SENSITIVITY IMPROVEMENT OF MICRO-DIAPHRAGM DEFLECTION IN OPTICAL MEMS SENSOR AS APPLIED TO PULSE PRESSURE DETECTION

By
Eng. AbdelHaleim Hasan Elhag Osman AbdAllah
B.Sc. in Biomedical Engineering 2007
Sudan University of Science and Technology

A Thesis Submitted to
The Faculty of Engineering, Cairo University

In Partial Fulfillment of Requirement for the degree of
(MASTER OF SCIENCE)

In
(SYSTEMS AND BIOMEDICAL ENGINEERING)

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
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Under supervision of
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Title of Thesis: Sensitivity Improvement of Micro-Diaphragm Deflection in Optical MEMS Sensor As Applied To Pulse Pressure Detection

Key Words: Microdiaphragm corrugation technique, Corrugation factors, Optical MEMS sensor, Pressure pulse, Deflection sensitivity, von Mises stress

Summary:

In this thesis, sensitivity of micro-diaphragm deflection in optical Micro Electro Mechanical System (MEMS) sensor as applied to pulse pressure detection was improved. Thus was introduced to determine the safety of the person measured pulse of cardiovascular disease and atherosclerosis. The deflection sensitivity improvement was simulated using Finite Element Analysis in ANSYS software. Corrugation technique for periphery-clamped silicon nitride microdiaphragm based on the variation of the diaphragm thickness (t_d) and some corrugation factors such as the corrugation angle (β) and the corrugation depth (h_c) was implemented to reduce bending and tensile stresses which limit the microdiaphragm deflection sensitivity and which was depicted by von Mises stress. Therefore, the application of corrugation offers the possibility to control mechanical deflection sensitivity and is often an easier way as compared to the approach of the film deposition process control.
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Finally, and most importantly I would like to thank my wife and kids who have been emotional anchors throughout my entire life, for their belief in my ability to succeed, for their unlimited encouragements, and for the love and support. I dedicate this thesis for them and my parents’ spirits.
ABSTRACT

Cardiovascular diseases are one of the leading causes of death. Globally, they underlie the death of one third of the world’s population. These diseases can be divided into coronary, cerebral or peripheral artery diseases. The main cause of cardiovascular diseases is atherosclerosis which makes arteries less elastic (called “hardening of the arteries” or “arterial stiffness”).

To obtain parameters such as distension and stiffness of the arteries, the movement of the arteries walls during pulsation must be accurately detected.

An ideal site for the measurement is provided by the radial artery in the wrist, since it is located near the skin surface, and the wrist serves as a good attachment for the measuring device.

The optical Micro Electro Mechanical System (MEMS) pressure sensor has shown its potential in the diagnosis of arterial stiffness that can be conducted by detecting the pulse pressure in the radial artery. An optical sensor typically utilizes a sensor head that consists of a diaphragm and optical fiber which in turn, converts the light rays to electric signal.

The diaphragm is one of the most important parts in the optical sensor because the sensitivity of the sensor is highly dependent on its performance. Therefore, the aim of this work is to improve the deflection sensitivity of the diaphragm.

As we know, a periphery-clamped circular diaphragm has the disadvantage of possible high stress in its deposition process, which reduces the diaphragm sensitivity. Therefore in addition to the assessment of fabrication processes for low stress membrane film (micro-diaphragm), the corrugation technique is an
effective way to reduce this high stress in the diaphragm and to optimize its
deflection sensitivity.

The mechanical deflection of the proposed \textit{corrugated} silicon nitride
\((\text{Si}_3\text{N}_4)\) diaphragm is analytically calculated based on the variation of the
diaphragm thickness \((t_d)\) and some \textit{corrugation} factors such as the \textit{corrugation}
angle \((\beta)\) and \textit{corrugation} depth \((h_c)\) showing agreement with ANSYS software
simulation results in static response of 1.27 \(\mu\)m maximum deflection with an
applied pressure of 300 mmHg in the case of the \textit{corrugated} micro-diaphragm,
compared to a 0.32 \(\mu\)m maximum deflection in the case of the \textit{flat} micro-
diaphragm modeled before, and for the same applied pressure, maximum
deflection sensitivity of \(4.23 \times 10^{-3}\) \(\mu\)m/mmHg for the \textit{corrugated} micro-
diaphragm compared to \(1.07 \times 10^{-3}\) \(\mu\)m/mmHg for the \textit{flat}, and the reduction of
micro-diaphragm bending and initial tensile stresses exhibited by maximum
equivalent stress (von Mises stress) of 159.99 MPa for the \textit{corrugated}
compared to 175.9 MPa for the \textit{flat}.

To prove the feasibility of the model and its solution, two cases of normal
and atherosclerotic were chosen for dynamic responses, the simulation results
show a maximum deflection of 0.54 \(\mu\)m and maximum von Mises stress of
66.124 MPa with normal 117 mmHg pressure, as it is a maximum value for
periodic pulse applied to the diaphragm, compared to a maximum deflection of
0.63 \(\mu\)m and maximum von Mises stress of 76.692 MPa with atherosclerotic
137 mmHg pressure, as it is a maximum value for periodic pulse applied to the
diaphragm, this response was not studied in any previous work.

At a particular diaphragm radius, the deflection and the equivalent stress
increase as the corrugation angle and corrugation depth increases and
decreases, respectively. The results also indicate that the thinner the
diaphragm thickness, the higher the deflection. All these concepts agree well
with the deflection sensitivity improvement objectives.

The equivalent stress simulation shows that the resulting stresses are within
the safe range of yield stress, thus avoiding material failure. Obviously, the
application of corrugation offers the possibility to control mechanical
deflection sensitivity and is often an easier way as compared to the
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>WHO</td>
<td>World Health Organization</td>
</tr>
<tr>
<td>Si3N4</td>
<td>Silicon Nitride</td>
</tr>
<tr>
<td>3D</td>
<td>Three Dimensional</td>
</tr>
<tr>
<td>2D</td>
<td>Two Dimensional</td>
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<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
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<td>FEM</td>
<td>Finite Element Modeling</td>
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<tr>
<td>MEMS</td>
<td>Micro Electro Mechanical Systems</td>
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<td>Biological Micro Electro Mechanical Systems</td>
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<td>Si</td>
<td>Silicon</td>
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<td>CVDs</td>
<td>Cardiovascular Diseases</td>
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<td>MRI</td>
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<td>TNN</td>
<td>Thresholding Neural Network</td>
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<td>CT</td>
<td>Computed Tomography</td>
</tr>
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<td>ROIs</td>
<td>Regions of Interest</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Diagnosing</td>
</tr>
<tr>
<td>CM</td>
<td>Contrast Media</td>
</tr>
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<td>Acronym</td>
<td>Abbreviation</td>
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<tr>
<td>---------</td>
<td>---------------------------------------</td>
</tr>
<tr>
<td>MI</td>
<td>Myocardial Infarction</td>
</tr>
<tr>
<td>IVUS</td>
<td>Intravascular Ultrasound</td>
</tr>
<tr>
<td>ECG</td>
<td>Electrocardiogram</td>
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<td>FOPS</td>
<td>Fiber Optic Pressure Sensor</td>
</tr>
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<td>EFPI</td>
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<tr>
<td>IFPI</td>
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<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
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<tr>
<td>PECVD</td>
<td>Plasma Enhanced Chemical Vapor Deposition</td>
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<tr>
<td>DRIE</td>
<td>Deep Reactive Ion Etching</td>
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<td>Bpm</td>
<td>beat per minute</td>
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# LIST OF SYMBOLS

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<td>Microdiaphragm deflection under applied pressure</td>
</tr>
<tr>
<td>$P$</td>
<td>Pressure</td>
</tr>
<tr>
<td>$t_d$</td>
<td>Diaphragm thickness</td>
</tr>
<tr>
<td>$R$</td>
<td>Effective diaphragm radius</td>
</tr>
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<td>$E$</td>
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</tr>
<tr>
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<td>$N_c$</td>
<td>Corrugation number</td>
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<tr>
<td>$q$</td>
<td>Corrugated profile factor</td>
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<td>$a_p \text{ and } b_p$</td>
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<td>$S$</td>
<td>Corrugation arc length</td>
</tr>
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<td>$K$</td>
<td>Kelvin</td>
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<td>Symbol</td>
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<tr>
<td>C</td>
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<tr>
<td>g</td>
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<tr>
<td>mmHg</td>
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<td>μ</td>
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<td>m</td>
<td>Mill, $10^{-3}$</td>
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CHAPTER 1

INTRODUCTION

1.1 Motivation to this work

Cardiovascular diseases (CVDs) are number one of the leading causes of death. Globally, they underlie the death of one third of the world’s population, as World Health Organization (WHO) Reported.

Furthermore, it was reported that, Low- and middle-income countries are disproportionately affected over 80% of CVD deaths take place in low- and middle-income countries and occur almost equally in men and women.

By 2030, almost 23.6 million people will die from CVDs, mainly from heart disease and stroke.

1.2 Cardiovascular disease definition

As WHO reported, cardiovascular diseases (CVDs) are a group of disorders of the heart and blood vessels and include:

- Coronary heart disease – disease of the blood vessels supplying the heart muscle.

The coronary arteries arise from the aorta, which is adjacent to the heart. The plaques narrow the internal diameter of the arteries as shown in Fig. 1. 1