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Novel concept inspired by campaniform sensilla for the design of strain sensors used in space applications

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ABSTRACT

This paper presents a bio-inspired approach for the design of strain sensors embedded in space structures. Campaniform sensilla, which are natural strain sensors, are used by insects for monitoring deformations of their bodies. The strategy used in nature is to locally amplify, through arrays of elliptical micro-holes, mechanical deformations. The authors focused their research on campaniform sensilla because of their simplicity and straightforward theoretical implementation in engineering systems. In this paper, the biological concept is presented and a structural analysis of an isotropic model, which was performed to understand underlying principles, is presented and discussed. Space applications, in which novel bio-inspired strain sensors could successfully be used, are investigated.

1 INTRODUCTION

Campaniform sensilla, responding to mechanical strain, are found in the external skeleton (cuticle) of insects and are able to sense displacements of the order of 1 nm. The campaniform sensillum is basically a hole extending through the cuticle, arranged such that its shape changes in response to specific loads. The shape change is rotated through 90° by the suspension of a bell-shaped cap whose deflection is detected by a cell attached to the inner layer of the cuticle. When the sensor is strained, a train of impulses is propagated to the central nerve system. Insects such as cockroaches and flies can thus use the sensilla to sense strain deformations and to determine both internal loads such as muscle forces and body weight, and external loads such as aerolastic forces on the wings in flight.

Embedded strain sensors are of interest for many space applications, especially when slender structures are used (solar panels, booms, solar sails etc.) or structural frames must be monitored during hazardous mission phases such as during launch and landing. Strain sensors can also be used as force sensors, especially when they are embedded in cantilevers. Therefore, they are suitable for use in several systems and devices including unlocking systems, docking mechanisms, limit switch devices, robotic arms.

In this paper we investigate strain sensors inspired by campaniform sensilla and propose the design of a new engineered strain sensor that synthesizes the main characteristics of the natural sensor. In this paper, the integration of the novel sensors in an isotropic material is investigated and the effect of the aspect ratio of the hole is analysed in terms of both its sensitivity and its effect on the compliance of the plate in which it is embedded. A comparison between the proposed bio-inspired sensor and existing strain sensors for space applications is presented, and possible improvements for further developments are suggested.

2 SPACE APPLICATIONS

In the space engineering field, strain sensors are used on many occasions and for different purposes. The application and the environment conditions strongly determine the requirements that the sensor should meet.

Strain sensors are widely used when *ground tests* of space hardware are performed. In this case, sensors are added to the payloads and structures. Integration of this kind of sensor in the hardware is generally not required. During ground testing, strain deformations are of interest to confirm numerical simulations and to verify if the hardware satisfies the imposed specifications. Thermal deformation, in particular, can induce non-negligible stresses, leading to thermo-elastic failures of the structure. Thermal deformation can also determine poor performance of the payload (especially in the case of optical payloads), and bearings and mechanism to seize and malfunction.

Deformation measurements *in space*, on the other hand, require the sensors to be embedded in the space structure, and power to be supplied by the space system itself. Strain sensors should also withstand the harsh space environment, and thus cope with radiation, vacuum, a wide thermal range, vibration, and other space disturbances. The sensor should also comply with the accuracy and linearity requirements of the particular application, and should have an adequate size (nano, micro, mini, or macro scale). Strain deformations are measured in several circumstances in space scenarios, including when it is necessary to monitor spacecraft health, feed-back signals in active control systems, or perform scientific investigations. Monitoring of space system deformations is of interest especially when counter-measure can be taken. For instance, in the active control of a slender structure used to dampen mechanical vibrations, strain monitoring assumes fundamental importance. Also in the case of force-feedback of a robotic manipulator or in the case of automatic docking, the force measurement at the interface, often sensed through strain measurements, is fundamental to the success of the operations.

Promising technologies that will probably find application in future missions, will greatly benefit from possibly extensive use of strain sensors distributed and integrated in the space vehicle structure. For instance, gossamer structures, inflatable locomotion systems, solar sails, and other compliant structures and mechanisms, may be controlled via the use of a sensor network distributed on their surfaces and lattices.

3 STRAIN MEASUREMENTS

A wide variety of methods can be used to sense deformation in structures. No method is excluded *a priori* and new scenarios and applications may require the use of uncommon strain sensors.

One of the most popular sensors is the strain gauge. This deformation sensor is usually made of a conducting foil supported by an insulating backing which is attached to the structure through a suitable adhesive. The deformation imposed on the foil by the structure makes the electrical resistance change. A Wheatstone bridge is commonly used to monitor the variation of electrical resistance. This kind of sensor is often used during spacecraft ground testing, as a large number of strain gauges can be attached to surfaces and then removed without damaging the structure. Strain gauges are however external bodies, and therefore their presence may disturb the deformation pattern, especially on ultra-thin structures. In addition, they cannot withstand large deformations, and their accuracy strongly depends on the attaching interface. Thermal deformation can also compromise the accuracy of the measurement.

Another typical method of measuring local deformation is based on the piezoelectric effect. Natural materials like quartz, synthetic crystals, polarized ferroelectric ceramics, and some polymers, display reversible electro-mechanical energy conversion when deformed. The piezoelectric sensor can be designed to respond to several kinds of mechanical deformation, such as thickness shear, face shear, thickness expansion, and transverse expansion. These materials have been widely considered for space applications. This possibility of using them also as actuators was considered and implemented for active control of structures. The development of micro-machining technologies now allows the fabrication of miniaturized piezoelectric sensors that can also be embedded in structures.

Electro-optical measurement systems represent another category of deformation sensors which combine optical and electronic principles. In 1967, Medanier et al. proposed the “Photonic Sensor” that used fibre optics to measure displacements. Interferometric systems, such as the Michelson interferometer or other advanced techniques, allow very accurate measurements. When the structure is made of composite materials, electro-optical systems can easily be embedded, thus allowing continuous monitoring. However, their integration in the structure is often difficult to implement, and the mechanical resistance that this system exhibits can compromise the quality of the measures.

Imaging techniques represent another way of detecting deformations. These techniques rely on the acquisition of images by one or more cameras and on the data processing needed for the reconstruction of displacements with time. Imaging measuring systems have the advantage of being contact-less and therefore they do not introduce disturbances into the measurement of the deformation. However, they need to have a precisely positioned camera with respect to the surface to be monitored, thus complicating their utilization, especially in space.

Another method is based on birefringence properties that some transparent materials show under load. Reflective photo-elasticity presents some advantages as it can be used as a coating, although the thickness must be finely controlled.

Translation can be also monitored by taking advantage of variation in capacitance of a variable capacitor. Miniaturization using MEMS technology is today possible and increases the opportunity of using such a displacement system. The integration of this kind of system into space structures is often challenging although good performance could be obtained.

Several studies have been carried out to obtain reliable strain sensors specifically for space applications. Wnuk et al. [2] investigated a weldable strain gauge employing the NASA Lewis PdCr/Pt wire strain sensor; Ounaies et al. [3] focused on the development of high temperature piezoelectric polymers for active flow control sensors and health monitoring sensors; Mckenzie et al. [4] investigated the use of fibre optic sensing in space structures to provide critical information about the spacecraft health during fabrication, testing and service lifetime; Udd et al. [5] analyzed and tested transversely loaded fibre grating strain sensors for aerospace applications; and many other researchers in industry and universities have worked on this area, achieving remarkable results.

New strategies allowed by the progress of technology are now under investigation. Wireless systems, capable of transmitting deformation signals without the need to increase the spacecraft harness, have been miniaturized (e.g. the MicroStrain® wireless strain gauge), in order to be suitable for easy integration and use. *Ad hoc* wireless sensor networks are under development for use in space systems and preliminary results are promising [5]. Another technology that could lead to outstanding performance in far future space applications relies mechanical deformation of nanotubes which induces noticeable changes in their conductance, as their electronic properties are a strong function of their atomic structure [7].

All the aforementioned strain sensors rely on measurement of the deformation of a structure, without taking advantage of possible mechanical amplifications of the signal due to a modification of the structure itself. Natural systems, on the other hand, monitor deformations of localized areas where deformations are locally amplified by arrays of micro holes. The influence of such arrays on the mechanical characteristics of a structural surface is analyzed in this paper. The strain sensor proposed in this paper can, in principle, take advantage of most of the aforementioned strain measurement systems in order to transduce the amplified mechanical deformation into an electrical signal.

The novel sensor proposed in this paper could be easily integrated on composite structures in which miniaturized cavities could be formed during the fabrication process. Tri-axial composites [9], which are of particular interest for the manufacture of several space structures (including large antennas [10]), have a particularly suitable configuration for the proposed sensors.

The shape and geometry of individual miniaturized holes could also be determined and selected to sense deformation in particular directions. By combining arrays of differently shaped holes, optimal strain mapping is theoretically possible.

4 BIOLOGICAL CONCEPT

Insects have a strain-sensing organ, the campaniform sensillum, which is a round or oval hole extending through the outer shell or cuticle with a bell-shaped (hence ‘campaniform’) cap or plaque suspended in its centre. The shape of the opening is generally oval and sometimes almost circular. Its long and short axes vary from 6 to 24 µm and 2 to 5 µm respectively [12,14] this producing a short: long aspect ratio of between 1.2 and 12.0. The cuticle is a fibrous composite (stiff chitin microfibres in a protein matrix) with the microfibres extending around the hole [13] so that the sensillum is equivalent to a formed hole in a sheet of fibrous composite material. The geometry and mechanical properties of the suspension cause the cap to move up and down as the hole changes its dimensions when the plate is stretched, compressed, bent or twisted. Thus the cap system rotates deformation in the plane of the plate by 90°, allowing the deformation to be detected, out of the plane of the plate, by an associated sensory epidermal cell with a long extension (Fig. 1) packed with, and therefore stiffened by, microtubules. Confusion exists as to whether the transduction of displacement into sensory signal is by the cap pinching the tip of the cell or by the extension transferring the displacement to the cell body. The pinching school has yet to explain why the extension needs to be stiffened.

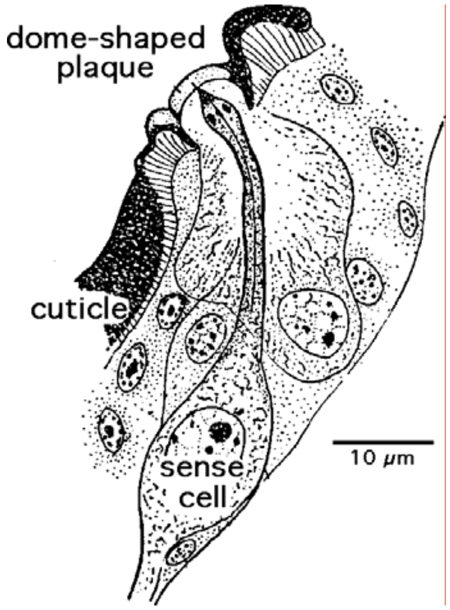

Fig. 1 Cross section of a Campaniform Sensillum

The morphology of the sensillum suggests a number of aspects of its design and integration.

1) The greatest strains will be experienced in areas of greatest stress, yet the sensillar hole never seems to initiate fracture. Calculation suggests that it is smaller than the critical Griffith size, but there is also a stiffening ring around the hole, which can modulate its sensitivity to global strain [16].
2) Greater sensitivity can be achieved by arranging holes in a more or less regular pattern. Thus although there are many single sensors, in areas where strain sensing is important, such as at the base of a wing (Fig. 2), there are several easily distinguished

groups of sensilla which are innervated in common.

3) If the hole is oval it can be aligned to sense specific strain directions. This is seen particularly in the leg of the cockroach [19] where two oval sensilla with their long axes orthogonal can detect tension, compression, bending and twisting, depending on which sensillum is being stimulated and in which direction.

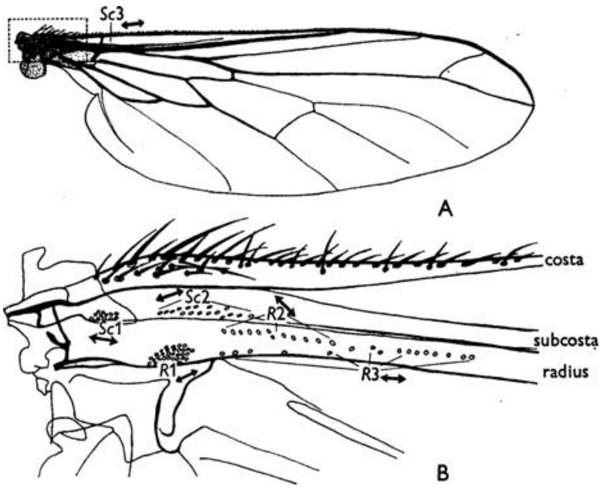

Fig. 2 Groups of sensilla

4) By controlling the shape of the hole or its relationship with other holes it can have a response tuned to the rate of change in the strain with time. The mechanical basis for this is unexplored, but physiologically and experimentally it has been shown to be true. It is a necessary consequence of the viscoelasticity of insect cuticle and the increase in compliance induced by the reduction of material which a hole imposes.

5) The sensilla often occur in groups with a common orientation. This is most readily seen at the base of the haltere in the fly (Fig. 3). Presumably such groups of sensilla are more sensitive than a single sensillum, and may also provide information regarding the direction of origin of the time-varying strain.

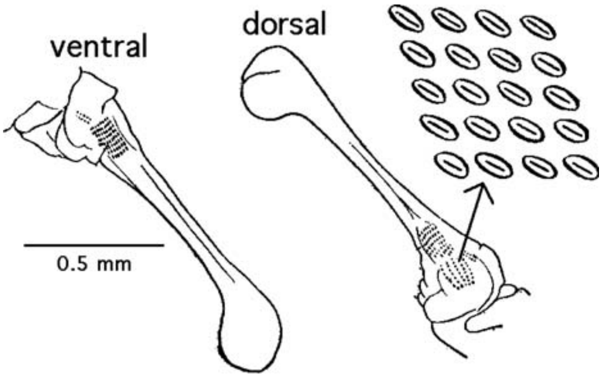

Fig. 3 Groups of sensilla with a common orientation

6) There are many different types, geometry and sizes of campaniform sensilla in insects, and even more if one takes into account other arthropods (crabs, spiders, scorpions, etc). The advantages and specialisation of each type has not been explored.

The sensillum, together with its associated sensory and nerve cells, forms a simple yet sensitive mechanism which is capable of detecting displacements of the order of 1 nm [19] though whether this sensitivity is achieved at the mechanical or nervous level is unknown [11]. The deformations can be due to environmental loads, due to the weight of the insect’s body, due to the actions of its muscles, or all three at once [10,18].

5 INTEGRATION OF BIOMIMETICS WITH ELECTRONIC DEVICES

The conceptual simplicity and operational versatility of the campaniform sensillum render it a strong candidate for biomimetic implementation with sensor electronics. There are associated engineering advantages in that a hole can be an integral part of the structure in which it occurs, on or below the surface, and so will interact with that structure in a reliable fashion. This is not always possible with a conventional strain gauge which has to be bonded to a structure and may come unstuck. A foil strain gauge may not be able to withstand temperatures as high (or low) as those borne by the structure it is monitoring. A hole has no such disadvantages. The distortion of a hole can be monitored electrically or optically; a single laser can scan a large number of slits and thus reduce the overhead cost of the measuring system. This would improve simplicity and reliability, save weight, and allow it to be easily embedded in the host structure.

Finite elements modelling of a campaniform sensillum [16] showed that global deformation of a fibre-reinforced plastic plate (which can be flat, curved or tubular) with a hole in it induces higher deformation of the hole due to its higher local compliance, and is strongly dependent on the orientation of the fibres. This *local amplification* of deformation offers a sensitive mechanism for sensing complex, time-varying strains, for example arising from vibrations.

6 ANALYSIS

The ABAQUS finite element package has been used to predict the deformation under load of each of the holes in a 4 by 5 array arrangement as in Figure 4. A regular array of holes has been modelled with a common orientation, as shown earlier in Figure 3. Each elliptical hole had a ratio of minor to major axis of 6.5, a mid range value as earlier outlined (in section 4 of this manuscript).

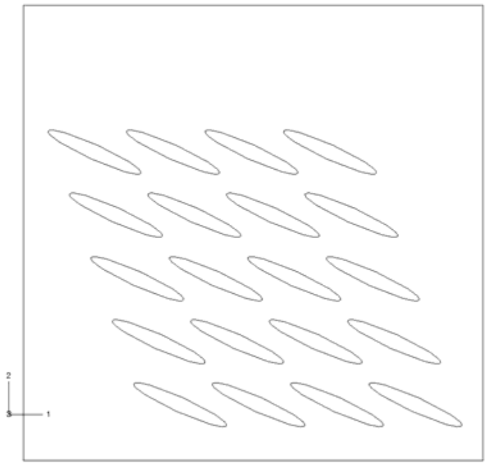

Figure 4: Arrangement of holes in FE model.

The model was meshed using 8-noded biquadratic plane stress elements (ABAQUS element type CPS8R) producing a total of 12823 elements. A Young's Modulus of 1.5 GPa and a Poisson's Ratio of 0.3 were assigned to the mesh. A tensile deformation corresponding to 1% of the model height was applied to the top surface of the mesh. Symmetry boundary conditions were applied to the left hand edge and also the base of the model (i.e. ux=0 at x=0, and uy=0 at y=0). These boundary conditions were chosen as they produced a uniform strain field of 0.01 (1% strain) in a model without holes. Thus, the strain amplification effect in the model with holes could be readily quantified.

7 FE PREDICTIONS

Changes in the major and minor diameters of each of the holes have been used to calculate percentage diamteral strains (Tables 1 and 2).

From these Tables it can be seen that the major axis was not sensitive to the applied deformation, however preductions at the minor axis indicated significant strain amplifications. The largest mutliple of the 1% applied strain, i.e. 8.75, was recorded for the bottom right hand hole in the model. It must be noted that at these high strain levels the validity of the linear elastic materials properties used in this model must be called into question. However, for lower applied levels of deformation, these strain amplifications would be valid up to the point of yield.

Row/Column	A (left)	B	C	D (right)
1 (top)	-0.42	-0.22	0.16	-0.04
2	-0.31	0.51	-0.19	-0.06
3	-0.23	-0.23	-0.20	-0.17
4	-0.20	-0.19	-0.25	-0.26
5 (base)	-0.24	-0.30	-0.26	-0.45

Table 1: Hole major axis % strain

Row/Column	A (left)	B	C	D (right)
1 (top)	0.75	6.57	6.12	1.42
2	-0.01	2.30	2.41	2.50
3	5.94	6.22	5.44	6.00
4	1.28	3.46	6.96	7.14
5 (base)	0.67	5.60	7.33	8.75

Table 2: Hole minor axis % strain

It might reasonably be questioned as why the predictions in Table 2 are not more uniform, since these holes have been located in what was otherwise a uniform strain field. If the holes had been widely spaced and thus did not interact, then uniformity in their predictions would have been expected. However, these holes are in a close packed arrangement. The predictions therefore suggest that the local sensitivity of the hole to deformation is significantly influenced by perturbations in the strain field caused by the deformation of other holes in the array. Thus a uniform strain field has been turned into a highly non uniform one by the presence of the holes, thus creating spatial strain gradients in the material surrounding the holes.

8 PERSPECTIVES

The analysis that was performed suggests promising results for a future engineering model of the bio-inspired sensor. The future step concerns the identification of a theoretical or empirical model necessary for the optimal design of the micro-hole array. In addition, the selection of suitable miniaturized transducers should be performed. Promising technologies, which are currently under investigation, are based on dielectric electro-active polymers or piezoelectric materials. Micro-machining processes for embedding such transducers on the artificial campaniform sensilla should be carefully considered.

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