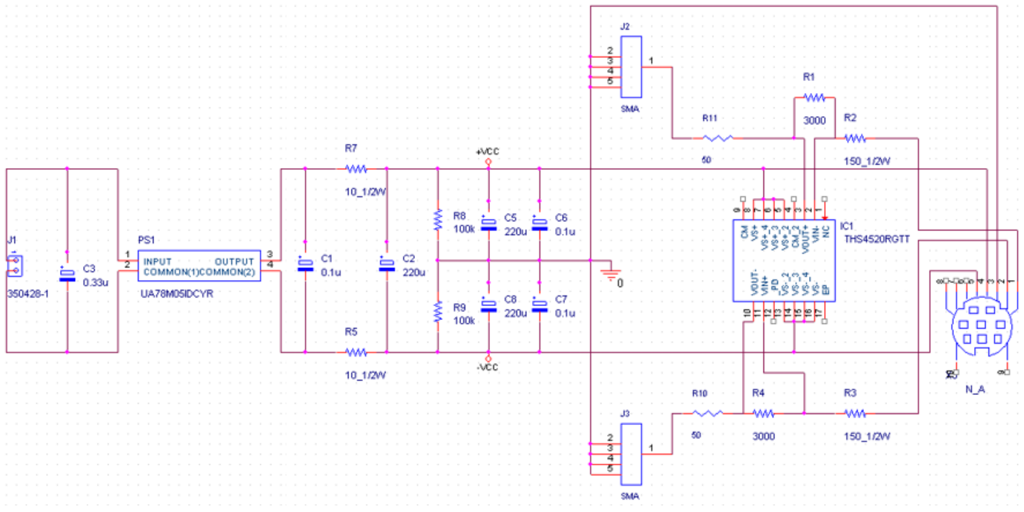
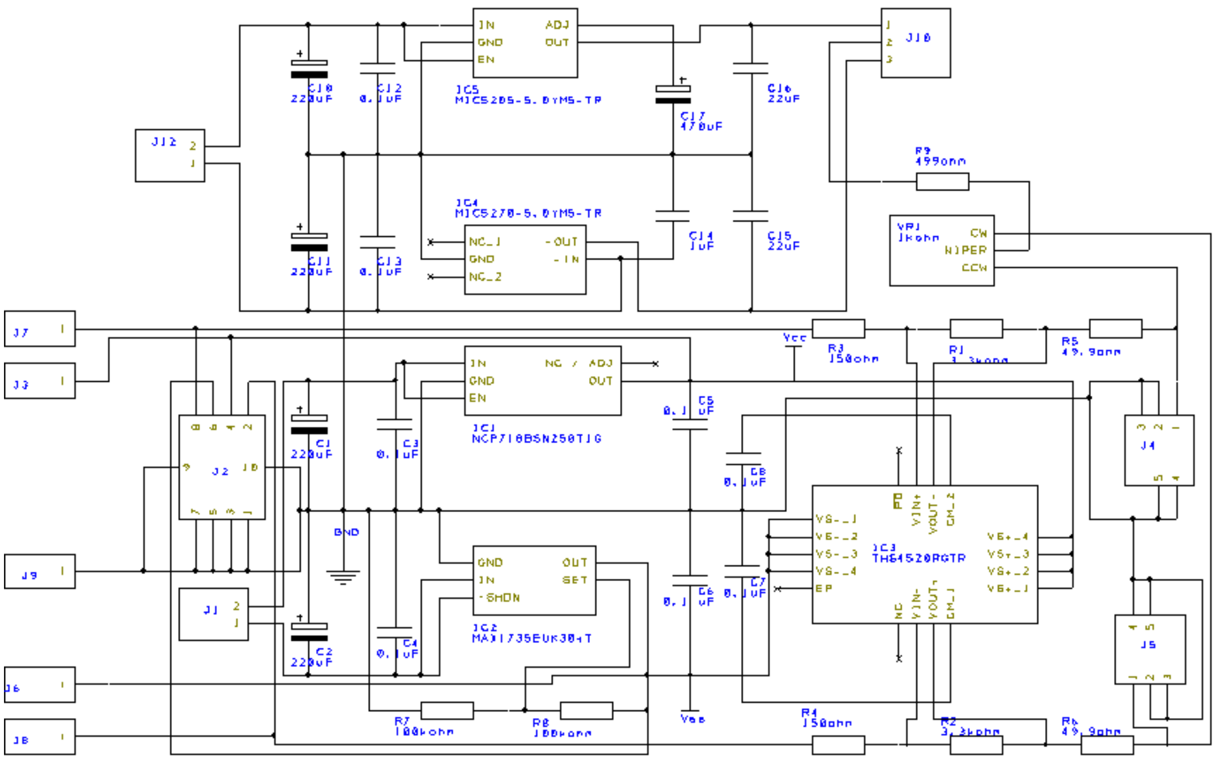
LIST OF ANNEXES

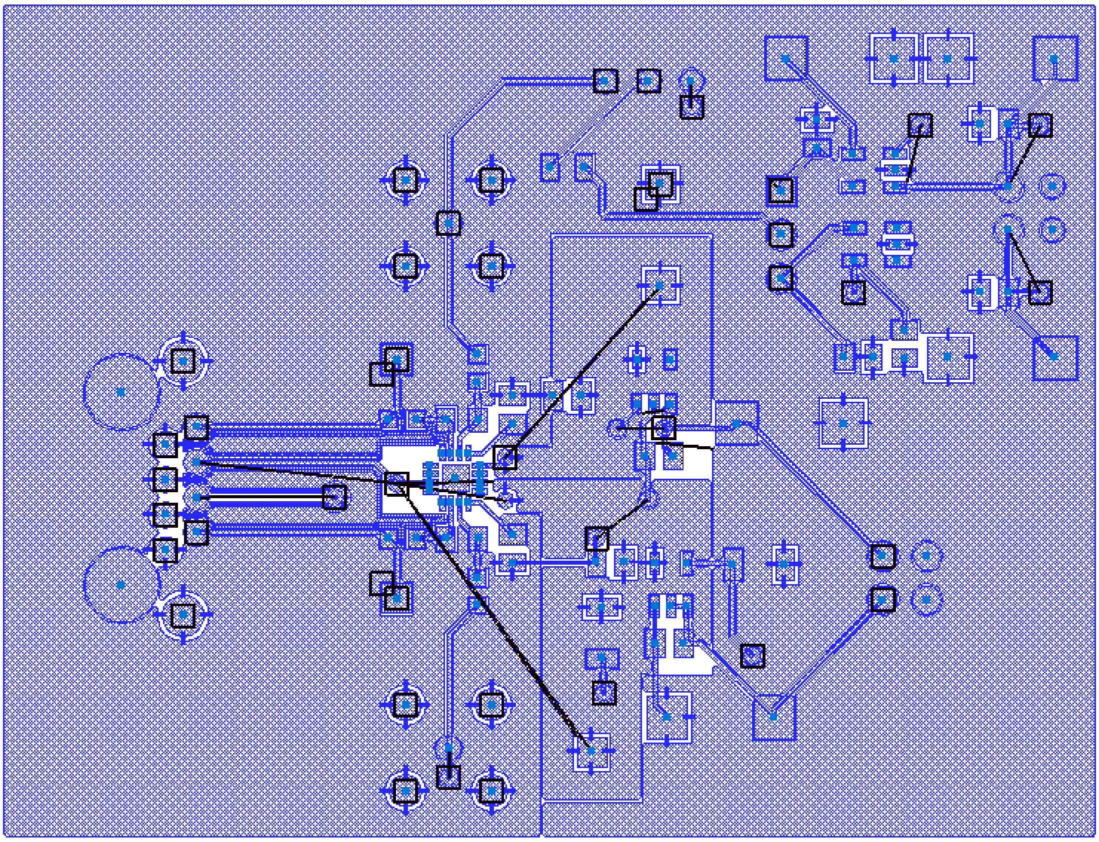
ANNEXE A: SCHEMATIC OF ACTUAL VERSION



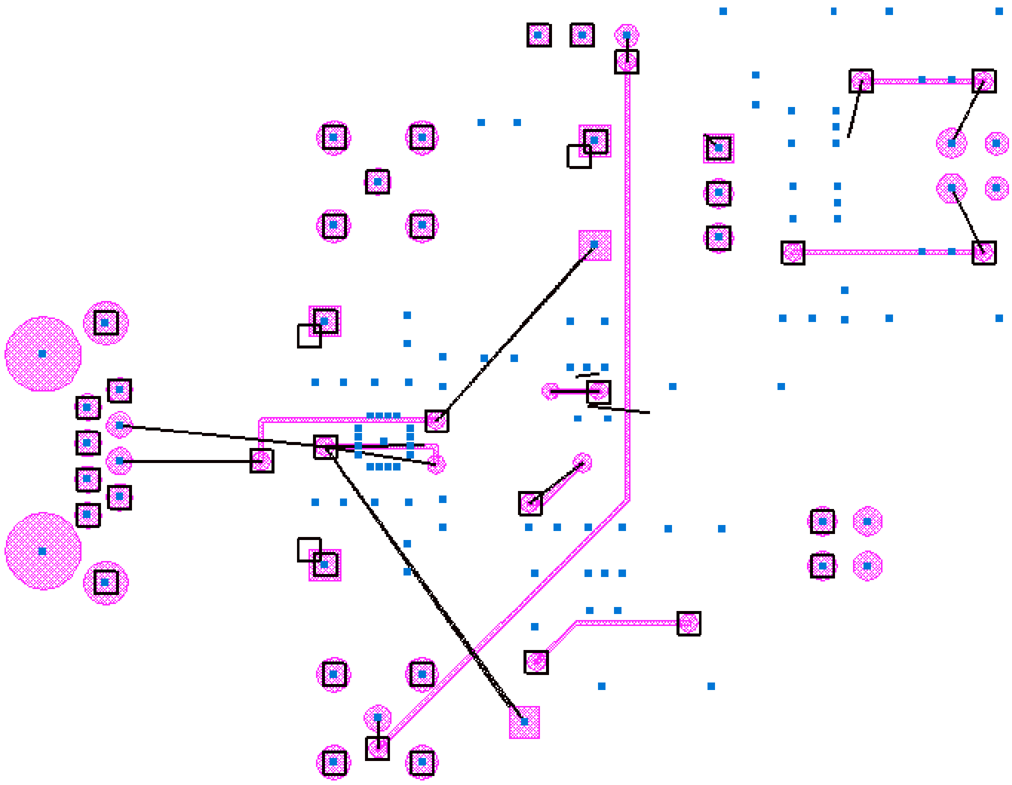
ANNEXE B: SCHEMATIC OF NEW DESIGN



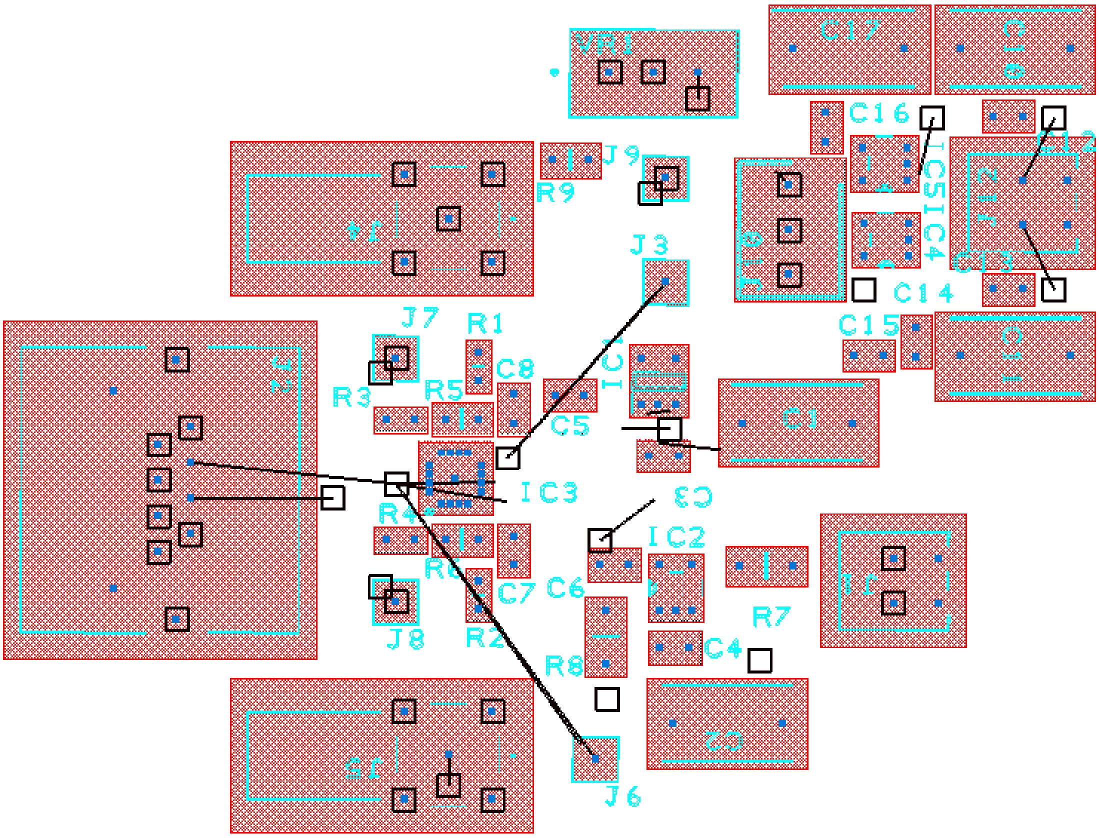
ANNEXE C: NEW PCB TOP COPPER LAYER



ANNEXE D: NEW PCB BOTTOM COPPER LAYER



ANNEXE E: NEW PCB SILKSCREEN LAYER



ANNEXE F: NEW PCB 3D MODEL