Innovative hyper-thin sensor for cartridge valves diagnostics and prognostics

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Abstract.

Functional Safety asks for diagnose-ability of systems and components in order to make the systems observable and to check for faults to be recovered in real time to avoid dangerous consequences of the faults themselves. At the same time, new technologies offer new materials and new production processes, which allow the creation of new sensors to meet the requirements of the functional safety certification procedures. Diagnostics and predictive diagnosis are not only related to functional safety, but rather to reliability and function availability, which represent two very important aspects of products quality. Finally, cartridge valves are widely used in many hydraulic systems, both in mobile and in industrial applications, and they are often part of systems that must meet functional safety requirements. Traditional sensors does not contain information on the state of health of the valve itself and its state with respect to the average life and the distance from a dangerous failure. This contribution deals with describing some type of failures of cartridge valves and describes how an innovative sensor is able to detect such failures before they can occur, also with a reasonable warning of the moment of failure. The innovation is described and both mechanical, electromagnetic, fabrication and installation problems are addressed.
A set of real tests on prototypes are reported, and it is shown that the tests prove the efficacy of the sensors in valve failures due to high pressure damages. Finally scenarios for new application ideas are described.

Keywords. Cartridge Valve, Fatigue breakage, Pole Tube, Strain Gauge, Valve Coil.

1. INTRODUCTION

In many electro-hydraulic applications nowadays, sensors are placed in manifolds and along the hydraulic circuits, as well as in pumps and motors, in order to acquire data useful for closed loop controls. As very well described in [1], the sensing technology has grown in the years in parallel to control techniques and, in recent years, in parallel with the need for health status of hydraulic components and, in special way, for the health information of valves.

Searching for special sensors “in valves”, it is hard to find anything new, while it is very interesting to learn how much research has been done trying to deduce the health status or simply the status of valves using different inference techniques. Most of these techniques are using remote sensors and data collected from the effects of the valve status in the hydraulic circuit.

The reliability of hydraulic components it is a very heartfelt topic, but in many papers like in [2] it is treated using traditional pressure sensors, based on traditional strain gauges. In fact, reliability is one of the key arguments of safety, but safety is also related to faults and to be aware of faults, the component must be observable. Therefore, sensors are necessary for safety reasons, as it is demonstrated in [3], where traditional sensors placed in the hydraulic circuit are used to evaluate the valve faults in an independent metering system. Many different strategies have been developed to try to evaluate the health status of hydraulic components and, in particular, of valves, due to the difficulty of integrating sensors for a direct acquisition of the health status of the valve itself. In [4] authors propose a multi stage diagnosis based on sensor fusion, using accelerometers to analyse the vibration of the hydraulic directional valves. Even in this case, a direct acquisition of the status of the spool or of the health status of the valve is inferred using external and indirect sensors, i.e. sensors not acquiring the primary physical parameter responsible for the information to be collected. In [5] the importance of a real-time, accurate fault detection and isolation system is described for mobile hydraulic valves, and an inference method is proposed, using traditional pressure sensors and a reduced order model with adaptive thresholds. In the already cited [1] it is also described how the diagnosis of the valves is increased for the digital hydraulic valves. This is confirmed for example in [6] and [7], where authors propose an identification method for faulty valves recognition, based on combination of pressure measurements made during the normal operation of the machine and a mathematical model describing the flow balance of the hydraulic system, once again using traditional pressure sensors in the hydraulic circuit. The only experiences of integration of new thin sensors are in [8], where strain gauges are used to acquire and evaluate the correct functionality of a hydraulic clamping system, and in [9], where strain gauges are used to measure micro leakages of a hydraulic cylinder using internally installed strain gauges. This last experience is not a solution for the industrial production, but is useful in order to understand the strain gauges applicability even inside hydraulic components.

Based on the previously described experiences, the strain gauge technology seems the only one applicable to the problem the research wants to address, which represents an open issue as described in [10]. However, there are several problems to solve, in order to create a new type of sensors capable to cover the faults of the valve body. The proposed sensor is something that could represent a new sensitization methodology and technique for valves, applicable to both spool valves and cartridge valves. The main difference from the described experiences, in the case treated in this article, is that the aim of the proposed sensor is to acquire directly the main physical phenomenon responsible for valve pole tube breakages. The main principle is to acquire the anomalies in the mechanical strain of the pole tube, using the electrical-mechanical properties of the strain gauges and a proper design of the sensors tailored on each valve model, in order to maximize the sensitivity and to adapt perfectly the temperature compensation. In next paragraphs it will be described the sensor and its production technology, the necessary adaptation of the electro-actuated cartridge valves and the practical experiences at test bench for sensor validation.

2. STRAIN GAUGE TECHNOLOGY

Among the different improvements implemented in the years in this branch of mechanical sensors, ultra-flexible and ultra-thin strain gauge sensors represent a class of devices with multiple advantages in terms of sensitivity, conformability, costs etc. Indeed, the conventional fabrication of strain gauges often relies on MEMS-based technology, where controlled environments and expensive microfabrication processes are requested, while roll-to-roll and printing techniques together with additive manufacturing can allow tuning production according by the case, thus reducing the costs of these devices [11]. Especially in biomedical applications and robotics, ultra-flexible strain gauge sensors embody a suitable choice, since a wearable device fits well with human body or garments and it can show proper conformability to non-conventional surfaces [12]-[13]. Depending by the high sensitivity of these sensors and by the specific range of strain requested, different materials can be implemented from elastic or stretchable substrates to extremely soft polymers (reaching strain >100%) [13]. To tune the conductivity and mechanical properties, nanocomposites usually based on carbon like materials or piezoelectric composites are used [14]-[15]. In this way, through percolation among conductive nanoparticles, it is possible to control the changes in conductivity during the sensors operation [16]. Alternatively, very stretchable polymers (e.g. PDMS) filled with metal nanoparticles can still be utilized to manufacture extremely long-range strain gauge sensors [17]. Generally, with the implementation of metal nanoparticles it is also possible to obtain very high gauge factors in specific sensor operation range (up to few thousands) [18].

3. THE CARTRIDGE VALVE AND ITS FAILURES

For this research, a proportional Flow regulation Cartridge Valve not pressure compensated, electronically controlled, of VIS Hydraulics was used.

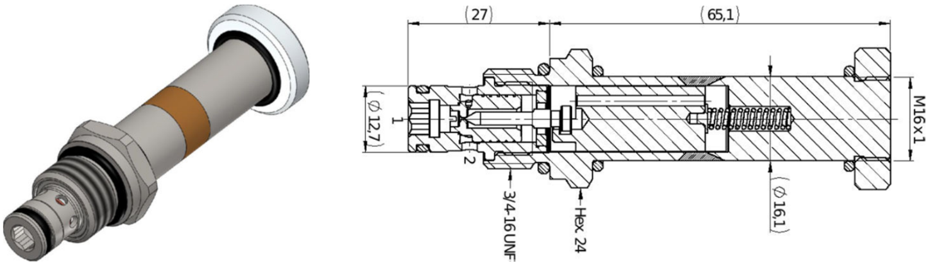

Figure 1. The Flow regulation Cartridge Valve and its section

The valve is one of the three new valves the company developed in the project, and this one was the first ready for the tests and it is shown in Figure 1, while its characteristic and symbol are shown in Figure 2. The Valve is actuated using a coil of 26 W either 12 or 24 VDC electronically controlled by a new electronic control unit directly connected to the coil connector.

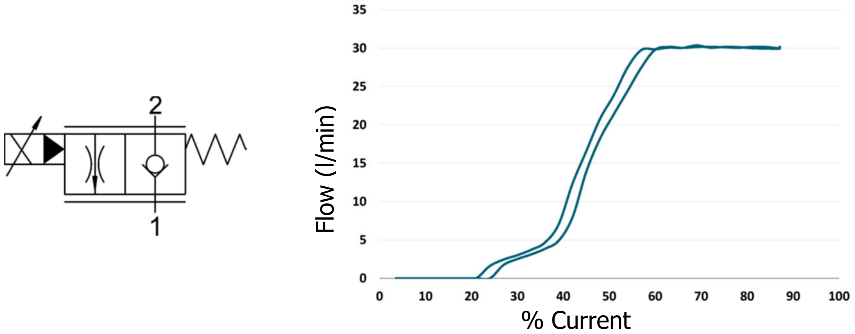

Figure 2. The valve hydraulic symbol and the Current vs Flow characteristic

There are several breakages of a cartridge valve to be analysed and that can occur during the valve operational life. Different types of breakages can be caused by excessive pressure in operation, which results higher in respect to the maximum pressure declared by the valve producer for the correct usage of the valve itself. Some of them can be caused by fatigue, due to excessive usage of the valve, exceeding the average or declared life of the valve. Others can be caused by mechanical stress, due to external factors or wrong installation of the valve. Finally few of them can be caused by production defects or process defects or material defects. These valve faults can lead to different types of malfunction, the ones we are interested in monitoring are the ones can lead to an oil loss with dangerous consequences, or with function unavailability that can cause damages and high cost consequences.

The faults we are discussing of are the faults that can provoke a breakage of the pole tube, whose consequences are shown in Figure 3.

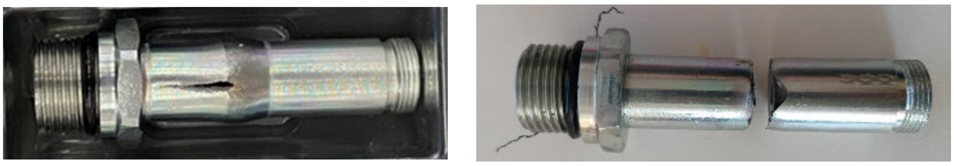

Figure 3. Excessive pressure breakage and process or fatigue breakage of the valve

The idea developed in this research is to apply sensors to the pole tube, which can directly monitor the health status of the valve. As discussed in the introduction, a sensor type that could fits the requirements, suitable to be installed in between the coil and coil enclosure and the pole tube, is the strain gauge. In fact, any mechanical deformation, or even an oil loss or oil spilling could lead to a sensor deformation and to a variation of the sensor value, then to a recognition of a malfunction of the valve. The different models available have a thickness that is not compatible with the available air gap in the valve. Moreover, it is impossible to find a strain gauge fitting perfectly the envelope of the cylindrical surface of the pole tube. But in the last years the flexible electronics technology had interesting improvements both in materials and in processes, so it is likely possible to design and produce an ad hoc sensor for each valve model.

The opportunity of a specific design for each valve model will ensure that any type of breakage of the pole tube will be under the observation area of the sensor. Therefore, theoretically the sensor could reveal any type of breakage during the valve operation life. This is the thesis the research would like to demonstrate. The first step is to understand the sensor technology applied to the sensor prototypes made for this experiment.

4. THIN STRAIN GAUGE SENSOR

The flexible strain gauge sensor has been designed according to a classical meander configuration to obtain a total resistance in the range of [2; 4] kohm. For the manufacturing of the device, we started using a 3’’ silicon oxidized wafer as carrier and we deposit a layer of 8 μm by spin coating. After a thermal treatment at 250°C for mechanical stabilization of the polymer, we patterned with a positive photoresist the metal track by using an EVG610 equipment. Then we evaporated a film of Aluminium of 150 nm and we removed the resin in an acetone bath for 2 h. To protect the sensor we deposit another layer of polyimide, 2 μm thick, and we photolithographically open vias to reach out the contacts by using an oxygen plasma treatment for 15 min. After this step, the sensor was cut from the wafer and mechanically peeled off, obtaining a thin freestanding device with a total thickness of about 10 um.

Prototype	Substrate thickness (μm)	Metal thickness (nm)	Sacrificial layer (nm)	Reference resistance
1	8	120	none	Yes
2	8	200	none	Yes
3	12	120	25	Yes
4	12	200	25	Yes

Table 1 Sensor Prototypes main characteristics

Different devices were tested with diverse thicknesses of Aluminium, ranging from 120 to 200 nm as shown in Table 1, and a sacrificial layer of chromium 25 nm thick to protect additionally the Aluminium film during the manufacturing process was implemented.

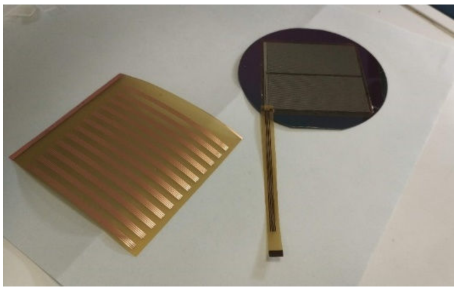

Figure 4. A photograph of the strain gauge with the adaptor.

Figure 5. The device wrapped around the valve

Additionally we fabricated for each device two equal sensors, in order to compensate the temperature variations during the testing procedure. The overall dimension of the sensor was designed for wrapping exactly the entire pole tube. To take out the signal from the sensor, a flexible adapter in copper was properly designed, manufactured and connected to the polyimide substrate through the usage of anisotropic conductive tape (Figure 4). Finally, the sensor was glued and wrapped around the valve to follow conformably the metal part subjected to the oil pressure (Figure 5).

The strain gauge sensor obviously reacts to any type of strain, so even to the temperature strain. It is then necessary to create a sensor capable of distinguish between pressure strain and temperature strain, in order to understand the part of the strain due to temperature and the part due to the normal pressure strain, or any abnormal strain, due probably to fatigue or excessive pressure, or pole tube defects. For this reason, a double strain sensor was designed, adapted to the structure of the valve. As shown in Figure 6, it can be noted that part of the pole tube is solid and part is hollow to allow the sliding of the mobile part. Consequently, the first part of the body will change its shape only for temperature, while the second one for both temperature and pressure or fatigue. Hence, the sensor was designed to have one resistance facing to the solid part of the pole tube (SG2), to be used as a reference for temperature strain, and a second resistance to be connected to the hollow part of the pole tube (SG1), sensitive to both pressure and temperature.

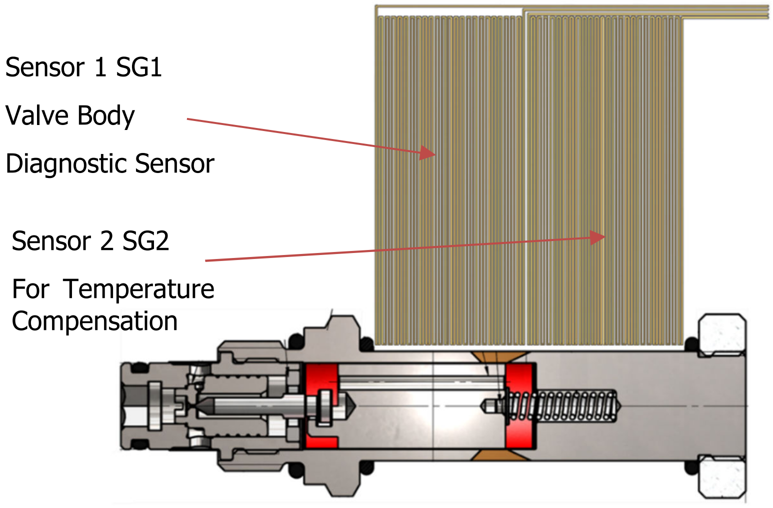

Figure 6. correspondence between pole tube structure and double sensor design

By a classic full bridge connection in the electronic readout system, it is possible to compensate the strain for temperature in the acquisition of the deformation of the SG1 sensor, subtracting the strain of the SG2 sensor, taking into account in the electronic circuit any difference in resistance of the two sensors. The same can be obtained using two half bridges readout circuitries and correcting the SG1 strain by a software function, with the advantage of reading both sensors values and having a more complete information on the valve. In this experience, we used this second approach due to the need to test different sensors with different characteristic resistances and the easiness of correcting Temperature strain by software.

5. THE NEW COIL SHAPE AND MAGNETIC FIELD ANALYSIS

Due to the specific design of the sensor, a problem that arose in the feasibility study related to the application of these sensors, was related to their installation on the valve. In particular, the strain gauge is placed above the pole tube, and the solenoid will be placed above the assembly of valve and strain gauge sensor. However, the solenoid enclosure is accurately designed in order to maximize the magnetic flux and part of the design is the minimization of the air gap between the valve coil and the pole tube. Consequently, the thickness of the sensor, although limited, requires a modification of the internal dimensions of the solenoid enclosure, to allow its insertion in between pole tube and coil enclosure. Figure 7 represents a sectional view of the valve and the solenoid. In the figure, a hypothetical magnetization path is highlighted with the dotted red line, which runs through the armature of the solenoid, the fixed core and the moving plunger and control cone.

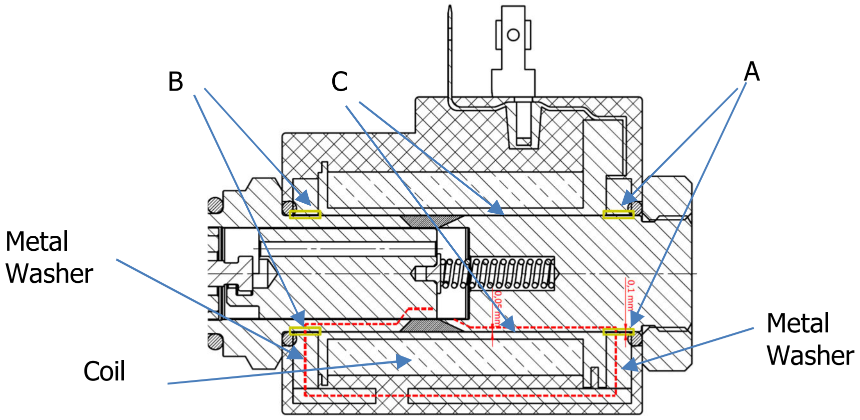

Figure 7. Valve section with Air Gaps Indication

This Figure shows also the air gaps that are to be redesigned, in order to allow the sensor placement. As it can be noted in red a very reduced air gap of 0,05 mm is available all along the pole tube and the coil, while in the two metallic rings at the end of the coil the air gap is 0,1 mm. The air gaps corresponding to the rings are highlighted in yellow in the figure. Each air gap represents a source of dispersion of magnetic flux that in these positions is not conduct in a magnetic guide. The magnetic flux dispersion ends in a reduced Coil force, proportionally. Then, the areas highlighted in yellow represent the air gaps along the path. The upper side, where the connector is placed, is not highlighted, nor the empty area on the lower side, since in reality the armature completely envelops the solenoid. Therefore, those areas are only "punctual" and are seen only in the plane chosen for the section, in the real valve the flow will pass around. Furthermore, the nominal thickness of the gaps between metal washers and tube, and between coil and tube, are shown, to indicate the space available for the sensor. The problem to be addressed in this case concerns the magnetic performance of the assembly, which is influenced by the presence of these air gaps, which introduce real losses. In fact, a circuit analogy can be made and the magnetic path can be represented as a sort of electrical circuit, where the various parts crossed are similar to electrical components. Each source of loss is schematized as a resistance, and all the air gaps encountered (for example the one between the metal washer that makes up the armature of the solenoid) will therefore be resistances that oppose the passage of "current" that is the analog element of the magnetic flux.

Although the thicknesses involved seems sufficient compared to the thickness of the sensors (we are talking about 25 µm in the worst case), it must be considered that the sensor includes a plastic film that encloses the actual sensor, and the output cables. It is therefore necessary to obtain sufficient space for their accommodation, increasing these values. Losses will inevitably be introduced, and this is why a study was conducted using the EMS electromagnetic FEM (*EMS, Advanced Electromagnetic Design and Analysis Tool* dedicated add-on of the *Solidworks* suite), to evaluate the impact of any structural modifications to the coil on the electromagnetic performance of the valve. In order to understand how the analysis was performed and how the best configuration was chosen, the various case studies analyzed and the impact they had on the magnetic flux are reported. With reference to Figure 7, it is defined thickness A the thickness of the air gap between the tube and the upper armature of the solenoid, thickness B the thickness of the air gap between the tube and the lower armature of the solenoid, while thickness C the thickness of the air gap between the tube and the solenoid. The three air gap zones are shown in the Figure.

In order to define the range of use of the valve and to calculate the absolute stroke in the simulations, we consider the stop between the plunger and fixed core at the position of 4,5 mm stroke, with the valve completely closed at lower stop. Considering a core stroke of approximately 2,75 mm, reaching the mechanical stop in the shuttle part of the valve at 1,75 mm stroke with the valve fully open. This defines the range of use of the valve, since the equilibrium position between the force of the coil and the opposing force of the spring will necessarily be reached in this range of travel. In order to evaluate the worsening due to the modified coil enclosure in the air gaps, the steady state current was analyzed, which defines the "limit" of use in terms of current applicable to the solenoid.

case	Thickness A	Thickness B	Thickness C
Standard (Production)	0.1 mm	0.1 mm	0.05 mm
A	0.3 mm	0.3 mm	0.3 mm
B	0.4 mm	0.4 mm	0.4 mm
C	0.1 mm	0.4 mm	0.4 mm
D	0.1 mm	0.3 mm	0.3 mm
E	0.45 mm	0.45 mm	0.45 mm
F	0.1 mm	0.45 mm	0.45 mm
G	0.5 mm	0.5 mm	0.5 mm
H	0.1 mm	0.5 mm	0.5 mm

Table 2 Coil Air Gaps cases for Simulation

Various simulated cases with different air gaps were analyzed from the Electromagnetic point of view, calculating the electromagnetic field intensity, its dispersion and the field density in the area of the plunger movement control, especially near the control cone of the valve. All the analyzed cases are reported in Table 2.

All these cases were simulated, in order to understand the effect of an increased air gap and how the negative effect of the air gap can be reduced, using a washer with minimum air gap in the critical area of the end of the coil. In fact, in this area the magnetic flux is conduct in a magnetic ring through the metal washer, in order to maximize the magnetic flux near the mobile core of the valve and the control cone. For that reason, a couple of cases are shown, to evaluate the dispersion of the magnetic flux and the consequent coil force reduction and its acceptability in function of valve functionality, energy balance and cost.

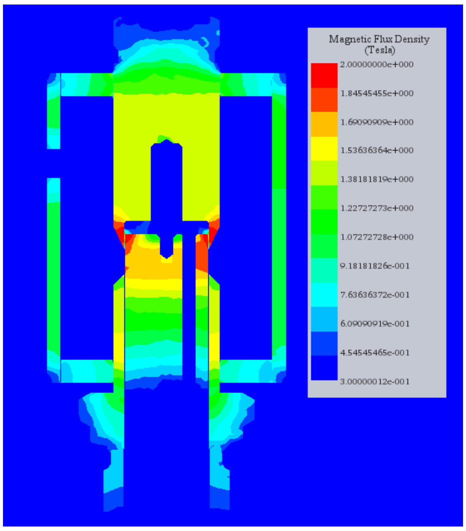

Figure 8. Case Std at maximum current

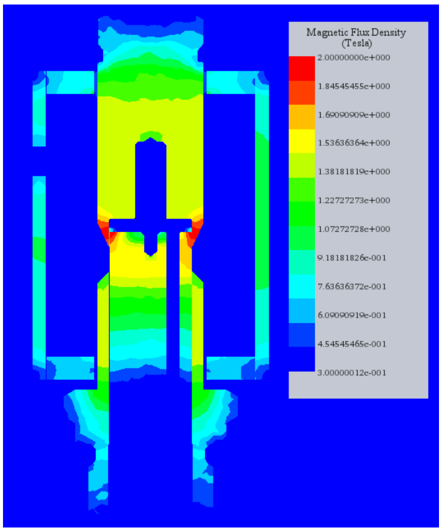

Figure 9. Case G at maximum current

In Figure 8 and Figure 9, it is evident the difference between the case standard, with minimum air gap, and the case G, which can be defined the worst case. As it can be observed, in correspondence of the metal washers, both upper and lower, in Figure 9, the field is interrupted and consequently the flux is dispersed. This is due to the larger air gap. The consequence is the reduction of the flux intensity also in the area of the control cone, where the field should be maximum, in order to control the valve plunger position. The yellow color, in respect to the orange available in the standard case, indicates that the field is lower. The final consequence is the reduction of the coil force and the impossibility to control properly the valve even at maximum current.

To justify mathematically this conclusion, the EMS simulator method shall be introduced. In particular, EMS solves the Maxwell equations of the electromagnetic interaction. In particular, it solves the two magneto-static analysis equations (7.1) and (7.2), which is the most useful for identifying the intensity characteristics of the magnetic field generated in each topology under study.

$$\tilde{N} \times H = J_S \tag{7.1}$$

$$\tilde{N} \cdot B = 0 \tag{7.2}$$

The simulator calculates the attraction force Fs between fixed and moving parts of the valve using the virtual work method and it calculates the value of the total magnetic energy when an object moves from a position 1 (W1) to a position 2 (W2) at a Δs distance (equation 7.3).

$$F_S = \frac{W_2 - W_1}{Ds} \tag{7.3}$$

$$W = \frac{1}{2}\int B \cdot H dv \tag{7.4}$$

$$B = \mu_0 \cdot \mu_r \cdot H \tag{7.5}$$

In the case of magnetic elements, the Work W is calculated in equation 7.4 in the Volume of the elements under study and the reason of the magnetic field flux density reduction is clear in equation 7.5. In this equation, B is the magnetic induction field or magnetic field flux density, H is the magnetic field, v is the volume, μ_0 is the magnetic air permeability and the μ_r is the magnetic permeability of the metal used for the valve (μ_r(AVP)≈1.000). It is then clear that, in case of a larger air gaps, the Fs is reduced of a μ_r factor in the incremental volume of the air gap in respect to the standard case. The magnetic field H does not change, because it depends on number of turns of the coil winding and the current, while B changes due to change of the air gap size.

The analysis justifies the reason higher currents are needed to control the valve plunger in all cases analyzed other than the Standard one. Then, in order to reduce as much as possible the deterioration of performance, it is necessary to optimize the air gap. From the analysis of the simulation results, it appears that the optimal case is case D, where it can be noted that metal washer that makes up the ring armor in area A (Figure 7), has the same air gap of the standard case, in order to not disperse the magnetic flux in that area. The case D is the one used for all the real tests.

6. TESTS OF FINAL VALVE ASSEMBLY

Once the coil and coil enclosure air gaps have been defined, the coils have been modified in order to assemble the prototypes. The air gaps have been modified by mechanical tooling enlarging only one ring, with the configuration of the case D. Furthermore two milled flats of the plastic layer in the rear part of the coil were made by mechanical tooling, to allow the housing of the flat cable which brings the poles of the two resistive sensors which make up the strain gauge to the outside (Figure 10 left).

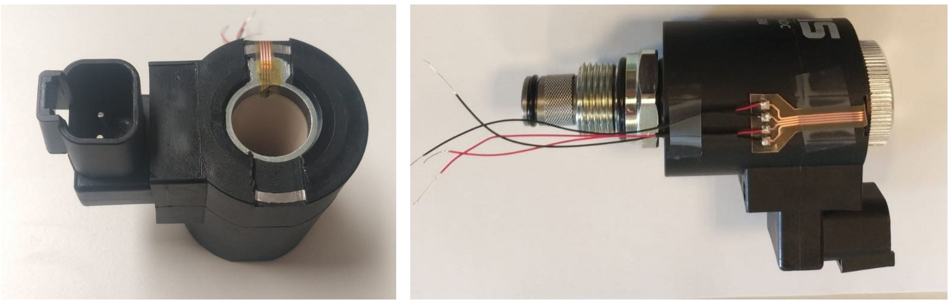

Figure 10. Modified coil and Valve Assembly

This was done to allow the fixing of the nut that holds the coil in place, once placed in the correct position with respect to the spaces available in the manifold, without risking damaging the flat cable itself. The result of the assembly ready to be tested at the test bench is shown in Figure 10 right.

The Valve with the new sensor must be characterized and the expected behaviour is that the sensor should not detect signal variations during valve operation under nominal and healthy conditions, because of the very limited deformation of the valve body expected, while it should detect signal variation, if the valve is subject to higher-pressure levels.

Figure 11. Static Pressure Test Bench

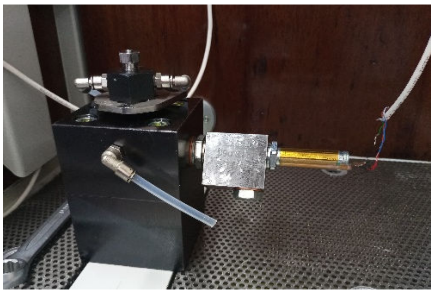

Figure 12. Dynamic Pressure Test Bench

The first tests have been conducted at the static test bench (Figure 11), in order to characterize the sensor resistances in nominal and ambient temperature conditions. In the range [0; 250] bar a barely detectable change in sensor resistance was observed, confirming that the sensor is not working in nominal conditions, exactly as other strain gauges used in past experiences. While the tests at the dynamic pressure bench (Figure 12), used for valve burst tests, made possible to fully characterize sensors in respect to valve deformation.

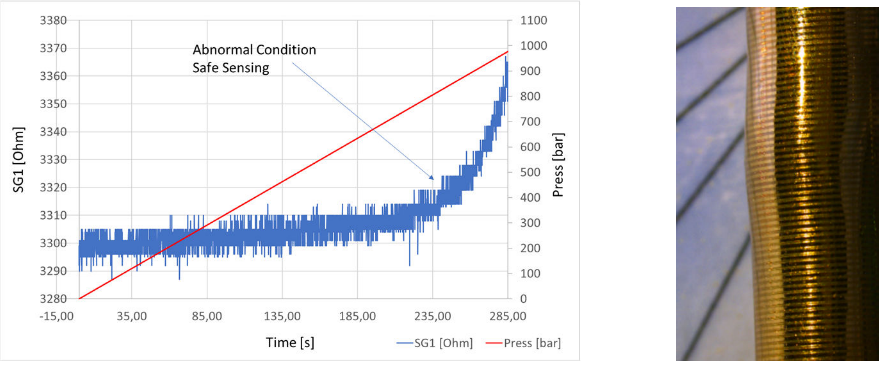

Figure 13. Pressure Transient Test

The tests were conducted in two different conditions: valve without coil and valve with coil. In fact, the coil presence changes the fault conditions for the sensor which, due to excessive deformation of the pole tube and the limited air gap, it is crushed between the pole tube and the coil. For that reason, the sensor often breaks in short circuit, resulting in a zero resistance measurement. On the contrary, without coil the more frequent fault for the sensor is case of excessive strain is in open circuit condition.

The described faults happen at the end of the burst tests or pressure tests, when the valve breaks with a consequent oil loss, or even before that condition if the sensor breaks due to an excessive pole tube deformation. The described tests were necessary to validate the capability of the sensor of providing a useful signal when in faulty conditions, to detect faults of the sensor itself, because of the valve failure or breakage.

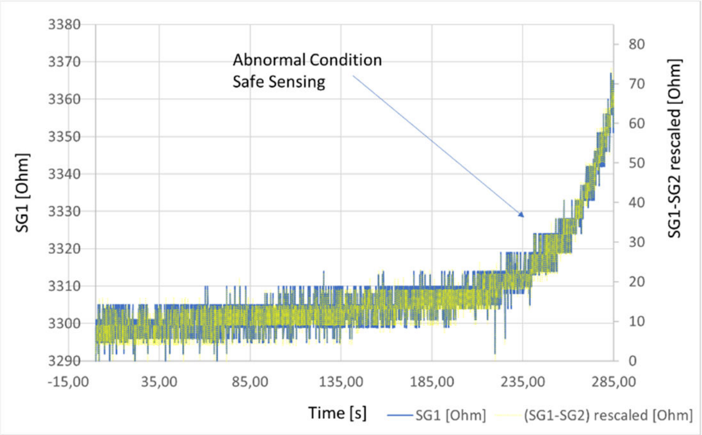

Figure 14. SG1 sensor signal comparison with (SG1-SG2) rescaled and referred to zero

However, the tests allowed recognizing abnormal conditions much earlier than valve failure conditions, so sensor breakage it represents a limit condition that should rarely be reached in real applications. In fact, a series of tests were conduct stopping the dynamic pressure test bench once the electronic control system was able to recognize a changing signal of the sensor in respect to its base line (Figure 13). In fact as it can be noted in Figure 13, the sensor in nominal working conditions is stable at a constant value, temperature dependent, while when for pressure or yielding of the pole tube, the tube shape changes, then the sensor acquire a signal that differs from the baseline of SG1 more than the 0,5% or 1% (15-30 Ω).

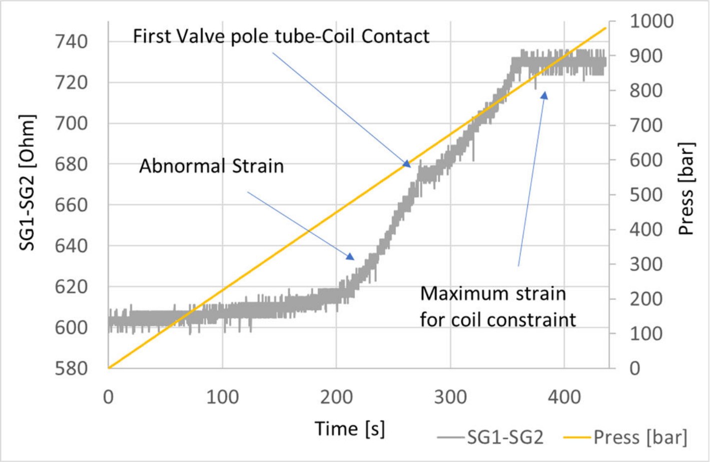

Figure 15. (SG1-SG2) in respect to Bench pressure in the test with Coil

The Electronic control is equipped with an analogue readout circuit adapted to the resistance of the sensor and with an amplification of the analogue signal, which is also adapted to the specific sensor. In these conditions 70 ohm can represent the 40 or 50% of the entire signal variation captured by the Analog to Digital converter (ADC) dedicated to the SG1 (sensor) input. The SG2 sensor is connected with a similar circuitry, so the resolution can be very high in respect to signal transition. In Figure 14, in fact it is represented how the two signals of SG1 and the signal SG1 referred to the SG2 sensor signal (SG1-SG2), which represent the pure temperature strain, are equivalent in shape and range. This consideration leads to prove that both configurations described (full bridge or two half bridges) are equivalent from the signal resolution point of view and are both functional for detecting anomalous deformations of the pole tube. The characterisation of the solution also analyses how the sensor reacts to the deformation in presence of the coil, which is a restraint in the pole tube expansion.

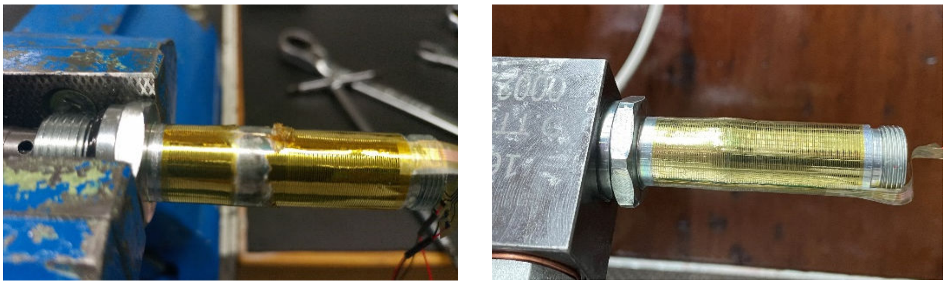

Figure 16. Valve pole tube in case of Coil and no coil

In Figure 15 it is shown a test on the dynamic pressure test bench where the test is stopped before the pole tube damage. In the chart, it is clearly visible the limit for sensor acquired strain that is also the limit of the pole tube enlargement due to small air gap available between pole tube and coil (and plastic coil enclosure). In addition, in this case, the sensor was able to capture the abnormal strain and the limited space did not affect the sensor's ability to detect an anomalous condition of deformation of the pole tube. Unfortunately, due to the hard contact, it is impossible to analyse the sensor after the test because the tube deformation is inelastic, and pole tube and coil are stuck and the sensor is crushed between the two elements. The described condition is shown in Figure 16, where it is visible the resulting deformation of the pole tube when the coil is extracted using a puller to overcome the resistance caused by the deformed pole tube. As it can be noted the shape of the pole tube deformation it is not rounded as in the case of no coil, so it is limited by coil presence.

7. CONCLUSIONS

The sensor presented is a specialized version of a strain gauge sensor. The sensor is not only special in its shape, but both materials and process are new. A very thin substrate and a nano-metric conductive material deposition allowed generating a sensor capable of sensing phenomena that normal strain gauges were unable to sense in past experiences. The sensor is a safety relevant sensor for cartridge valves, which allows detecting abnormal pole tube deformation at early stage, before valve breakage or oil leaks due to vale cracks. The sensor demonstrated its efficacy in static and dynamic conditions, both with and without coil, and it has been characterized until sensor breakage and valve breakage. This research demonstrates that shape design freedom offered by flexible electronics technology represents an interesting opportunity to equip hydraulic components with new sensors, which can bring to electro-hydraulic systems an unseen diagnostic coverage level, matching with more stringent requirements of fault tolerant applications in various fields, like: submarine, avionics, autonomous systems, steering and braking, and in military applications. This project represents a first implementation of these new sensors to cartridge valves, the tests executed and the use cases are a part of the whole set of tests that can be planned and executed with valves and is of interest of the authors to validate sensors in all possible conditions, especially in endurance tests. These tests activities will be planned with the company for a full application characterization. Also the sensor itself will be revised in order to make it more robust in the connector part which had turned out to be delicate during the valve mounting phases at the test bench. Finally, the shape of the sensor and its resistive lines, as well as the number of resistive elements and the direction of resistive lines in respect to the direction of valve breakages will be deeply analysed and revised, in order to maximize the sensor response when under stress. In fact, based on strain gauge theory, each sensor element response is maximized, when the whole element is under stress due to incoming pole tube breakage. A sensor system with more than two independent elements as shown in this research, could maximize the sensor response. More in detail, authors will continue to develop the sensor by modifying its design and by applying it to other type of valves; from the tests side point of view, the authors will investigate the sensors response in endurance tests at rated pressure, to make them work under real conditions of use and to characterize them fully.

8. ACKNOWLEDGEMENT

The research was carried out under the financed project “Mechatronic hydraulic valves equipped with innovative intrinsically safe sensors” granted to VIS Hydraulics Company under the Italian Law 14/2014 for European funding for regional development.

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