GENERAL LECTURE:

MEMS SENSORS IN HYDRAULICS, AN OPPORTUNITY TO CREATE SMART COMPONENTS

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ABSTRACT

Modern electronic technologies allow for the design and production of Micro Electro-Mechanical Systems, also called MEMS. These microchips are widely used as sensors in many fields of application, also in embedded systems in heavy-duty and agricultural vehicles and in automotive applications. In addition to the classic uses of these sensors, new architectures and sensor topologies exploit electromechanical principles of great interest for the field of hydraulic applications. This paper presents some examples of the application of a new MEMS architecture based on self-oscillating micro-resonators, which offer interesting capabilities in the measurement of mechanical deformation of mechanical components. MEMS are applied as non-invasive pressure and oil flow sensors, and represent an interesting option for creating smart components. All the applications described are intended to show the sensor's potential and have a qualitative and exemplary character, but they can provide a basis for in-depth studies on the potential and applicability of these sensors.

Keywords: MEMS, DETF, Sensors, Flow, Pressure, strain

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1. INTRODUCTION

Sensors and sensorization are two of the most important keywords for future components and systems in hydraulic and mechatronic applications. There are several reasons to invest in sensors. One of the first reasons is that, considering functional safety standards both for earthmoving and construction machines ([1] and [2]), agricultural machines [3] and the automotive sector [4], including newly approved [5] (the ones soon to come into effect), it is clearly impossible to reach a high performance level in terms of functional safety, without a wide diagnostic Coverage (DC); DC is only possible through direct observation, then through sensors.

The second reason, which is probably the most evident to customers and users, is performance: machine manufacturers demand for hydraulic systems performing better in terms of precision, dynamics and efficiency. Precision control and the best working point can be obtained only with sensors and a high level of system observability. Finally, yet importantly, confidence in reliability

is still an open point for many products. For new products there is no historic information on lifetime and product fatigue testing under real working conditions, due to the use of accelerated tests, the only ones compatible with time-to-market requirements. Interest in sensors is growing not only in mechatronics, but also in the whole field of electronics applications. The most important industry associations in the European Community, like Ecsel, Artemis, Penta and Eposs, are promoting research on sensors through specific calls in H2020 related programs. This heterogeneous research trend represents an opportunity in the field of hydraulics, where sensors are not the primary business but they are becoming an indispensable necessity.

2. MEMS TECHNOLOGY

MEMS is the acronym for Micro-Electro-Mechanical Systems. MEMS techniques allow both electronic circuits and mechanical devices to be manufactured on a silicon chip; the process of manufacturing MEMS chips is similar but more

complex than the one used for integrated circuits.

MEMS are widely used today and there are many success stories about MEMS chips used as: Pressure sensors, Accelerometers, Inclometers, IMU and AHRS units, Gyroscopes, RF Microphones. MEMS are also used as Actuators: Inkjet Nozzles, Piezoelectric actuators and generators, RF switches.

In recent years, production technology has reached optimal component quality and reproducibility of performance and many new architectures have been invented and proposed.

Figure 1: Example of Capacitive MEMS with moving part and anchored part

The MEMS principle is generally based on moving parts in a microchip (as shown in the example in **Figure 1**), and the small mass and the silicon-based material's characteristics allow mechanical principles and forces to be combined with electric principles and forces. This relationship leads to fast processes and high operating frequencies, thanks to the stiffness of silicon-based materials and high dynamics allowed by silicon-based junctions and components.

Thermal, electrostatic, capacitive, resistive and strain effects and mechanical levers and torques, controlled or measured using both resistive and capacitive effects are generally the physical phenomena underlying the operating principles of MEMS sensors.

3. DOUBLE-ENDED TUNING FORK TOPOLOGY

Not all MEMS are applicable for acquiring the same physical phenomena and it is very important to choose the best MEMS for each physical measurement. One of the most

promising MEMS geometries and functional principles that has been invented in recent years in the field of mechanical systems sensorization, is the Double-Ended Tuning Fork (DETF) MEMS ([7], [8]).

This sensor architecture was recently successfully tested in various systems and there are examples of promising applications. In [9] a pressure sensor with temperature compensation was developed, and this application is one of the most interesting in the field of fluidics. It must be noted that, as it is a strain sensor glued or fixed to surfaces of different materials, the thermal strain effect could be significant and should be considered; nonlinear strain characteristics of the nonlinear DETF subclass of sensors was analysed in [10]. A step ahead in the design of DETF sensors was made with linear DETF sensors based on CMOS elements, as presented for example in [11]. This evolution has also led to more accurate control of the geometry, which allows a wider linear range of measurement, as shown in [12], and higher measurement precision.

A very high-speed strain measurement allows DETF technology also to be used for different types of applications, like accelerometers [13] and tilt sensors [14], useful in the field of heavy duty and agricultural machines.

Regarding classic mechanical strain sensing applications, the ones discussed in this paper, in recent years DETF technology has been refined to increase sensitivity, like in [15], where a CMOS resonator with 33 nano-strain resolution was designed and tested, and at least one DETF has recently been developed in a production-ready configuration, as reported in [16].

Figure 2: The CNR MEMS DETF Resonator

The DETF used for this experimental work was developed over the years by CNR. In the next paragraph, the functional principle is explained in order to clarify the benefits of its application to hydraulic components in fluid power applications.

4. THE CNR MEMS DETF

The Italian National Research Council (CNR) is the largest public research body in Italy and is organized into departments and institutes. The MEMS technology described in this paper was developed in the Institute for Microelectronics and Microsystems (IMM) of the CNR Department for Materials and Components .

Figure 3: The DETF Resonator Asymmetrical Strain Geometry and Direction for compression (Red) and extension (Green)

Figure 4: The DETF Resonator Frequency Shift for compression (Red) and extension (Green) strain, respectively

The Institute has a clean room, a chip factory where MEMS and other components are made.

The MEMS used to create new examples of hydraulic applications sensorization was designed, built and adapted by IMM researchers and is described in [17], [18] and [19].

The sensor in **Figure 2** is composed of a DETF on silicon substrate, which is maintained at the resonance frequency through the action on two electrodes, connected to an external electronic circuit. The external analogue electronic circuit has the dual function of supplying power and providing a stimulus at the resonance frequency, in a frequency tracker topology. The same circuit is also used to acquire the resonance frequency through the digital part of the control system, using a microcontroller. As shown in **Figure 3** and **Figure 4**, the DETF element changes its resonance frequency when it is subjected to mechanical strain, and the frequency shift is opposite in opposite strain directions: compression and extension.

The sensor structure is vacuum packed in a chip. In a 5 mm × 5 mm chip, 8 sensors are assembled. Chip thickness is approximately 0.1 mm. The chip can be fixed to mechanical components with epoxy glue, like traditional strain gauges.

Figure 5: MEMS DETF output signal acquisition in no-strain condition (up) and in extension condition (down) at frequency of 320.280 Hz and 351.228 Hz

5. MEMS DETF CHARACTERIZATION AND GEAR PUMP APPLICATION

In [20], the sensor had already been characterized

and presented. The study was focused on sensor linearity and resolution; both characteristics were found to be considerably higher compared to other similar sensors, such as the one described in [15]. In fact, the CNR DETF sensor can reach a resolution of 190 pε (Figure 6), while the previously presented ones have a maximum resolution of 33 nε.

Figure 6: The DETF resonator resolution compared to traditional strain gauges function of acquisition time.

The only aspect that should be underlined is that, when acquiring a frequency-based signal, the accuracy of frequency acquisition is directly dependent, not only on sensor characteristics and on quality, but also on electronic system performance. In fact, due to the *reciprocal frequency counter* driver structure, the sensor waveform is acquired by the microcontroller at the resolution of the base counter, whose maximum frequency is a function of the main oscillator of the microcontroller itself. The limit of the base counter resolution is compensated by acquiring more than one pulse of the sensor, collecting a buffer of pulses and counting the number of pulses in the period. One immediately realizes that accuracy is proportional to the number of pulses, while the maximum dynamic of the resulting sensor is limited by the interval of time needed to collect the pulses.

In order to characterize the sensor, a first application was implemented and described in [20] where the strain model was calculated using the method described in [21].

In order to define how the adoption of a better performing microcontroller will positively affect the precision of sensor signal acquisition, a new electronic control unit was designed and prototyped using a 168 Mhz ARM Cortex M3

microcontroller, whereas in the previous electronic control unit a 40 Mhz-based microcontroller had been used. The higher oscillator frequency allows a counter resolution that is 4 times higher. The calculation can be made by comparing the performance of both microcontrollers in acquiring the resonance frequency of a DETF operating at 370.300 Hz. As the same resonant sensor is in the same condition for both microcontrollers, the time for each pulse is always the same, but the resolution of the measurement is different, due to the maximum resolution of the microcontrollers. The two examples of this calculation are shown in **Table 1** and **Table 2**; it can be noted that, using a 1000 pulse buffer, the error in Hz is 3,42 and 0,81 respectively.

If this measurement is applied in the example of a gear pump application, it corresponds to an error of 0,94 and 0,22 bar, respectively, for the two microcontrollers. It can also be noted that the signal acquisition and digital conversion of strain will take 2,7 ms and corresponds to a dynamic of more than 350 Hz in sensor signal acquisition.

Table 1: Microcontroller 40 MHz

n.of pulses	Measuring time [ms]	Max error [Hz]	error (%)	Pressure. Error (bar)
1	$2,7 \times 10^{-3}$	3.454,45	0,9336	943,84
10	27×10^{-3}	342,57	0,0926	93,60
100	0,27	34,23	0,0093	9,35
500	1,3	6,85	0,0019	1,87
1000	2,7	3,42	0,0009	0,94

Table 2: Microcontroller 168 MHz

n.of pulses	Measuring time [ms]	Max error [Hz]	error (%)	Pressure. Error (bar)
1	$2,7 \times 10^{-3}$	816,68	0,2207	223,14
10	27×10^{-3}	81,51	0,0220	22,27
100	0,27	8,15	0,0022	2,23
500	1,3	1,63	0,0004	0,45
1000	2,7	0,81	0,0002	0,22

This example demonstrates that, using a better performing microcontroller, will increase the accuracy and resolution of the strain measurement linearly, as a function of the base frequency and number of pulses considered (measurement buffer).

6. SENSITIVITY DEMONSTRATION APPLICATION: THICK PIPE

The first application was successful and the calculation executed to compare the performance of different microcontrollers in terms of measurement precision suggested setting up a new application in order to stress the limit on the sensor's measurement resolution and evaluate the limits for applicability in hydraulic applications. In fact, the measurement acquisition method is virtually capable of detecting even a very small strain on a component, using both the basic signal acquisition frequency and the length of the measurement period. Based on experience, the limited signal acquisition frequency can be compensated by using a longer measurement period (measurement buffer), as shown in the previous experiment.

Figure 7: 100 x 96 mm steel cylinder with 8 mm pipe and DETF sensor.

In order to set up the new application and new test bench, a 100 mm diameter steel cylinder was made, with an 8 mm hole simulating a thick pipe for hydraulic oil flow. A DETF sensor was externally applied on this thick pipe, and the pipe was mounted on a static pressure test bench, equipped with a certified pressure measurement digital sensor, connected through a serial line to a personal computer. One of the cylinder sides was connected to the hydraulic oil port of the static test bench, while the other side was plugged in order to prevent oil flow and allow the generation of a static pressure in the pipe, without oil leaks

through the bench actuator. The aim of this bench configuration was to perform a static pressure measurement and experimentally assess the limits of the MEMS sensor.

The steel cylinder construction data and the related theoretical deformation data, obtained from classic literature formulas, are shown in **Table 3**.

Table 3: Parameters of the Steel Cylinder

Cylinder parameter	Value
Cylinder length [mm]	96
Cylinder Diameter [mm]	100
Hole diameter [mm]	8
Tangential def. ($\mu\text{m}/\text{mm}$)	0,0004578
Tangential def. (nm/mm)	0,45
Strain [ne]	450
Young Module E (Pa)	210.000

The table shows a theoretical deformation of 450 ne, which, given the sensor resolution (190 pe), could allow an internal pressure measurement by cylinder external strain sensing under the pressure effect.

Therefore, as shown in **Figure 7**, the sensor was glued externally to the cylinder surface, halfway up to reduce edge effects, and bonded through micro-wires. Then it was connected to the hardware digital electronic unit in order to power and stimulate the sensor and acquire the feedback signal of the oscillator at resonance.

The electronic control unit is connected through a USB port to a personal computer, where an application was set up to acquire the sensor data. To demonstrate the DETF's sensitivity, a series of tests were executed, always under the same oil and ambient temperature conditions, in order to evaluate only the pressure strain effects and reduce the thermal strain effects, which are not negligible for steel.

Figure 8: Static Strain/Pressure measurement in the thick cylinder

The results of some tests are reported in **Figure 8**; a complete test session is represented in the graph, where the strain values (in Hz on the vertical axis) are shown with respect to time (in s

on the horizontal axis). In the figure, it can be noted that the strain is not regular on pressure changes, but this is due to the test bench set-up, where pressure is manually adjusted. It can also be noted that the strain is constant after the transient and adjustment phases.

Considering a sensitivity of $120 \text{ Hz}/\mu\epsilon$, the strain can also be calculated. The average data of the experiment are shown in **Table 4**. Both pressure (acquired by the instrument on the bench) and the resonant frequency (acquired through the electronic control system) are shown together with some calculated data in the left columns. It is important to underline that the resolution is less than $1 \text{ Hz}/\text{bar}$, but that 1 Hz is much higher than the microprocessor resolution for frequency acquisition, so that hundredths of Hz can be easily calculated.

Table 4: Parameters of the Steel Cylinder

Oil Pressure [bar]	Resonant Frequency [Hz]	Strain($\mu\epsilon$)	$\Delta(\text{Hz})$
0	351835	0	0
40	351850	1,8	15
90	351872	4,44	37
130	351892	6,84	57
170	351912	9,24	77
210	351932	11,64	97
250	351952	14,04	117

The experiment shows that even under extreme steel thick pipe conditions, the sensor is able to sense the strain on the material. Based on this experience, we could imagine how to apply the sensor to hydraulic components like pumps and valves, because the sensor is able to acquire the internal pressure even when the metal thickness is greater than the typical pipe thickness. Indeed, the oil pressure generates a force sufficient for good strain, with respect to sensor sensitivity. In order to find other new applications, it is necessary to think differently.

As an example, it may be inferred that it is also possible to acquire small forces capable of creating minor strain in materials with a small thickness.

That idea suggests the possibility of also acquiring oil flow-related data.

7. NEW COMPONENT: FLOW SENSOR

Oil and, in general, a fluid flowing in a pipe, generates forces against any obstacle. This was the main concept for the design of the new flow sensor.

7.1. The Mechanical Design of the Flow Sensor

The principle is to create a new component where an obstacle to the oil flow, placed in a pipe, is capable of transferring to the outside part of the force applied to the obstacle by the oil itself. The aim of this experiment was to calculate the amount of force at the oil flow rates and pressure rates normally available in a mobile application. For this experiment and all related simulated mathematical models, a maximum pressure of 250 bar and maximum oil flow of 190 l/m was considered.

Figure 9: The Flow Sensor mechanical component

In order to set up an experimental rig, a pipe with the simplest obstacle was designed by drawing a parallelepiped shaped, obstacle with a rounded apical part. This partial obstruction was fixed orthogonally to the oil flow, so as to intercept the flow in the area of maximum speed (with reference to the laminar flow profiles). One of the design requirements was to generate a minimum reduction in the pipe cross-sectional area, in order to minimize pressure losses. The form factor of the obstacle represents a critical part of the project, because it has to be enough to generate a sufficient resistance to the fluid flow, but should not create too big a pressure drop in the section. Optimization of the form factor is the main goal of the mechanical sensor's component design.

7.2. The Design Methodology

The solid model of geometry was analysed through 3D CFD (Computational Fluid Dynamics) analysis, in order to evaluate the oil flow and calculate the pressure flow forces applied to the obstacle. In a second phase, a structural FEM (Finite Element Method) was used to calculate the resulting strain on the outer wall of the pipe, at the base of the obstacle to the hydraulic flow subject to the force of the flow itself. If the strain is of a magnitude compatible with the DETF sensor, then a new flow sensor is possible.

Figure 10: The Flow Sensor design recursive method

Simulations were carried out from 10 bar to 250 bar and with oil flow from 10 l/min to 150 l/min $T = 50^{\circ}\text{C}$, $\nu = 44 \text{ mm}^2/\text{s}$ for temperature and kinematic viscosity of the oil used.

One result is shown in **Figure 11**, where it is evident in which area the greatest force resistant to the oil is located; this is also the area that generates the maximum torque on the outer wall of the pipe. The resulting pressure is around 0,31 bar, which corresponds to $3,1 \text{ N/cm}^2$. The area of the obstacle is around $0,5 \text{ cm}^2$, thus the resulting force is around 1,55 N. These data were used in the structural analysis to evaluate the resulting strain on the outer wall of the pipe.

Figure 11: Fluid Dynamic Analysis at 150 l/min oil flow

Figure 12 shows the resulting solid model of the mechanical component, where the fluid force is applied in the centre of force of the obstacle, as

per fluid dynamic analysis. In the figure, the two areas of greatest strain are highlighted by two arrows oriented in opposite directions, respectively in front and behind the base of the parallelepiped, which constitutes the barrier to the hydraulic flow. In these two points the strain is respectively inward, upstream of the obstacle, and outward, downstream of the obstacle, from the oil flow point of view. This will enable a very good measurement, because the pressure strain has the same outward direction in both points, so that the difference in the resonance frequency shift will be the exact strain measurement.

Figure 12: Structural Analysis with maximum strain points in the outer wall of the pipe for sensor placement.

The combined effects of direct pressure deformation and of indirect flow force deformation are evident in the figure, which shows the extent of deformation in upstream and downstream of the obstacle. The directional deformation on the Z axis (vertical axis in the figure), in the area in front of the obstacle is an order of magnitude higher than in the area behind it ($1,2 \times 10^{-6} \text{ mm}$ vs. $6,8 \times 10^{-5} \text{ mm}$). The deformation values are in the range of measurement of the DETF sensor; therefore the sensor is theoretically feasible. The main problem to be addressed, in order to move to a sensor prototype, is the optimal positioning of the microchip with DETF resonators.

7.3. Prototype and Testing

For a rigorous test of maximum deformation in a real prototype, two chips positioned above the areas of maximum deformation should be used. However, given the limited distance between the two areas (3 mm) and the availability of 8 DETF resonators inside each chip, it was decided to glue only one chip onto the external surface of the

sensor. The chip size is 6 mm × 6mm. Therefore, two DETF resonators placed at the two far ends of the chip were used, each very close to one of the two areas of maximum deformation.

In **Figure 13**, the DETF sensor and the bonding interfaces are shown mounted in the prototype in the sensor on the outer wall of the pipe.

Figure 13: Sensor prototype with 1 chip and 2 DETF bonded.

One of the most critical points for the mounting phase and for testing on a real test bench are the micro-wires needed to connect the DETF stimulation terminals to the external wiring interfaces. A plastic protection was thus made with a 3D printer (in red in **Figure 14**) and the sensor assembly was installed on the bench in order to test it under real working conditions.

Figure 14: Oil flow sensor with DETF resonator test bench.

Some tests were carried out at a constant oil temperature of 50 °C in order to reduce the temperature effects in the strain on the component. Temperature strain is compensated using two sensors with different spatial orientations (90°) and applying the compensation formula:

$$f = f_1 - (f_2 \times 0.38) \quad (1)$$

instead of a simple difference in resonator frequencies, which could be applied if both

sensors had the same spatial orientation, but in that case temperature compensation would not be possible. Equation 1 was obtained experimentally by testing the sensor inside a climatic chamber and acquiring the difference in resonance frequency of the different DETF resonators as the temperature changes. The need for experimental determination derives from the dimensional differences of the resonators, which are still obtained by growth of silicon elements in an experimental process.

The test bench allows the initial inlet pressure and oil flow to be adjusted and tests were conducted at different pressures and oil flow rates. The data of one of the test sessions is represented graphically in **Figure 15**, where it can be noted that the sensor measures a mixed effect of pressure and flow force.

The sensor output was filtered using a low pass Butterworth filter (1st order at 50 Hz).

In the Figure it is also possible to note that the sensor shows no hysteresis error either in pressure or flow measurements.

Figure 15: Oil flow sensor with DETF resonator test results.

In the awareness of the need for a pressure sensor that takes into account the contribution of pressure in the component strain, a correlation analysis was performed, using the acquired pressure and flow data from the test bench, in order to infer a mathematical equation.

A first and second set of tests were performed maintaining 20 bar and 70 bar of oil pressure, respectively. The frequency shift values for both DETF resonators were collected at different oil flow rates. The first results are presented in **Figure 16**, where a linear relationship may be noted between the two series of data (lower blue line and dots at 20 bar and upper orange line and dots at 70 bar).

Figure 16: Oil Flow Sensor Characterization

Multiple test sessions are needed to completely characterize the sensor and a second DETF sensor must be installed in an area of the pipe not affected by deformation due to oil flow. In this way it will be possible to isolate the contribution of pressure, so as to divide the two components that contribute to deformation of the sensor's mechanical component. In any case it will be necessary to characterize the resonators and to derive the empirical relationships correlating them to temperature-induced deformation.

The first experimentation of this new component gave interesting results and further studies will be carried out both on the geometry of the element resistive to the oil flow and its position and on the sensor placement and composition, in order to arrive at an interesting component for industrial and mobile applications.

8. CONCLUSIONS

The MEMS DETF application experiments presented here in relation to the field of hydraulic components and circuits, demonstrate that DETF sensor architecture represents a very interesting MEMS technology for new hydraulic components and for new sensorization techniques in both industrial and mobile applications. The examples described demonstrate the sensor's ability to measure, from the outer wall of components and pipes, both pressure and flow without energy losses. Further research and investigations will be conducted in order to thoroughly evaluate DETF technology and arrive at a complete characterization. The CNR DETF chip will be further developed and improved, to allow a simpler and more robust application to mechanical production systems:

- metal pads will be added to the silicon chip to allow direct bonding on the sensor side,

thus avoiding the need for micro-wires and a bonding machine,

- a floating DTEF resonator will be added inside each chip, in order to obtain a temperature reference oscillator and compensate for temperature frequency shift effects.

As regards the possible applications, new mechatronic components will be tested, combining new geometries and applying more than one DETF component, in order to acquire pressure, temperature and oil flow data and completely characterize system working conditions.

Today, the high number of studies related to MEMS technologies are an incentive to evaluate more sensor architectures and create new sensorization models and technologies for hydraulic components and systems.

NOMENCLATURE

ε	Strain ($\mu\text{m}/\text{m}$)
f	Resonance Frequency (Hz)
F	Force (N)
ν	Fluid kinematic viscosity (mm^2/s)
P	Pressure (bar)
T	Temperature ($^{\circ}\text{C}$)

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