THE EFFECT OF GEOMETRY ON THE MICROMECHANICAL BEHAVIOUR OF CAMPANIFORM SENSILLUM BIOMIMETIC STRUCTURE AS STRAIN SENSOR

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ABSTRACT

Campaniform sensillum is a very sensitive strain sensing organ even though it is small in size. Various geometrical features which could contribute to strain sensing detection as being employed by the insect sensing organ were investigated. This study was carried out with the objective to investigate the effect of the geometry on the mechanical behaviour of campaniform sensillum by using biomimetic structures. The four structures were modelled as chip block, chip block with through hole, chip block with flat membrane-in-recess, and chip block with dome-shaped membrane to represent the features of campaniform sensillum. The potential of these structures as new sensing mechanism for strain sensing were evaluated using the finite element software as the result could be predicted together with associated strain and displacement. The results showed that hole and dome shape structure features were the main features that contributed to the excellent sensing behaviour of the mimetic structure. The sensing mechanism was started with the localization of strain around the hole several times higher than the applied load (first amplifier), before it was further transduced and amplified by the dome structure that acted as a transducer and second amplifier. Compared to the previous biomimetic structure of campaniform sensillum, the suggested biomimetic with the dome shape structure performed better by increasing the strain by a strain concentration factor of 5.45, whereas the structure with hole was 1.03 lower. Besides, combination of these features makes the devices to have higher sensitivity in term of a ratio of output signal to the input signal. In addition, the output signal in the form of vertical displacement was also improved. This makes the structure act efficiently to deliver the information related to strain detection. The obtained understanding can be applied in the design of highly miniaturized strain sensor for medical application.

ABSTRAK

Campaniform sensillum adalah organ deria yang sangat sensitif kepada terikan walaupun bersaiz kecil. Pelbagai ciri-ciri geometri yang meyumbang kepada pengesanan terikan disiasat sebagaimana yang digunakan oleh organ deria serangga. Kajian yang telah dijalankan dengan bertujuan untuk menyiasat kesan geometri kepada sifat mekanikal campaniform sensillum dengan mengunakan model struktur yang dimimikan. Struktur dimodelkan dalam empat bentuk bongkah yang berbeza iaitu bongkah, bongkah dengan lubang, bongkah dengan selaput nipis yang leper dan bongkah dengan selaput nipis berbentuk cembung bagi mewakili ciri-ciri yang terdapat pada campaniform sensillum. Keputusan kajian menunjukkan rongga dan struktur kubah adalah ciri-ciri utama yang meyumbang kepada sifat pengesanan yang sangat baik. Mekanisma pengesanan bermula dengan lokalisasi terikan disekitar rongga beberapa kali lebih tinggi daripada memuat yang dikenakan (penguat pertama) sebelum terikan yang dialami seterusnya diubah dan dikuatkan lagi oleh struktur kubah yang bertindak sebagai pengubah dan penguat yang kedua. Berbeza dengan struktur biomimik campaniform sensillum yang lepas, struktur biomimik yang dicadangkan ini dilengkapi dengan struktur berkubah yang berpotensi meningkatkan terikan dengan faktor penumpuan terikan sebanyak 5.45 berbeza 1.03 dengan struktur yang hanya dilengkapi oleh ciri rongga.Di samping itu, pengabungan ciri-ciri menjadikan struktur yang dimimikan memiliki sensitiviti yang tinggi iaitu pecahan isyarat keluaran per isyarat masukan. Malah, isyarat keluaran dalam bentuk anjakan menegak juga diperbaiki menjadikan struktur berupaya menghantar maklumat berkaitan dengan pengesanan terikan secara efisien. Pemahaman yang diperoleh boleh digunakan dalam mereka bentuk sensor terikan bersaiz kecil bagi aplikasi perubatan.

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LIST OF ABBEVIATIONS

MEMS	-	Microelectromechanical systems
TRIZ	-	Teoriya resheniya izobretatelskikh zadatch (Russian acronym)
N	-	Newton
2D	-	Two-dimensional
3D	-	Three-dimensional
CAD	-	Computer-aided design
TIPS	-	Theory of inventive problem solving
PRIZW	-	Pravila ReshenijaIzobretatel'skih Zadach Modernizirovannye.Translated as 'The Rules of Inventive Problem Solving
BIOTRIZ	-	Biological version of TRIZ
IGES	-	Initial graphics exchange specification
MPa	-	Mega Pascal
GPa	-	Giga Pascal

LIST OF SYMBOLS

ε	-	Strain
E	-	Young's modulus
σ	-	Stress
υ	-	Poisson's ratio
A	-	Area
%	-	Percentage
F	-	Force
µ	-	Micro
Δx	-	Horizontal displacement
Δh	-	Vertical displacement
α	-	Angle
M	-	Moment

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

The demand for a new strain sensor in medical application has indicated an increase since the introduction of new surgical technique known as a minimally invasive surgical procedure. This technique is popular among the surgeons and become more familiar in the developing countries. The growth is catalysed by the desire to reduce pain and recovery time through small incisions instead of conventional surgery in order to access patience's tissues or wound. Using this innovation, many surgical procedures such as endovascular surgery, spine surgery, and arthroscopic surgery are improved [1, 2].

The ability of the technique to improve the capability of standard surgery procedure has been proven. However its efficiency remained questionable since the instruments used by the surgeon can cause a loss of tactile sensation during tissue manipulation. The feel of touch is important for the surgeons when they attempt to inspect the condition of patience organ and also via the sense of touch, the surgeon can estimate how much force should they apply order to avoid tissue trauma [3]

In order to solve the problem, one of the solutions is by introducing the new sensing method that can be installed on the instruments [4]. Through this method, surgeons will know the magnitude of the force that is applied at the site of surgery. Minimally invasive surgery involves the procedure of the making three holes on the patience body. A device just the same as a camera known as laparoscope is inserted through one incision whereas the other two incisions will be used to put on the surgical instruments such as stripper, knife, scissors, clamps, etc [4-6]. As explained before, the main improvement of this surgical procedure is small surgery opening of the patience's body, therefore small surgical tools is used. However in order to get better sensing performance, high endurance and precision, miniature strain sensor with the novel feature of sensing detection should be considered.

In terms of material selection of the surgical tools, stainless steel is one of the most commonly used metallic material in manufacturing of instrument for the minimally invasive surgery [7, 8]. Besides, highly corrosion resistant and chemically nonreactive with tissue body, that makes it suitable for medical, its natural properties of solid mechanics also valuable to provide the stress strain feedback information signal to the surgeon through proper geometry modification. This concept is promising since the structure is deformed as force is applied. However, in performing the surgery procedure, the gripping force must be in the range of 16 N [9] up until 40N [10]. As the young's modulus of the stainless steel is around 200GPa so the resulting strain that's expected to generate is lower than 1 micro strain and it required powerful amplifier to enlarge the associated signal up to certain appropriate level.

The problem of size limitations and tiny stain generation that occurred can be solved as inspired by the nature. These aspects lead to the new demand of novel sensing mechanism which it is possible because the nature had produced a huge number of excellence engineering systems than human ever invented.

Campaniform sensillum of the insect for example, is mechanoreceptor organs that respond to stimulation. Embedded in the cuticle of cockroach leg and integrated with sensory systems, this organ is very sensitive to the strain of the deformation [11]. Thus, using the appropriate methods in extracting the sensing concept of the sensor organ and converting its working mechanism into engineering application is adaptable. It is expected that the investigation of the potential of the sensor mechanism of the campaniform can improve the existing sensor as a result; the new concept of sensing detection will be realized.

1.2 Problem Statement

Understanding the working mechanism and the structural parts that contribute to the excellence sensing behaviour of campaniform sensillum is important as these features can provide special sensing performance that can cope with medical application requirements. However, due to the complexity of the campaniform parts and its miniature size as well the sensing process, attempts and efforts toward deeper understanding of this sensing organ of the insect received little interest.

In order to obtain the related result, sometime researchers have to spend their time to adept with various fields of expertise such as biology and engineering but most of time, the technology that can be used to investigate the sensing behaviour of the organ from the main source which is the mechanism of campaniform sensillum on the living insect is unavailable. Therefore the actual working concept left unclear and require a lot of further work to be done.

Nevertheless, under the proper solid mechanics theory and the assumption of the biomechanics of the campaniform sensillum, several researchers have attempted to use computer simulation to simulate structure response [12-14]. The work was included three dimensional model of campaniform sensillum found on the fly body and its mimetic structure that simplify certain interesting features which can represent the behaviour of the structure.

At the same time, most of the publications were aimed on the hole features inspired from campaniform sensillum [12-14]. This featured capable to concentrate the strain that distribute on the solid structure to the location around the hole opening. Besides that, the effect of the campaniform arrangement as the array of hole also attracts the interest of researchers because this strategy can be used to lower down the magnitude of dangerous stress concentration without compromising the sensing concept – locally amplified global strain on the structure [14]. As well as, the literature related to campaniform sensillum is limited and the discussion related to the topic become fairly restricted, thus this research intends to investigate further on the behaviour of the mimetic structure with some improvement on the sensing features. Based on that, the current research will focus on the dome shape structure as a thin membrane that represents the cuticle cap of campaniform sensillum besides its potential in sensing application.

According to engineering aspect, the presence of holes in the structure can reduce the live service as hole cause stress concentration becomes higher in the area closest to the hole edge and reduce the ability of carrying a tensile load of the member which can lead to catastrophic failure. Yet, the idea that presented by the campaniform sensillum somehow, offer the different point of view rather than catastrophic structural failure, instead, the structures are simplified modification to provide the useful information.

In addition to hole, there are also reports that mention about the function of dome shape of campaniform sensillum [12]. Under specific loading direction, the lateral displacement is rotated 90° out of plane by means of dome shape of cuticle cap. At this point, it is clear that the geometrical shape of this part plays the role as a transducer and in addition, the converted signal is then amplified further before delivering to the sensory system of the insect. Intended to create new strain sensor with the new features inspired from the insect sensor, the dome shape of cuticular cap is identified as one of the important parts that have to be considered in the investigation.

Based on the previous explanation, the problem statements of the research are summarized as the following:

1. How to extract the important features of campaniform sensillum in order to transfer the idea from nature into sensing technology.

2. How the mechanical features of mimetic structures of campaniform sensillum such as hole and dome shape membrane behave toward strain sensing detection?

3. How can mechanical part of the mimetic structure inspired by campaniform sensillum amplify and traduce the strain in term of sensing application.

1.3 Objective

Due to limited knowledge and available data related to the working mechanism of campaniform sensillum, it requires a lot of continuing work to point-out the clear information regarding to this proprioceptor organ. There is a necessity to find out the working mechanism of campaniform sensillum that associated with the strain sensing detection, so the concept can be used as an alternative for a novel strain sensing device.

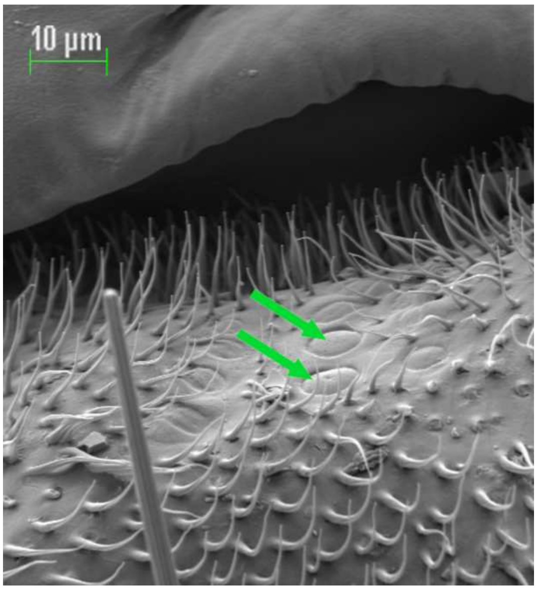

Figure 1.1 Two sensilla of the group of campaniform sensillum found on the leg of a fly which is the arrows show the location of the cuticular cap.

Several researchers had carried out the investigation of the potential of campaniform sensillum before it can be applied as a miniature strain sensor. However, since the progress is at an early stage, therefore most of them only focused on the types of opening which is may influence the strain and displacement of the structure. The results however, aren't representing the mechanism of the whole structure since the real structure of campaniform sensillum consists of several parts. Therefore the mechanical behaviour of campaniform sensillum is required to be explored further detail before the idea of new strain sensing mechanism can be realized, and solve the limitation on field of sensor applications.

The objectives of the study are as follows:

1. To identify the important parts of campaniform sensillum and convert the idea from nature into sensing technology.

2. To investigate the mechanical behaviour of the mimetic structure of campaniform sensillum which is by considering important features of the sensing organ in order to apply the idea as strain sensor for biomedical application.

3. To study the potential of strain amplification and transduction that related to geometric features of the mimetic structure.

The magnitude of structure response among all structure models is identified to allocate reasonable evaluation, based on strain sensing detection. Excellence sensing behaviours are expected to obtain which can generate better perceptive for strain sensing mechanism inspired from the nature. The study was carried out using a simulation approach which is a technique commonly used in biomedical investigation.

1.4 Scope of Study

The present study is done to highlight the behaviour and the performance of the mimetic structure of the campaniform sensillum under the static loading. The structure consists of two segments which are the chip and the dome shape. These two structures have been identified as parts of interest all along the investigation. Two approaches are applied. Firstly, the investigating on the mechanical behaviour of the dome shape structure which comparing the respondent with the other models. Second, the investigation on geometric parameter of dome shape of the mimetic structure inspired from campaniform sensillum.

The whole structure is fixedly supported as statically determinate. A structure is said to be statically determinate as the component of the reaction can be determined from the equation of static equilibrium which is in this state the relative position on the structure do not vary over the time and the resultant force that acting on the structure is equal to zero. Yet, the structure also is allowed to be loaded with the force in elastic range by paying attention on bucking phenomena of thin plate structure and saturated condition of dome shape under the indentation deformation.

Three-dimensional models of the mimetic structure with particular geometric features represent the biological structure of an insect sensing organ were made using 3D mechanical computer aided design software, Solidworks. The designed model then transferred into a finite element software program, ABAQUS in order to simulate the effect of the expected stimulus condition. Referring to MEMS technology, the model is assigned with silicon material property and assumed to be deformed linearly, homogeneous and isotropic in all load directions [15, 16]. The result of associated strain and displacement is simplified and represented in colouring contour in the graph.

1.5 Importance of The Study

This study provided an additional understanding of the biomechanical behaviour of campaniform sensillum via its mimetic structure. The study was carried out using computational analysis with the purpose to study the effect of strain and bending displacement of the mimetic structure especially the dome shape for the sensing application. The simulation approach employed finite element method to predict the deformation condition according to proper mathematical formula in order to obtain the most precise result that can represent the circumstance under static loading condition.

In fact, the role of the cap of campaniform sensillum as a transducer and amplifier not well understood. Previously, researchers had done investigation on the strain and displacement due to the presence of the blind hole that inspired by the feature of campaniform sensillum [12-14]. Although, it is proven that blind hole can process the stimulus, yet to know deeper how the environmental information is transferred to the insect nervous system via proprioception organ still required a lot of studies in order to complete the puzzle. Thus, the study is found to be important. With supporting evidence and some idea from previous study [12-15], the present study can elucidate the response of the dome shape as it can further amplify the strain several orders higher out of sensing plane.

1.6 Conclusion

In this chapter, the demand in new sensing inspired by natural has been described. Every important point that related to the limitation and requirement of the novel strain sensor also have been described and elaborated in detail in order to provide a clear scheme of sensing the in medical application. The motivation of the research, as explained in detail in several subtopics is to investigate the mechanical behaviour of campaniform sensillum. By understanding the working mechanism of campaniform sensillum which represents the as biomimetic structure, the study is expected to contribute better understanding related to the role of the cap of campaniform sensillum as a transducer and amplifier through the computational study.

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