Capacitive sensors of mechanical strain

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Abstract. The paper reviews recent research and applications of both laboratory prototypes and commercially fabricated capacitance gauges of mechanical strain. Basic operational principles as well as advantageous points of each type of sensors are considered. The prospective areas of applications of the capacitive gauges are briefly considered. The properties of other strain gauges are briefly discussed and compared with those of the capacitive sensors.

1. Introduction
Measurement of deformations and mechanical stresses is widely used in the study and monitoring of building constructions and structures, as well as rocks, machine parts and mechanisms, measuring the mechanical properties of materials and performing strength tests. Strain measurement is used in technical diagnostics, as well as in the measurement of related physical quantities – forces, moments, pressure, flow velocity, etc., which are converted into strain of the sensitive element [1, 2]. The use of sensors for smart health monitoring and biomechanics [3], [4], wearable electronics and “electronic skin” [5], industrial Internet of things (IIoT) [6] is becoming more and more relevant. In particular, the IIoT monitoring system would benefit from real-time measurements of the deformation state of the observed structure [7].

Strain measurement can currently be performed using various physical sensors: resistive (piezoresistive), piezoelectric, capacitive, optical, etc. Similarly, for mechanical stress measurement – in most methods of such a measurement the sensor perceives the absolute or relative value of the strain, since the natural input value of the transducers used is displacement. Sensors of any type have advantages and disadvantages, determined by the physical principles underlying their functioning, which determines the specifics of choosing a device for a specific task.

The capacitive sensors are attractive because of their effectiveness for wireless applications and wearable electronics due to low power consumption, ability to register steady strains, stretchable applications such as “electronic skin” with its high strain limits etc. A series of cheap commercial solutions for signal processing is available in the wide market, also. In this review, capacitive strain sensors will be considered. Other types are excluded, but their properties are briefly discussed and compared with those of capacitive sensors.

2. Strain characterization and sensors parameters
The elementary types of strains are linear tensile and compressive strains, which can be expressed in terms of absolute and relative elongation (normal strain):
where $\Delta l$ – absolute elongation, $l_0$ and $l$ – original and resulting length, respectively. When a compressive strain is applied both values are negative [8]. Except for linear strain and compression, different types of more complex deformation can be applied to a rigid body such as bending, twisting, and shear.

The tensile and compressive strain correspond to normal stresses which are perpendicular to the surface and given by the ratio of applied force $F$ and the cross-sectional area $A$:

$$
\sigma = \frac{F}{A} \quad (2)
$$

Shear stresses correspond to off-diagonal components of strain tensor and usually correspond to shifts parallel to the surface of the deformed body. Practically shear stresses always occur together with normal ones. Mechanical stresses are important to be monitored for study and design of building constructions and machinery, fundamental science such as geology, but at the same time they are not accessible for direct measurement. Stresses can be either calculated according to the theory or from strain measurements [8].

Typically, key demands for strain gauges are the ability to detect small strains and high accuracy, but sometimes key demand can be another. For instance, this could be contactless measurement requirement or large strain working limits. In the branch standards (e.g. [9]), one introduces the notions of maximum capacity, sensitivity of a measuring system and accuracy class for characterization of strain gauges. However, the analysis of these notions shows that maximum capacity can be improved by adding springs, sensitivities of a measuring system for different types of sensors have different dimensions and are not comparable, and the accuracy class can be determined by an external ADC. Practically, the sensitivity threshold as the minimal value of mechanical stress or relative strain the sensor and the accuracy in terms of measuring of strains (or loads) are more important. The first one is determined as the minimal deformation $\Delta l / l_0$ which can be confidently detected. To describe the accuracy of the measurements with the use of strain gauges, the following quantities are introduced in [9]: hysteresis, creep, repeatability, durability; the influence of extraneous factors is introduced separately. The term "expanded uncertainty" is used in [9] for accuracy in the usual sense – the width of the interval around the measurement result into which the true value is likely to fall. Therefore, when describing specific strain gauges, it is desirable to have their sensitivity threshold and expanded uncertainty values. Unfortunately, the authors of academic works often do not provide such data. Sometimes these data can be estimated from the figures etc.

All the sensors could be either self generating (active transducers) or modulating (passive) [10]. A useful tool for comparison parameters of the latter type is gauge factor ($GF$):

$$
GF = \frac{\Delta Y / Y_0}{\Delta X / X_0} \quad (3)
$$

where $Y_0$ and $X_0$ are initial values of output and input signals, $\Delta Y$ and $\Delta X$ are their increments, respectively. This can be applied to input and output signals of different nature. In case of strain $\Delta X / X_0$ is the normal strain $e = \frac{\Delta l}{l_0}$.

3. Sensors review
The operation principle of capacitive sensors is based on the transformation of the controlled parameter into a change in the electrical capacitance of the capacitor, which is measured directly [11]. A series of techniques for capacitance measurements have been developed such as charge-discharge time, resonant
frequency shift of LC circuit, capacitance-to-digital $\Sigma - \Delta$ conversion. Specialized IC chips existing on the commercial market are able to measure small quantities of electrical capacitances with digital resolution and accuracy of several fF, at the same time they have low power consumption and low cost [12]. The examples of such IC’s are products of Analog Devices (AD7745-AD7747), Texas Instruments (FDC1004, FDC22XX), etc.

3.1. Stretchable elastomer based sensors

Recently, flexible capacitive sensors have been actively developed for use as wearable devices on the body, "electronic skin", and also for monitoring specific technological processes. These applications impose strict requirements for weight, convenience, flexibility, mechanical strength and sensor's operation life. Compact and flexible capacitive sensors based on elastomers (polymers with high elasticity) are being developed [13-17]. Commercial sensors are available, also [18,19]. These transducers are able to track both small and large strain levels, significantly exceeding the limit of metal (resistive) strain gauges.

The use of elastomers as a deformable dielectric material is one of the approaches to expanding the limits of measured strains. An uniaxial strain $\varepsilon$ causes increase of the initial length $l_0$ to $(1+\varepsilon)l_0$, whereas due to the Poisson effect the width of the plates $w_0$ and the interelectrode distance $d_0$ decrease to $(1-\mu\varepsilon)w_0$ and $(1-\mu\varepsilon)d_0$, respectively [15, 20]. Here, $\mu$ is the Poisson ratio. Thus, in the case of a plane capacitor the capacitance $C$ under applied strain and $GF$ are as follows:

$$C = (1+\varepsilon)C_0, \quad GF = \frac{\Delta C / C_0}{\varepsilon} = 1,$$

A series of academic research papers confirms this result [13,14,16,17].

In [13], an elastomer-based sensor obtained using laser techniques is described. Manufacturing of the sensor consists of the following stages: obtaining a silicone elastomer substrate, fabricating the surface as a set of grooves using a DPSS laser, pre-stretching the elastomer up to ~80%, applying layers of metal that serve as electrodes, and cutting sensors of a given size from the workpiece. The dependence of the capacitance change on the applied strain is perfectly approximated by the linear dependence ($R^2=0.998$) and has an extremely small hysteresis. The gauge factor $GF = \frac{\Delta C / C_0}{\varepsilon}$ was found to be ~0.9. The noise level measured at the 50 Hz bandwidth allows absolute strains of ~0.5 mm to be resolved with the gauge length of 40 mm. In a series of loading cycles, a sharp drop in the relative change in capacity is observed for strains $\varepsilon > 0.8$ during the first cycles, it is caused by the elastic properties of the elastomer, and then this value is stabilized. In case of $\varepsilon = 1$, the capacity continues to fall with an increase in the number of loading cycles, which is associated with the successive crack formation in the metalized layers. The sensor delay time was found 0.146 s, which makes it possible to measure strains with frequencies less than 10 Hz. [13] demonstrates the potential use of the sensor as a sensor of movement and position of human body parts.

In [16, 21] carbon nanotubes coatings embedded in a polydimethylsiloxane (PDMS) matrix are used as top and bottom electrodes of the capacitor separated by an elastomer layer. The sensor [16] is transparent and can detect deformations both when pressed or stretched. The sensor [21] is characterized by both a change in the resistance of the electrodes ("piezoresistive" response) and a change in the capacitance during deformation. The dependence of the resistance change on the strain shows a significant hysteresis, which is expressed in a change in the resistance in the unloaded state at a level of more than 100%. The change in the system capacity, however, shows excellent linearity and no visible hysteresis (depending on the prehistory of deformations). The sensor [21] shows a capacity change of less than 3% at 3000 load cycles of 100% strain. The gauge factor value is close to the theoretical limit and is 0.99 with a temperature error of 0.1%/°C. In [22], similar results were obtained for a sensor based on silicone rubber and nanotube plates. The sensor can withstand 1800, 3800 and 10000 cycles with
strains of 200%, 150% and 100%, respectively, though the potentially detected strains are of 1% to 300%.

Graphene [23-24] is also considered as a material for the plates of capacitive sensors due to its elasticity and optical transparency. The latter is especially important when building optical touchpad displays. A capacitive sensor based on graphene nanoplastics and PDMS was proposed in [24]. The sensor demonstrates linearity in the range of applied deformations up to 0.2%, the GF is about 3.

Elastomer based sensors are available in the market for use in wearable electronics [18]. The SSD18 sensor [18] can withstand stretching up to 80% and has an elongation sensitivity of ~5 pF/mm, which gives a gauge factor of $GF = \frac{\Delta C / C_0}{\varepsilon}$ – 0.8 for the total length of the sensitive area $l_0 = 70$ mm and an initial capacity of $C_0 \approx 450$ pF. Flexible capacitive bending strain sensors based on silicone elastomer are commercially available by Bend Labs [19]. The temperature coefficients of expansion of the materials are matched together, which is especially important taking into account the large length of the sensor. The company has developed single-axis sensors that respond only to strains along one of the axes, and two-axis sensors are offered to control two-dimensional deformations. The internal capacitive sensing elements are connected according to a differential scheme, which allows one to exclude the influence of errors due to temperature, tensile strain, etc. The bending sensitivity of the sensors is 0.274 pF/°, the power consumption of the single-axis sensor in active mode 200 µa at 3.3 V at the acquisition frequency of 100 Hz.

A number of ways have been proposed to improve elastomer based strain sensors. An elastomer-based sensor described in [14] allows one to enhance the sensitivity for potential miniaturization by increasing relative permittivity $\varepsilon_r$. The increase in permeability is achieved by introducing a small amount of a conductive polymer into the elastomer matrix of the SEBS-g-MA with Young's modulus $E_Y = 4.5$ MPa and the permittivity $\varepsilon_r = 2.0$. The increase in permittivity is achieved due to hyperelectronic polarization – the ability of mobile charges to shift significantly, forming a macromolecular dipole. At a volume concentration of 2.3% of the doping substance, $\varepsilon_r$ increases up to 122 at a frequency of 100 Hz. The change in capacity is linear and is ~10% at the concentration of the doping impurity 2 and 2.3% by volume and 10% of applied strain. Increasing the dopant concentration enhances both the aggregate capacitance and its increment at an applied strain. The deviation of the capacitance $\Delta C / C_0$ (estimated noise) at 20% strain during 10 s was about $10^4$, which corresponds to the absolute strain of ~10 microns. At the same time, the level of fluctuations in long-term exposure (3600 s) is significantly higher.

![Figure 1](image1.png)

**Figure 1.** Manufacturing scheme and design of a film capacitive load cell based on a "wrinkled" Au film [13].

One more approach to enhance the sensitivity of sensors on elastomers and their working range is possible increase of the gauge factor. Thus, [13] describes a capacitive sensor based on wrinkled structure with gauge factor reaching 3 at the maximum value of the applied strain of $\frac{\Delta l}{l_0} = 140\% (1.4 \varepsilon)$. The higher $GF$ is obtained by introducing an additional degree of freedom to strain the film in the
transverse direction when stretched. This is achieved by the fact that the film in the unstrained state has a structure full of folds (figure 1) and its following transformation into a completely flat capacitor, which allows one to change the effective area of the capacitor by about three times.

While width contraction is cancelled, the strained capacitance can be found as

$$C = \frac{(1 + \varepsilon)C_0}{(1 - \mu \varepsilon)}.$$  

(5)

The folds are formed by sputtering a gold film on a prestressed (stretched) layer of a dielectric elastomer with an intermediate layer of Poly-para-xylene (PPX, parylene), which is necessary to improve the adhesion of the gold layer and prevent its destruction under large strains. After deposition, the dielectric film is unloaded and folds appear. The optimal thickness of the PPX layer found in the study was from 500 nm to 2.5 μm.

The sensor shows a fairly high linearity $R^2 = 0.98$ and minimal hysteresis, no sensitivity changes after 1000 load cycles with the change of capacitance of 5.4 % when heated to 50 °C. The paper demonstrates the possibilities of using the sensor for applications in flexible wearable electronics.

Another noticeable type of the elastomer based sensors is that with flat printed strip conductors [12, 25-27], the so-called interdigital capacitors being used as plates. A similar rubber-based sensor for diagnosing vehicle tire pressure is proposed in [25-26]. The sensor consist of a rubber substrate with printed by photolithography gold interdigital structure upon (figure 4). The pressure applied in the normal direction to the plane of the conductors causes a change in the distance between them and, consequently, in the capacity. The configuration of the capacitor plates (outline drawing) is shown in figure 2: $a$ - the length of the overlapping part of the strip, $b$ - the width of the conductor, $c$ - the total length of the plate, $g$ - the gap, $l$ - the total length of the capacitor.

When applying a tensile strain $\varepsilon$ the change in the capacity of the system is:

$$C = C_S + C_P = (2n - 1)\varepsilon, \varepsilon_0, a(l - \mu \varepsilon)h\frac{1}{g(1 + \varepsilon)} + C_P$$

(6)

where $n$ is the number of electrodes pairs, $\mu$ is the Poisson's ratio, $h$ is the thickness of the dielectric (rubber), $\varepsilon_r$ is the permittivity, $C_P = \alpha C_{S0}$ is the parasitic capacitance determined by the connecting conductors, $C_{S0}$ is the initial capacitance of the interdigital structure and $\alpha$ is the coefficient. The $GF$ of the sensor is as follows: $GF = \frac{\Delta C}{C_0} = -\frac{1 + \mu}{1 + \mu}$. From this ratio, the gauge factor does not depend on the sensor’s design, but only on the coefficient that determines the ratio between the parasitic and net capacity. The sensor reveals a small hysteresis of fairly linear dependence on the strain with the maximum deviation from linearity equal to 8 %. The sensor lifetime reaches $10^5$ load-discharge cycles, which is due to degradation of the electrodes, and when applying an additional protective coating based
on silicone rubber, it increases the life to $10^6$ cycles. The maximum measured strain reaches more than 14%.

[12] describes an interdigital sensor based on a flexible substrate. The substrate material is polyamide, a liquid crystal polymer. The gold conductors are built by photolithography and PVD, and sealed with an acrylic resin. The process limitations allowed one to fabricate an electrode of width $b = 45 \ \mu m$, height $h = 300 \ \text{nm}$, and gap $g = 15 \ \mu m$. The sensors are connected according to the half-bridge, which eliminates the influence of common mode errors acting on both capacitors simultaneously (temperature, humidity etc.). Both single sensors on polyamide (PI-45/15) and LCD (LCP-45/15) substrates show excellent linearity at low strain levels of less than 1%, while the change in capacitance lies in the sub-pF region at the initial value of ~48 pF in a dry atmosphere. The power consumption of the sensor system based on a half-bridge sensor together with the measuring electronics is about 0.6 mW, which makes it attractive for use in wireless systems.

3.2. Elastic sensors with liquid electrodes
Measuring large deformations using the capacitive effect imposes strict requirements on the mechanical and electrical properties of the electrode material. Despite certain advances in the design of capacitive sensors based on solid-state metal conductors, the lifetime of such sensors under periodic large strains can be significantly limited. In this regard, solutions based on liquid conductors that can withstand large strains with no disturbing electrical conductivity are relevant [28-31]. Recently liquid metals such as eutectic based on Ga and In (EGaIn), gallium–indium–tin (Galinstan) with low melting points below room temperature.

[28] and [29] demonstrate a possibility comb capacitor (interdigital structure) in which EGaIn or Galinstan is embedded in a soft silicone elastomer. The sensor can distinguish the stretch in directions parallel and perpendicular to the electrodes. The predicted values of the relative changes of the capacitance are $\Delta C / C_0 = \varepsilon$ and $\Delta C / C_0 = 1/\sqrt{\varepsilon+1}-1$ for the parallel and perpendicular axes, respectively, and the corresponding gauge factors are $GF = (\Delta C / C_0)/\varepsilon = 1$ and $GF = (\Delta C / C_0)/\varepsilon = 1 - \sqrt{\varepsilon+1}/\varepsilon\sqrt{\varepsilon+1}$. These predicted relations are confirmed by the experimental dependences. A spiral geometry of capacitor is fabricated and discussed in [28], also.

In [30], a stretch strain textile-mounted sensor based on a silicone elastomer and a conducting ionic liquid is proposed, a method for manufacturing is given, also. The liquid serves as the plates of the capacitor, which is built according to the coaxial scheme (figure 3).

![Figure 3](image_url)

**Figure 3.** Schematic representation of the design of a capacitive sensor based on an elastomer and a conducting liquid [30].

The core-shell coaxial threads were made using 3D printing, after which they were filled with a ionically conductive liquid (figure 3). Electrical contacts were created by inserting a silver wire into a liquid conductor. When the sensor is stretched, the capacitance of this coaxial system changes proportionally to the strain:
where \( r_{10} \), \( r_{20} \) are the outer radii of the liquid core and the inner dielectric layer, respectively. At the same time, the resistance of the conductor of the plates also changes due to the strain effect, but in proportion to the square of the deformation. The sensor can withstand deformations up to 250 % with no hysteresis under static and dynamic loads. For small deformations, the dependencies deviate from the theoretical ones due to the inadequate tension in the dielectric layer to ensure a straight inner tube.

A capacitive sensor of torsion or tension strains based on a liquid-metal conductor placed inside an elastomer fiber is proposed [31]. Conductors based on hollow tubes with a liquid metal (LM) conductor are known to be able to maintain metal conductivity under deformations up to \( \approx 800\% \) [32]. The fiber is quite compact and can be embedded in a textile. Eutectic based on Ga and In (EGaIn, Ga 75% and In 25%) has been used as a liquid conductor. Its advantages are the absence of toxicity, negligible saturated steam pressure at room temperature, and low viscosity. The sensor consists of two hollow tubes of triangular cross-section elastomer filled with a liquid metal conductor and twisted into a double helix. The triangular shape of the cross-section allows minimizing the non-linearity and hysteresis of the liquid-metal channels [33]. The sensor allows detecting stretching and torsion deformations, the possible level of the latter reaches \( \Theta \sim 10800 \text{ rad/m} \), which, according to the authors, is two orders of magnitude greater than the existing torsional strain sensors can measure. When maintaining a constant distance between the two ends of the fibers and twisting them, the main change in geometry is associated with an increase in the total length \( \zeta \), and this causes a change in the total capacity of the system. The sensitivity of the system increases with the increase in the diameter of the LM-filled fiber, while the limit of detected strain decreases. This is because larger diameter fibers must experience greater tensile strain at an equal torsional level and achieve destructive tensile stress at lower relative torsion angle. The dependencies \( C(\Theta) \) for all the selected diameters are linear with \( R^2 = 0.99 \). However, for large and small torsion, there is a deviation of the actual capacity from the linearity toward smaller values. The maximum values of the relative twisting angle are 10887, 8378, 5585 rad/m for sensors with fiber diameters of 235, 350 and 850 microns, respectively. When applying a cyclic load in the area of small torsional strains, gradually progressive deviations are observed, which is associated with the formation and increase of the gap between the fibers. At the same time, at loads of more than 200 rad/m, the repeatability is significantly higher and does not depend on the number of cycles of the applied strain. As the temperature changes, the capacity per length decreases by 0.0003 pF/cm for each degree when the temperature drops from 25 °C to -10 °C, which is 0.27 %/°C of the measurement limit. Stretching causes the fibers to converge, which also leads to an increase in capacity. Thus, the sensor can also detect tensile strains and, in principle, complex tensile-torsion strain. The paper [31] also provides an example of using a sensor as a tactile sensor in a touchpad type device.

### 3.3. Thick-film and MEMS sensors

The thick film type of capacitive strain sensors is the type of gauges based on thick films or layers of dielectrics [34-35]. High values of relative permittivity \( \varepsilon_r \) of some dielectric films allows one to increase the initial capacitance and provide a change of \( \varepsilon_r \) when compressed. A sensor with a thick-film dielectric based on lead-zirconate–titanate (PZT) (lead–zirconate-titanate, \( \varepsilon_r \approx 600 \)) and polyvinylidene fluoride (PVDF, \( \varepsilon_r \approx 13 \)) is described in [34]. The dielectric layer was fabricated by applying a specially made paste layer 150 μm thick on a substrate of aluminum oxide. The plates were created by applying a layer of a conductive paste. When applying a tensile strain, the film is deformed both longitudinally and transversely, and its thickness decreases. The theoretically predicted \( GF \) is obtained as \( GF = \frac{\Delta C}{C_0} = \frac{\Delta \varepsilon_r}{\varepsilon} \frac{l}{\varepsilon} - 1 \) and contains two terms: caused by a change in the permittivity
\[ \frac{\Delta e_r}{e_r} \] (the "piezo-capacitive" component) and due to a change in the geometry "−1". When applying a strain of up to 300 microns/m and then removing it, the sensor based on PZT cermet shows a $GF$ of 6, and $GF$ of that based on PVDF polymer yields $GF=3.5$. The obvious disadvantage of the thick film sensors in comparison with the elastomer based ones is low limiting strains.

Capacitive [36-41], resistive [42, 43-45], piezoelectric [42, 46], and resonant strain sensors [47-52] based on microelectromechanical systems (MEMS) technology are being currently developed. MEMS technology allows one to reach significant miniaturization of the sensor, provide precision manufacturing, reduce power consumption, and increase sensitivity. MEMS capacitive strain sensors are attractive due to high sensitivity, low noise, large dynamic range, and potential for integration with low power CMOS electronics [36-41].

The paper [36] describes a differential capacitive MEMS sensor of tensile and compressive deformations manufactured using a single-layer technology. The sensor's structure is shown in figure 4. The support ribs are supported above the surface by the bent beam suspensions. The edges hold the interdigitated tines, which play the role of capacitor plates. The plates are placed in such a way that when the strain is applied, the capacity increases on one part and decreases on the other. This provides a differential response of the structure. In this case, the ribs A move in the opposite direction, compared to the ribs B and C.

![Figure 4. Structure of the differential capacitive MEMS strain sensor [36].](image)

The sensor prototypes were fabricated of polycrystalline silicon for compressive deformations and electroplated Ni for tensile strains. The polysilicon Sensors were manufactured by CVD method on an oxidized silicon substrate. Silicon lithography was performed by the reactive ion etching (RIE), the sacrificial layer was etched in BHF. The MEMS capacitors were manufactured on a silicon substrate with a 2 µm layer of oxide coated with a 500 nm layer of nitride. After that, a 2 µm Ti layer was sputtered, which was covered by a layer of 100/100 Å Cr/Ni. The change of capacitance in the case of the polysilicon sensor amounted to several femtofarads when applying compressive stress of -40÷-42 MPa and tensile stress of 40÷55 MPa.

In [37,38], a capacitive MEMS bending and axial strain interdigital sensor is proposed. Each plane system can be displaced independently of the other when applying a tensile or bending strain. During manufacturing, they both are rigidly bound with ribs, and the ribs are destroyed during installation. Changing the distance between the plates causes a change in capacity, it is the basic operation mode of the device when applying tensile strain. However, when bending, the overlap area of the interdigitated plates also changes. When applying a tensile strain of 1000 µε, the change in the system capacity is about 3 pF. The nonlinearity of output characteristic of the sensor is a disadvantage of the capacitive sensors based on changes in the distance between the plates. At the same time, the advantage is high sensitivity.

Another approach for the interdigital MEMS sensors is the use of the overlapping area change which provides a more linear response. The sensor [39-41] consists of three amplifying bent-beam suspensions with interdigitated comb fingers positioned at the structural center. As it is expected, the output characteristic of the sensors [39-41] is close to linear (1.9% full-scale non-linearity), with the sensitivity equal to 265 aF/(µm/m). The temperature change of the capacity in the temperature range from room to
150 °C was 10 fF with a nominal sensor capacity of 440 fF. The authors developed an original low-noise readout, the measured noise level was calculated as 0.24 aF/√Hz (0.24 aF/√Hz) or 0.9 nm/m/√Hz (nε/√Hz).

4. Comparison with other transducers
Depending on the specific task, sensors can be selected that provide the desired resolution, measurement ranges, and also specific requirements. The obvious advantage of the capacitive sensors is the possibility to measure not only tension-compression deformations, but also torsion and bend.

The capacitive sensors are more attractive for high stretch applications than the resistive strain sensors which are generally suitable for measuring moderate constant and time-varying strains up to ~ 10³ µε. The power consumption of the capacitive transducers is much less. The read-out for a typical resistive strain system is easier, but measurement of the capacitance changes leads to a slightly greater complexity of processing methods and circuit solutions in comparison with those for capacitive and piezoelectric sensors. However, there is currently a wide range of relatively inexpensive specialized commercial IC’s and solutions for capacitive sensors. The piezoelectric sensors are self generating (active transducers), they directly produce output voltage with no power supply, but their lack is impossibility to measure static strains.

The elastomer-based sensors, both resistive or capacitive, can be used to measure larger strains up to ~1 ε. To build a "smart" sensors and sensing IC's with high degree of integration, one requires miniaturization of the size of the sensor, extremely low power consumption etc. The MEMS sensors are the most promising for such tasks. They are capable of measuring moderate strains up to 10³ µε with a resolution of less than 1 µε.

The magnetic sensors are sensitive to external magnetic fields and electromagnetic interference, but their unique advantage is the possibility of non-contact measurements with no power supply of the sensing element. The FBG (fiber Bragg grating) sensors provide remote measurements and dielectric strength when measuring objects potentially at high voltage, the ability to multiplex signals and measure strain at multiple points using a single line. Distributed sensors allow one to obtain the distribution of deformations along the fiber with a certain spatial resolution, using only one fiber. Nevertheless, the price of a FBG and a read-out is too high.

Table 1 provides a summary of the sensors reviewed.

| Sensor type                | Resolution, µε | Strain measurement range, µε | Advantages                                           | Ref                      |
|----------------------------|----------------|------------------------------|------------------------------------------------------|--------------------------|
| Capacitive                 |                |                              |                                                      |                          |
| - elastomer-based          | Up to ~ 1      | Up to ~10⁶                   | Large limit deformations, two-axis measurements, torsional strain measurement | [18, 13-15, 19]          |
| - with liquid conductors   | ~ 10⁶          | Up to ~10⁶                   | Large limit deformations, torsional and complex strain measurement | [30-31]                  |
| - with a thick dielectric  | ~ 0.1-1        | Up to ~10²                   |                                                      |                          |
| Resistive (piezoresistive) |                |                              |                                                      |                          |
| - metal                    | ~0.1           | Up to ~10⁴                   | Simple measurement and low price                      | [1-2]                    |
| - semiconductor            | ~10⁻³⁻¹⁰⁻²     | Up to ~10³                   | Dynamic and static deformations                       | [1]                      |
| Piezoelectric              | Up to 10⁴      | Up to ~10³                   | Direct conversion of strain to electrical voltage     | [42, 2, 53-54]           |
| MEMS                       |                |                              |                                                      |                          |
| - capacitive               | 1-10           | Up to ~10²                   |                                                      | [36-52]                  |
| - piezoresistive           | ~0.1-1         | ~10³                         |                                                      |                          |
### 5. Conclusion

In this paper, we reviewed capacitive strain sensors and provided a comparison with some other types. The power consumption of the the capacitive transducers is much less than that of the resistive ones. The read-out for a typical resistive strain system is easier, but measurement of the capacitance changes leads to a slightly greater complexity of processing methods and circuit solutions in comparison with those for resistive and piezoelectric sensors. However, there is currently a wide range of relatively inexpensive specialized commercial IC’s and solutions for capacitive sensors. These solutions as well as the sensors themselves are not so expensive as FBG and their optical read-outs. In comparison with the magnetic transducers the capacitive sensors are not sensitive to external interferences, especially low-frequency interferences.

The prospective areas of applications are wearable electronics, health care and high strain measurement (elastomer based sensors) and MEMS sensors. The elastomer based sensors provide a high sensitivity and large stretchability providing at the same time reliable electrical contact under applied strain and mechanical endurance under repetitive load. The existing commercial sensors show reproducibility in fabrication. The problems of such sensors are mechanical hysteresis, large relaxation time, narrow temperature range [20].

The MEMS sensors are the most promising to build a "smart" sensors and sensing IC's with high degree of integration. They provide required miniaturization of the sensor’s size, extremely low power consumption etc. The MEMS sensors are capable of measuring moderate strains up to $10^3 \mu\varepsilon$ with a resolution of less than 1 $\mu\varepsilon$.

### Acknowledgement

This research is implemented in Petrozavodsk State University with financial support by the Ministry of Science and Higher Education of Russia within Agreement no. 075-11-2019-088 of 20.12.2019 on the topic “Creating the high-tech production of mobile microprocessor computing modules based on SiP and PoP technology for smart data collection, mining, and interaction with surrounding sources”.

### References

[1]  Kester W 1999 Section 4: Strain, Force, Pressure, and Flow Measurements *Practical Design Techniques for Sensor Signal Conditioning* (Analog Devices, USA)

[2]  Du W Y 2014 Resistive, capacitive, inductive, and magnetic sensor technologies (CRC Press)

[3]  Laflamme S, Ubertini F and Li J 2019 Smart Sensors for Structural Health Monitoring (MDPI)

[4]  Miles A W and Kathleen E T 1992 *Strain measurement in biomechanics* (Chapman & Hall)

[5]  Mukhopadhyay S C 2015 Wearable electronics sensors: For safe and healthy living (Smart Sensors, Measurement and Instrumentation 15) (Springer)
[6] Chen B, Wan J, Shu L, Li P, Mukherjee M and Yin B 2017 Smart factory of industry 4.0: Key technologies, application case, and challenges IEEE Access 6 6505-19
[7] Korzun D, Balandina E, Kashevnik A, Balandin S and Viola F 2019 Ambient Intelligence Services in IoT Environments: Emerging Research and Opportunities: Emerging Research and Opportunities (IGI Global)
[8] Hoffmann K 2012 An introduction to stress analysis and transducer design using strain gauges (HBM)
[9] OIML TC 9: Instruments for Measuring Mass and Density. 4 Committee Draft OIML/4CD Date: 19 November, 2015. Reference number: OIML R60-1 4CD. Metrological Regulation for Load Cells
[10] Usher M J and Keating D A 1996 Sensors and transducers: characteristics, applications, instrumentation, interfacing Macmillan International Higher Education
[11] Baxter L K 1997 Capacitive sensors. Design and Applications IEEE Press, Piscataway
[12] Zeiser R, Fellner T and Wilde J 2014 Capacitive strain gauges on flexible polymer substrates for wireless, intelligent systems Journal of Sensors and Sensor Systems 3 77-86
[13] Atalay O, Atalay A, Gafford J, Wang H, Wood R and Walsh C 2017 A Highly Stretchable Capacitive Based Strain Sensor Based on Metal Deposition and Laser Rastering Advanced Materials Technologies 2 1700081
[14] Kollosoche M, Stoyanov H, Laflamme S and Kofod G 2011 Strongly enhanced sensitivity in elastic capacitive strain sensors Journal of Materials Chemistry 21 8292-4
[15] Nur R, Matsuhiba N, Jiang Z, Nayee M O G, Yokota T and Someya T 2018 A highly sensitive capacitive-type strain sensor using wrinkled ultrathin gold films Nano letters 18 5610-7
[16] Lipomi D J, Vosgueritchian M, Tee B C-K, Hellstrom S L, Lee J A, Fox C H and Bao Z 2011 Skin-like pressure and strain sensors based on transparent elastic films of carbon nanotubes Nature nanotechnology 6 788-92
[17] Xu F and Zhu Y 2012 Highly conductive and stretchable silver nanowire conductors Advanced materials 24(37) 5117-22
[18] StretchSense Limited Retrieved from: http://www.stretchsense.com
[19] Bend Labs Inc. Retrieved from: http://www.bendlabs.com
[20] Park J, You I, Shin S and Jeong U 2015 Material approaches to stretchable strain sensors ChemPhysChem 16(6) 1155-63
[21] Cohen D J, Mitra D, Peterson K and Maharrbiz M M 2012 A highly elastic, capacitive strain gauge based on percolating nanotube networks Nano letters 12(4) 1821-25
[22] Cai L, et al. 2013 Super-stretchable, transparent carbon nanotube-based capacitive strain sensors for human motion detection Scientific reports 3(1) 1-9
[23] Kang M, Kim J, Jang B, Chae Y, Kim J H and Ahn J H 2017 Graphene-based three-dimensional capacitive touch sensor for wearable electronics ACS nano 11(8) 7950-7
[24] Filippidou M K, Tegou E, Tsouti V and Chatzandroulis S 2015 A flexible strain sensor made of graphene nanoplatelet/polydimethylsiloxane nanocomposite Microelectronic Engineering 142 7-11
[25] Matsuzaki R, Keating T, Todoroki A and Hiraoka N 2008 Rubber-based strain sensor fabricated using photolithography for intelligent tires Sensors and Actuators A: Physical 148(1) 1-9
[26] Matsuzaki R, Keating T, Todoroki A and Hiraoka N 2009 Rubber-based capacitive strain sensor fabricated using photolithography for intelligent tires Transactions of the Japan Society of Mechanical Engineers, Part A 75(750) 235-42
[27] Ueno T, Mori K and Yoshida T 2003 Capacitive strain sensor and method for using the same U.S. Patent No. 6532824
[28] Fassler A and Majidi C 2013 Soft-matter capacitors and inductors for hyperelastic strain sensing and stretchable electronics Smart Materials and Structures 22(5) 055023
[29] Tabatabai A, Fassler A, Usiak C and Majidi C 2013 Liquid-phase gallium–indium alloy electronics with microcontact printing Langmuir 29(20) 6194-200
[30] Frutiger A, Muth J T, Vogt D M, Mengüç Y, Campo A, Valentine A D, Walsh C J and Lewis J A 2015 Capacitive soft strain sensors via multicore–shell fiber printing Advanced Materials 27 2440-6

[31] Cooper C B, Arusalvan K, Liu Y, Armstrong D, Lin Y, Khan M R, Genzer J and Dickey M D 2017 Stretchable capacitive sensors of torsion, strain, and touch using double helix liquid metal fibers Adv. Funct. Mater. 27 1605630

[32] Zhu S, So J H, Mays R, Desai S, Barnes W R, Pourdeyhimi B and Dickey M D 2013 Ultra-stretchable fibers with metallic conductivity using a liquid metal alloy core Adv. Funct. Mater. 23 2308-14

[33] Park Y L, Tepayotl-Ramirez D, Wood R J and Majidi C 2012 Influence of cross-sectional geometry on the sensitivity and hysteresis of liquid-phase electronic pressure sensors Appl. Phys. Lett. 101 191904

[34] Arshak K I, McDonagh D and Durcan M A 2000 Development of new capacitive strain sensors based on thick film polymer and cermet technologies Sensors and Actuators A: Physical 79(2) 102-14

[35] Arshak K I, Collins D and Ansari F 1994 New high gauge-factor thick-film transducer based on a capacitor configuration International Journal of Electronics 77(3) 387-99

[36] Que L, Li M H, Chu L L and Gianchandani Y B 1999 A micromachined strain sensor with differential capacitive readout Proc. 12th IEEE International Conference on Micro Electro Mechanical Systems 552-7

[37] Aebersold J W, Walsh K, Crain M and Voor M 2009 MEMS capacitive bending and axial strain sensor U.S. Patent No. 7509870

[38] Aebersold J W, Walsh K, Crain M and Voor M 2010 MEMS capacitive bending and axial strain sensor U.S. Patent No. 7854174

[39] Suster M, Guo J, Chaimanonart N, Ko W H and Young D J 2006 A high-performance MEMS capacitive strain sensing system Journal of Microelectromechanical Systems 15(5) 1069-77

[40] Ko W H, Young D J, Guo J, Suster M, Kuo H I and Chaimanonart N 2007 A high-performance MEMS capacitive strain sensing system Sensors and Actuators A: Physical 133(2) 272-7

[41] Guo J, Kuo H I, Young D J, and Ko W H 2004 Buckled beam linear output capacitive strain sensor Solid-State Sensor, Actuator and Microsystems Workshop pp 344-7

[42] Kon S, Oldham K, Horowitz R 2007 Piezoresistive and piezoelectric MEMS strain sensors for vibration detection Proc. SPIE 6529 65292V

[43] Cao L, Kim T S, Mantell S C and Polla D L 2000 Simulation and fabrication of piezoresistive membrane type MEMS strain sensors Sensors and Actuators A: Physical 80(3) 273-9

[44] Mohammed A A, Moussa W A and Lou E 2008 High sensitivity MEMS strain sensor: design and simulation Sensors 8(4) 2642-61

[45] Mohammed A A, Moussa W A and Lou E 2011 High-performance piezoresistive MEMS strain sensor with low thermal sensitivity Sensors 11(2) 1819-46

[46] Yamashita T, Takamatsu S, Okada H, Itoh T and Kobayashi T 2016 Ultra-thin piezoelectric strain sensor array integrated on a flexible printed circuit involving transfer printing methods IEEE Sensors Journal 16(24) 8840-6

[47] Wojciechowski K E, Boser B E and Pisano A P 2005 A MEMS resonant strain sensor with 33 nano-strain resolution in a 10 kHz bandwidth. Proc. IEEE SENSORS 4

[48] Wojciechowski K E, Boser B E and Pisano A P 2004 A MEMS resonant strain sensor operated in air Proc. 17th IEEE International Conference on Micro Electro Mechanical Systems 841-5

[49] Azevedo R G, et al. 2007 Silicon carbide coated MEMS strain sensor for harsh environment applications. Proc. 20th International Conference on Micro Electro Mechanical Systems 643-6

[50] Guo Z, Li B, Gao Y, Cheng F and Cao L 2016 Theory and experimental research for the double ended tuning fork in MEMS Sensor Review 36 217-24

[51] Shi X, Lu Y, Xie B, Xiang C, Wang J, Chen D and Chen J 2018 A Double-Ended Tuning Fork
Based Resonant Pressure Micro-Sensor Relying on Electrostatic Excitation and Piezoresistive Detection Sensors 18(8) 2494

[52] Belsito L, Ferria M, Mancarella F, Masini L, Yan J, Seshia A A, Soga K and Roncaglia A 2016 Fabrication of high-resolution strain sensors based on wafer-level vacuum packaged MEMS resonators Sensors and Actuators A: Physical 239 90-101

[53] Kistler Instrument Corp Retrieved from: https://www.kistler.com

[54] Piezo.com Retrieved from: https://piezo.com

[55] Praslicka D, Blazek J, Smelko M, Hudak J, Cverha A, Mikita I, Varga R and Zhuko A 2012 Possibilities of measuring stress and health monitoring in materials using contact-less sensor based on magnetic microwires IEEE Transactions on Magnetics 49(1) 128-31

[56] Ignakhin V S, Severikov V S and Grishin A M 2019 Tensile and torsional strain gauge based on Fe_{80}Co_{19}P_{14}B_{6} metallic glass Journal of Magnetism and Magnetic Materials 376 382-6

[57] Sabol R, Rovnak M, Bajzecerova V, Vojtanik P and Varga R 2015 Application of magnetic microwires for sensing stresses in structures Journal of Electrical Engineering 66(7) 164-7

[58] Campanella C E, Cuccovillo A, Campanella C, Yurt A and Passaro V 2018 Fibre Bragg grating based strain sensors: review of technology and applications Sensors 18(9) 3115

[59] Shivendra and Garima S 2015 Strain sensors for strain measurement: A Review Int. Journal of Electrical & Electronics Eng. 2 144-6

[60] Yuan W, Stefani A and Bang O 2011 Tunable polymer fiber Bragg grating (FBG) inscription: fabrication of dual-FBG temperature compensated polymer optical fiber strain sensors IEEE Photonics Technology Letters 24(5) 401-3

[61] Hottinger Baldwin Messtechnik GmbH Retrieved from: www.hbm.com

[62] Smartec Retrieved from: http://www.smartec.ch/

[63] Inversiya-Sensor Retrieved from: http://i-sensor.ru/

[64] Barrias A, Casas J R and Villalba S 2016 A review of distributed optical fiber sensors for civil engineering applications Sensors 16(5) 748

[65] Li J, Gan J, Zhang Z, Heng X, Yang C, Qian Q, Xu S and Yang Z 2017 High spatial resolution distributed fiber strain sensor based on phase-OFDR Optics Express 25(22) 27913-22

[66] Costa L, Martins H F, Martín-López S, Fernández-Ruiz M R and González-Herráez M 2019 Fully Distributed Optical Fiber Strain Sensor With 10− 12 e/√ Hz Sensitivity Journal of Lightwave Technology 37(18) 4487-95