

# Eddy current sensors on Printed Circuit Board for compact mechatronic application

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## Abstract

In a context of always smaller and smarter mechatronic devices, the need of more integrated sensors becomes critical. Particularly, small mechanisms using small actuators like piezo actuators require compact sensors, with performances that measure up to the actuators characteristics. Eddy current position sensors (ECPSs) are widely used for non contact position, displacement, and proximity measurement with very good performances (bandwidth resolution, linearity, robustness in dirt environment). Operating on the principle of magnetic induction, these detectors can precisely measure the position of a metallic target. With the performances increase in PCB manufacturing, a specific design of this kind of sensors on Printed Circuit boards allows a compact device which could be coupled with its electronic conditioner. The modeling of the magnetic behavior of the probe and the coupling with a dedicated electronic conditioning are studied in this paper. Tests are involved on a X piezoelectric stage mechanism to verify the final performances. PCB-based eddy current sensors allows less space offering reduced weight with more controllability in integrated mechatronic devices.

## 1 Introduction

The mechatronic demands more and more precise motion in compact volume. From several years, actuators [1],[2] are designed to answer to these problematic of integration and accuracy but the added sensors to help this last point are quite large and reduce the overall capability to scaling down the actuator-sensor pair.

In the high resolution/accuracy domain like piezoelectric actuators, only few technologies are in competition where the ratio between the range of few microns compared the embedded body of the sensor is very small (see **Figure 1.1**).

Sensor Type	Advantages	Drawbacks
Eddy current	Simple structure, low cost, light weight, durable, harsh environment, bandwidth is high	Measuring signal will change with material properties, calibration is necessary with specific material target.
Capacitive	Simple structure, resolution and accuracy are fine	Expensive, sensitive to change in the dielectric sensor gap
Optical	High precision, direct measurement of the position	Expensive, installation complexity and susceptibility to optical contamination; rather for ground based laboratory testing than harsh environments.
Strain gage	Direct measurement of stress in-situ,	Accuracy, difficult to be mounted on small part.

**Figure 1.1** Comparison of high accurate/small range contact less sensors in mechatronic systems.

In compact contactless Nano positioning, only the capacitive sensors or the Eddy Current Position Sensors (ECPSs) could be used in industrial application. The optical measurement is not competitive because of the cost and the allocated volume of the final solution. The strain gages are a contact sensor which have several drawbacks especially when small and fragile parts must be measured.

From this aspect, we have chosen to design a new Eddy Current Position Sensor able to sense nano-metric position in the sub-millimetric range able to be integrated on compact and embedded mechatronic mechanisms. The challenge is to reduce the overall volume and so to implement the ECPS on a standard Printed Circuit Board in respect to the optimal performances.

### 1.1 Physical phenomena

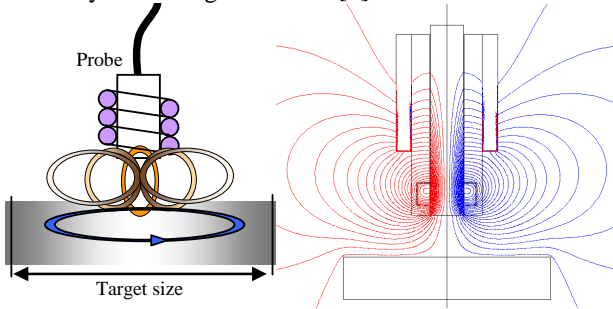
Eddy-current sensors have been studied for a number of years as a method of non-destructive testing and non-contact measurement.

Based on Faraday's law of electromagnetic induction,

$$\mathcal{E} = -\frac{d\Phi}{dt} \quad (1)$$

where  $\mathcal{E}$  is induced emf (electromotive force), and  $d\Phi/dt$  is the rate of change of the magnetic flux, the physical model of measurements (see **Figure 1.2**) consists of the target object and the main component of the sensor that is an induction coil. When an alternating voltage or current is applied to the induction coil, it generates an oscillating magnetic field, which induces eddy currents on the surface of the conductive target, according to the principle of eddy current induction [3]. Eddy currents circulate in a direction opposite to that of the coil, reducing the magnetic fluxes in the coil and thereby its inductance. Eddy currents also dissipate energy, and therefore lead to an increase in the resis-

tance of the coil. For high-precision measurements, preferable applications should make use of nonmagnetic conductive target materials like Aluminium, steel: The less resistive the target, the more eddy currents are produced in the target. This improves sensitivity and signal to noise ratio, ultimately increasing resolution [5].



**Figure 1.2** Physical principle of an ECPS.

From this physical phenomena, it is possible to define an inductor coil and an electronic conditioner to transform the Eddy current effect in electrical signal compatible with the position sensing application, i.e a position sensor with a voltage output and with a sensitivity in  $\mu\text{m}/\text{V}$ .

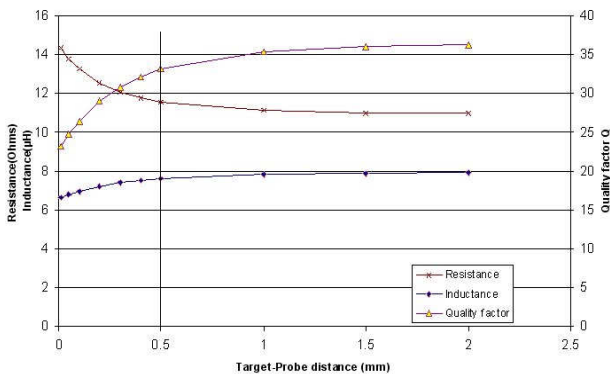
## 1.2 Concept

As explained, an ECPS is composed in a eddy current generator , i.e an inductor coil, and an electronic conditioner able to transform the impedance variation due to the position sensing in voltage.

The different relations to design this kind of sensors are well established in [6] and [7]. The complex impedance varies with the displacement between the inductor coil and the target. At fixed frequency and infinity target, the quality factor  $Q(x)$  can be explained as:

$$Q(x) = \frac{L(x)x\omega}{R(x)} \quad (2)$$

With  $\omega$ , the pulsation of the current/voltage,  $L(x)$  et  $R(x)$  respectively the inductance and the resistance over the range  $x$  (see **Figure 1.3**).



**Figure 1.3**  $R(x)$ ,  $L(x)$  and  $Q(x)$  variations over the range:  $500\mu\text{m}$  and  $F_{\text{excitation}}=8\text{MHz}$ .

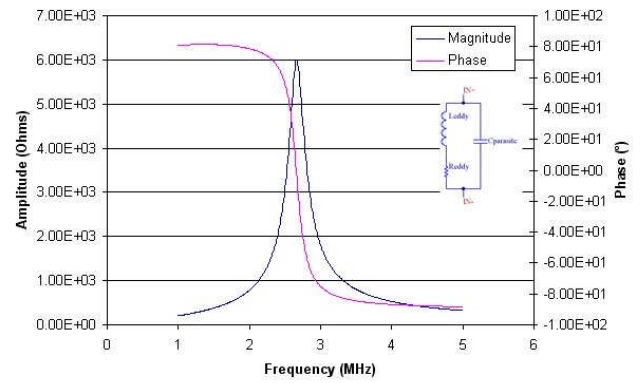
The design of a position sensor is intimately connected to the optimisation of the Signal to Noise Ratio and the line-

arity. The largest impedance changes per unit of displacement occur within the first 1/3 of the standard measuring range and is very closed to an exponential function. The design should maximise the variation of the  $Q(x)$  factor on the specified range. We will see later the importance of this exponential form to electronically improve the linearity.

As rule of the thumb, the diameter of the sensor should be designed to be 3 times greater than the range. In the **Figure 1.3**, the range is  $500\mu\text{m}$  for a  $1.5\text{mm}$  probe diameter.

The frequency response of the sensor is a like a resonant filter composed of the R and L components and the parasite capacitance C (cable, winding,...) with

$$\omega_{\text{res}} = 1 / \sqrt{L_{\text{eddy}} \times C_{\text{parasite}}}$$



**Figure 1.4.** Frequency response of the ECPS

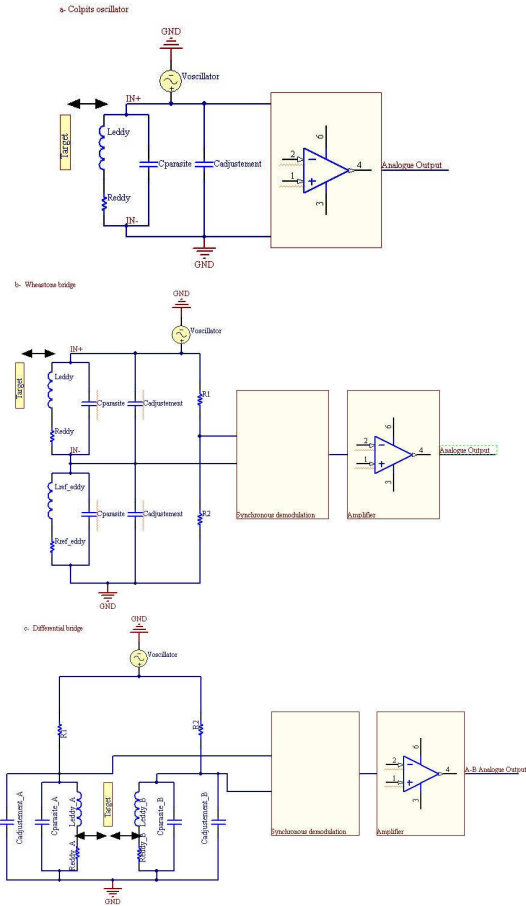
The working frequency is chosen to be 3 times lower than the resonant frequency  $F_{\text{res}}$  (see **Figure 1.4**) by adding an external capacitor.

In the industry, two main topologies are used based on an alternative current supply: The driving oscillator (or Colpitts oscillator) or the bridge oscillator.

The first one can be more embedded because only one inductive coil is used. In the Colpitts oscillator circuit, the sensor acts as the resonating coil for the oscillator. The proximity of the targets to the sensor coil pulls the oscillator, changing its frequency (small change not used) and amplitude (large change) of modulation. The signal is half-wave rectified (AC to DC) and filtered to obtain an analog voltage proportional to the target position. The main drawback is to implement a non linear function able to improve the intrinsic linearity.

A derived topology uses a Wheatstone bridge : The bridge is tuned to be near resonance so that slight changes in inductance in the sensor coil (caused by changes in the electromagnetic coupling between the sensor and the target) provide shifts in the output of the bridge. Target movement relative to the sensor causes impedance change in the sensor coil. The impedance of the coil is detected (measured) by the RF control circuitry. The dual coil has an active and an inactive reference coil for improved temperature stability.

In the differential bridge, the coils of a pair of sensors form the opposite legs of a balanced bridge circuit. the main advantage is the suppression of the anti-Log function and so improve the drift and the resolution by eliminating electrical noise from this electronic function. When two coils are used, the possibility towards a compact solution is slightly reduced. (see **Figure 1.5-a, b, c**). For this reason, the Colpitts oscillator is chosen to compact the final solution of the inductor coil.



**Figure 1.5** Concept of electronic conditioner for the ECPS a- Colpitts oscillator configuration , b-Wheatstone configuration, c- Differential configuration.

Standard solutions to realise the inductor coil use wired coil but are quite large due to electrical connections. Our solution is to use the latest improvements in PCB technology (See **Figure 1.6**) to obtain a sensor with a small area and a low profile. Several substrates like Low Temperature Cofired Ceramic, Printed Circuit Board can be used. The chosen substrate is FR4: The laminate is constructed from glass fabric impregnated with epoxy resin (known as "prepreg") and copper foil. The copper foil is partly etched away, and the remaining copper forms a network of electrical connections. For several reasons as a topology not enough complex (only two connections), as the PCB technology is improved since several years (see **Figure 1.6**), as the standard temperature will not reach more than 100°C, the classic FR4 substrate can be used as an industrial solution.

Years	Line width	Manufacturing	Substrates
1985	500 $\mu\text{m}$	Single sided board,	Rigid,
1985-90	250 $\mu\text{m}$	Dble sided board,	Flex,
1995-00	150 $\mu\text{m}$	Multilayers board,	Rigid, Flex,
2000-05	100 $\mu\text{m}$	Microvia High	3D
2005-08	75-50 $\mu\text{m}$	Density Interconnect board.	
2008-10	30 $\mu\text{m}$		

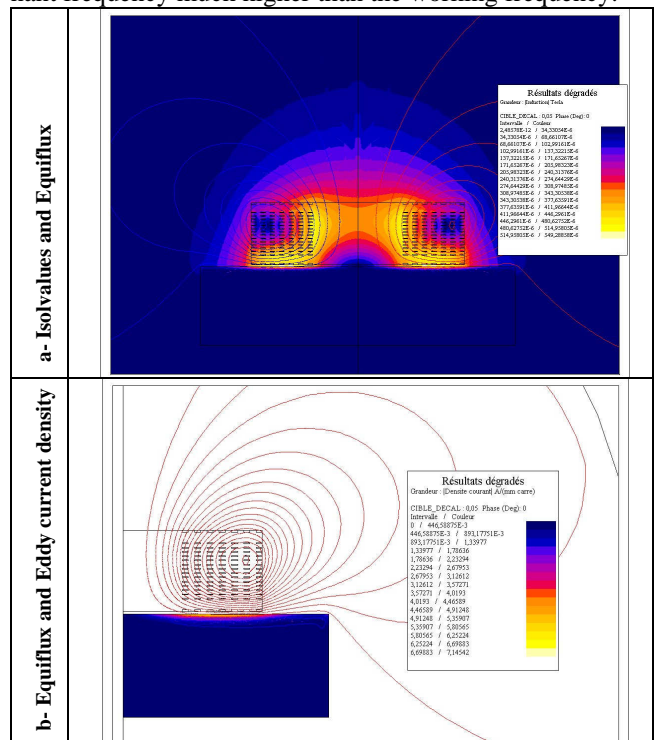
**Figure 1.6** PCB technology improvement since 1985 [10].

## 2 Design of the Inductor coil

The inductor coil is the core of the ECPS. The design of this part mixes modelling and manufacturing process management.

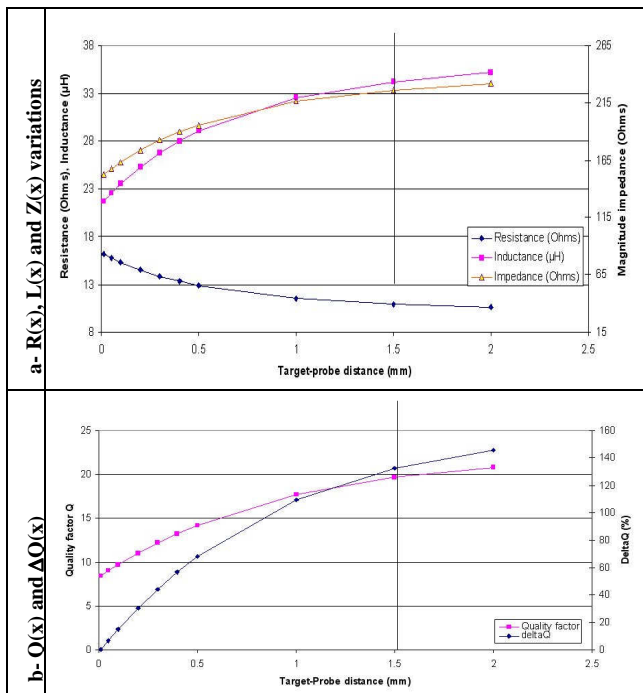
### 2.1 Modelling

The aim of the modelling work is to find the best coil configuration which maximise the eddy current effect to improve the sensitivity of the sensor on the range. The modelling is based on the analysis of the constitutive lumping element of the coil. The effective impedance depends on the complex interaction among several variables (target, distance, shield) and the FEM analysis gives a more efficient way to handle the design issues (see **Figure 2.1**). The modelling will be used to optimise the  $Q(x)$  variation and so the sensitivity of the ECPS. Flux 2D [8] and INCA3D [9] were performed to analyse the critical behaviours of the ECPS. The first one gives the behaviour of the  $R(x)$  and  $L(x)$  with the range and the second one is used to analyse the capacitive behaviour to place the resonant frequency much higher than the working frequency.



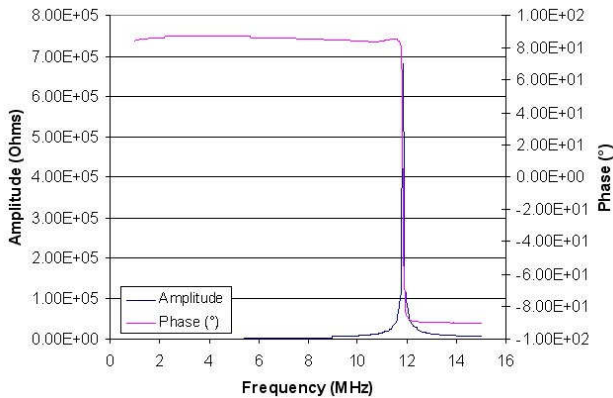
**Figure 2.1** FEM analysis of the ECPS: a-Equiflux, Iso-value; b-Equi-flux, Eddy current density.

The results of the FEM analysis are extracted in the **Figure 2.2 a, b** to trace the variation of the  $R(x)$ ,  $L(x)$  and  $Z(x)$  parameters and to obtain the  $Q(x)$  variation for the measuring range.



**Figure 2.2**  $R(x)$ ,  $L(x)$  and  $Z(x)$  variations-  $Q(x)$  and  $\Delta Q(x)$  for 2mm range at 1MHz

On a 1.5mm measuring range, the variation of the quality factor is more than 130%.



**Figure 2.3** Complex impedance of the inductor coil versus frequency

The modelling impedance shows a resonant frequency near 11.85MHz, which permits to work around the MHz by adding parallel capacitance. The parasitic capacitances from the PCB are near 6.3pF.

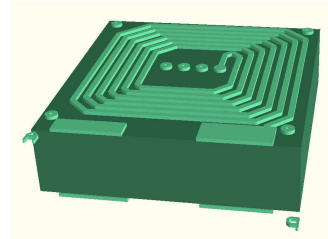
## 2.2 PCB manufacturing process

As the optimal performances are reached with a high density PCB, the solution has been found in the phone cellular technology. The High Density Interconnects PCB technology is a good candidate because of combining buried microvias, high pitches and small width of lines coupled with

fine substrates (core + pregs) to improve the mutual coupling between each layer.

Finally, the High Density Interconnects PCB technology was chosen with a standard FR4 based multilayer with a 2mm of height. The HDI PCB design follows the IPC-2226 - level A. [10].

For more integrated sensor with small range (see later), the HDI PCB is more challenging but substrates building with same number of layers were validated with height below 1mm and 2mmx2mm area following the IPC-2226-Level C [10].

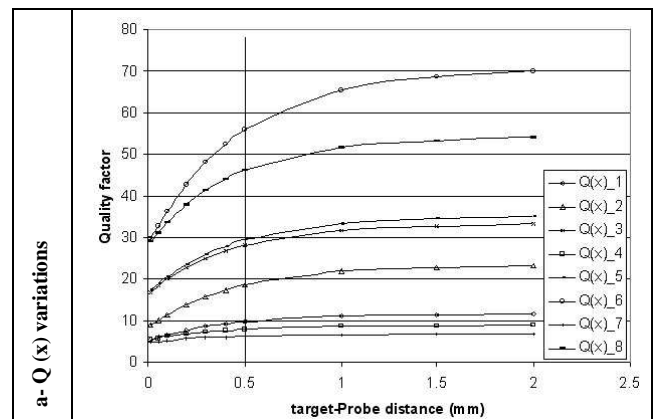


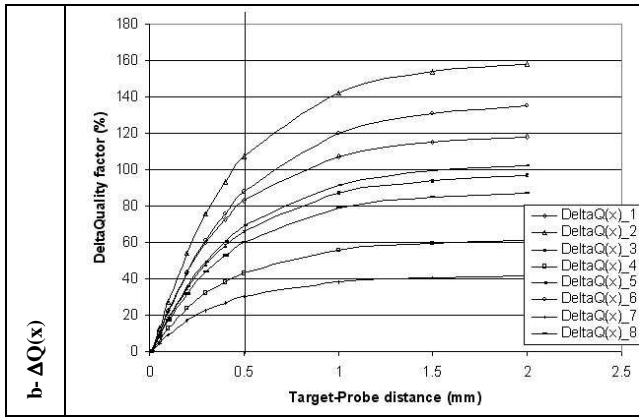
**Figure 2.2** 3D High Density Interconnects PCB of the inductor coil.

## 2.3 Scaling down

The presented solution for 2mm range used a 5mmx5mm multilayer planar coil. A scaling down of the overall dimension of the sensor will reduce the target size and focuses the field on a smaller area which improves the sensitivity. In [11], it is shown the relations between the  $Q(x)$  variation, the scaling factor and the frequency. Compared to a wired solution a scaling down of a planar coil without modification of the intrinsic characteristics of the planar coil accomplishes a reduction of the  $Q(x)$  variation. From [12] in a multilayer planar coil, the way to improve  $Q(x)$  is to increase the mutual and the self inductances and to reduce the resistance of the wire which is difficult in the same area.

Several simulations were performed to analyse the behaviour of the sensitivity with the physical dimension of the coil in **Figure 2.3**.

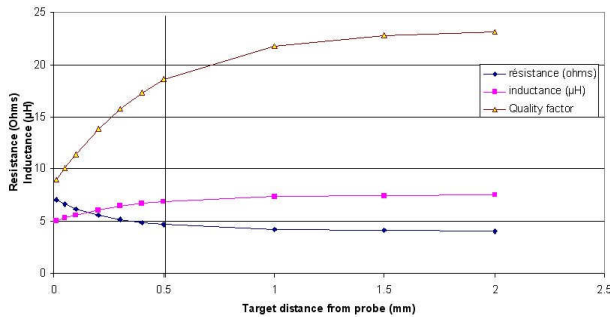




**Figure 2.3** a-  $R(x)$ ,  $L(x)$  and  $Q$  variations, b- Variation of  $\Delta Q(x)$  for 500 $\mu\text{m}$  range with different physical dimensions.

$Q(x)_{1,2,3}$  are issued from a same geometry and with frequencies 1,2 and 4 times than the nominal working frequency.  $Q(x)_{4,5,6}$  are issued from a same geometry and with less inductances from the 1, 2, 3 geometries (0.65 factor but with the same area and layers)) and with frequencies 1,2 and 4 times than the nominal working frequency.  $Q(x)_{7,8}$  are issued from a same geometry and with less inductances from the 1, 2, 3 geometries (0.3 factor but with the same area and layers)) and with frequencies 1 and 4 times than the nominal working frequency.

From **Figure 2.3**, we extract the best solution from the modelling steps to be compatible with the oscillator. The solution  $Q(x)_2$  is chosen.

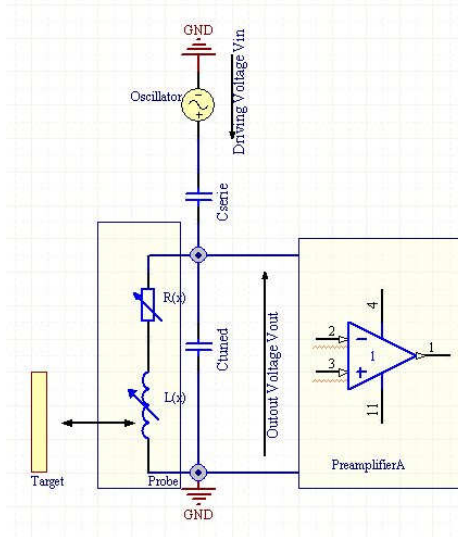


**Figure 2.4**  $R(x)$ ,  $L(x)$  and  $Q$  variations.

The variation of  $Q(x)$  is maximised to reach more than 100% in the 500 $\mu\text{m}$  range by increasing the frequency by 2.

By reducing the area of the probe, the height can be reduced by decreasing the number of layers. In this case the total inductance is reduced but the resonant frequency is increased allowing a higher working frequency.

### 3 Electronics for ECPS



**Figure 3.1** Principle of the electronics of the ECPS

As seen in the previous chapter, the ECPS conditioner is not only an oscillator. The electrical circuit is more complex with a demodulation function able to extract the amplitude of the modulated signal and a linearity function able to reduce the intrinsic non linearity of these kind of position sensor over a certain measuring range. A analogue based antilog function can be used to correct the non linear signal. This correction can be perform with a digital function (After analogue to digital conversion) able to add some other corrections like active temperature correction. Finally, a picture of the designed electronic conditioner is given in the **Figure 3.2**.



**Figure 3.2** Eddy current position sensor conditioner.

This board can include until 3 synchronised channels to be integrated on 3 axis mechanisms.

### 4 Practical tests on a single ECPS

A single planar coil based on a 2mm range is manufactured following the design rules of the chapter2 (see **Figure 4.1**) to check the resolution, the accuracy and thermal drift of the overall chain.

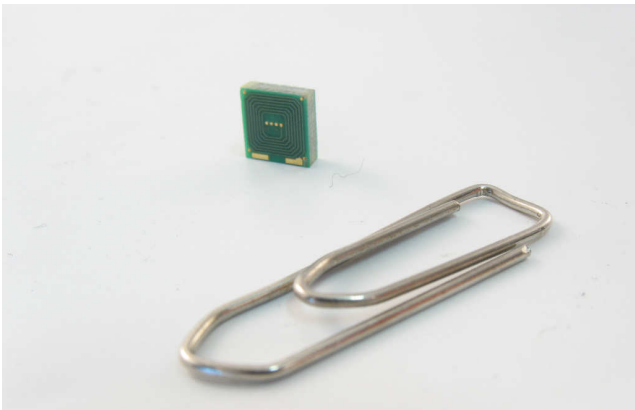


Figure 4.1 2mm range manufactured ECPS

### 4.1 Test setup

The philosophy of the first test bench is to compare the real time measurement of a 1000µm stroke piezoactuator with a capacitive sensor which is more accurate than the eddy current sensor (linearity, accuracy and resolution). The second one is a test bench to measure the thermal drift of an accurate distance. An Invar + Alumine structure is used to minimise the thermal drift of the distance between the probe and the target. A thermal sequence between -20°C to +70°C is applied on the Device Under Test (see Figure 4.2 a&b).

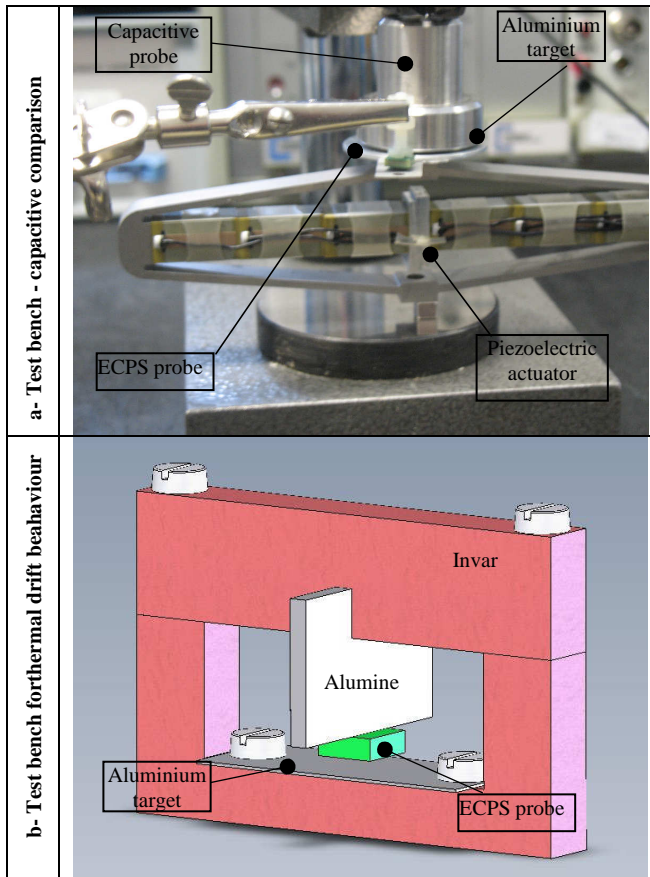


Figure 4.2 a- Test bench for resolution/accuracy testing of the single Eddy current position sensor. b - Tests bench for thermal drift testing of the probe.

### 4.2 Test results

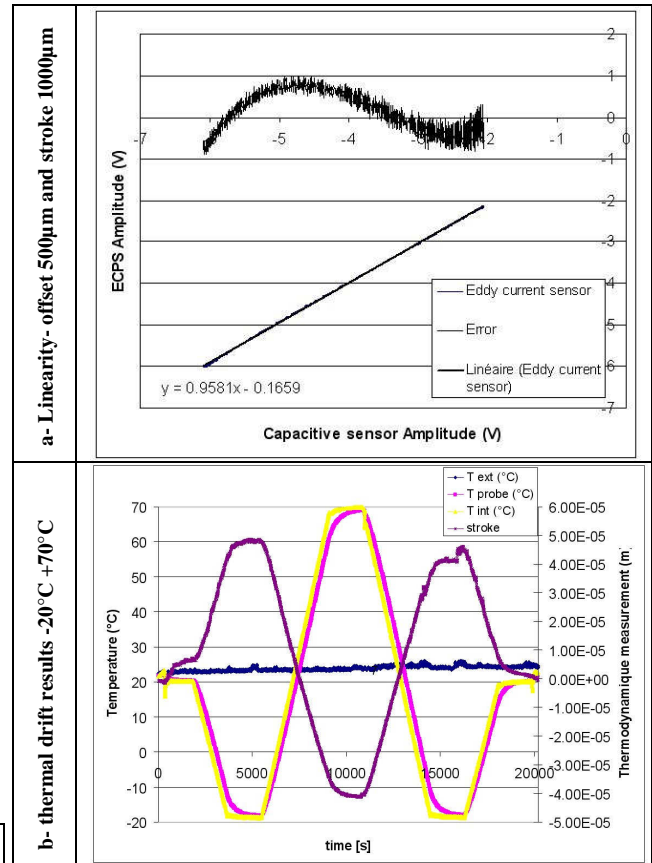


Figure 4.3 a- b- Thermal behaviour results on a -20°C to +70°C temperature range

The linearity is based on an offset of 500µm and a dynamic stroke of the piezoactuator of 1000µm. In this range, the linearity is under +/-1% and is basically function of the electronic correction. In the same time, the measured resolution is near 50nmRms on [10Hz-8kHz] bandwidth.

Band	Voltage Power Noise	Position Rms
10-110Hz	24.91 nVrms <sup>2</sup>	34nm
110-1710Hz	42.4 nVrms <sup>2</sup>	32nm
1.71kHz-8kHz	10n Vrms <sup>2</sup>	16nm

Figure 4.4 Resolution issued from noise measurement on the voltage output of the sensor

The temperature has a non negligible influence on the sensor behaviour. Fortunately, the inductance remains almost constant, a small increase is possible due to the coil thermal expansion, but this effect is negligible. On the other hand, the sensor electrical resistance increases dramatically with the temperature. It is more than 30% larger at 100°C than at room temperature. With the HDI PCB integration, it's possible to add a thermal sensor near the inductor coil to compensate the temperature drift with a look-up table. Finally a thermal drift of the probe around 800nm/°C can be given by deducting the thermo-mechanical drift of the stiffener.

All these parameters can be computed in a table to be compared with a standard wired coil eddy current position sensor (see **Figure 4.5**).

Performances	Wired coil	Planar coil
Range – Full Scale	1.25mm	2mm
offset	250 $\mu$ m	250 $\mu$ m
Dimensions (mm)	Dia 5, length 18	5.8x5.8x1.8
Resolution	0.009% of FS	50nm rms or 0.0025% of FS
Linearity	+/-0.25%	+/-1%
Bandwidth	80kHz	15kHz
Drift	0.04% of FS at mid-range	800nm/ $^{\circ}$ C or 0.04%/ $^{\circ}$ C of FS

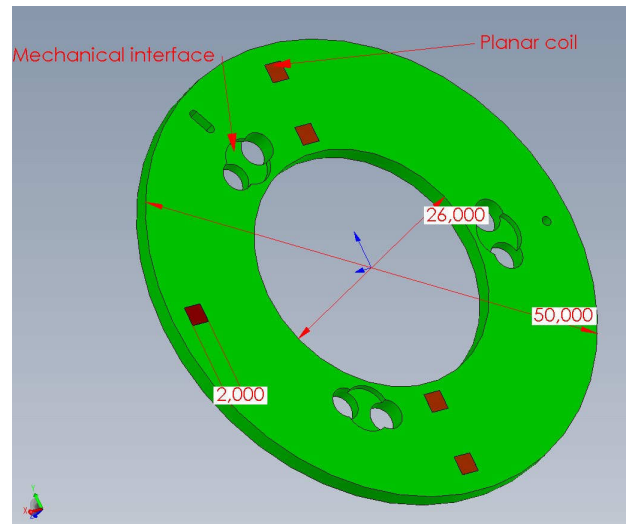
**Figure 4.5** Comparison with standard wired coil Eddy current position sensor [13].

The different characteristics are very similar: The resolution and the linearity are directly given from the electronic unit. On the volume point of view, the main advantage of a planar coil is the drastic reduction of the length of the sensor (i.e. 1.8mm versus 18mm for a standard wired coil). This allows a compact integration of the sensing function.

## 6 Integration in piezoelectric mechanisms

An example of a possible integration of this kind of sensor is shown in the following figure to sense the stroke between two (see **Figure 6.1**). The main possibility of this design is found in the PCB including five probes to measure the real displacement of a aluminium target. The mechanical integration is simpler than five autonomous probes. The principle of the Contactless force sensor is to create an measurement of a torque by sensing the displacement of two mechanical parts (part A and part B see **Figure 6.1**)-[14]. By combining several measurement, it's possible to minimise the parasite offsets and to read the torque and the angle of the shaft. As the mechanism is very small, standard eddy current sensors are not a good solution due to their lengths. The benefits of a printed circuit board can be directly used to be implemented inside directly close to mechanical parts. The dynamic stroke to be sensed is near 20 $\mu$ m with an offset near 200 $\mu$ m.

The PCB doesn't show the electrical interface with the electronic unit but it can be integrated on the rear face of the PCB to pre-amplify the signal before the final treatment away.



**Figure 6.1** Fives ECPS on a 50mm diameter HDI PCB in contactless Force sensor application.

## 7 Conclusion

In this paper, we have shown the new possibilities offered by improving the manufacturing process of PCBs to design compact eddy current position sensors with low profile. The chosen technology allows similar performances with wired coils used in the industry. The scaling down process can be done until parasite effects modify the performance of the sensor: a 1500 $\mu$ m range sensor in a 5.8mmx5.8mm\*1.8mm volume has been designed and tested to validate the performance and a 500 $\mu$ m range sensor has been simulated to validate the intrinsic probe performance in small volume 2mmx2mmx1mm. This last sensor will be implemented in applications where very small volume are required.

## 8 Acknowledgements

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