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MASTER’S THESIS

ТОПИС: АНАЛИЗ ОПТОМЕХАНИЧЕСКИХ СВОЙСТВ РЕЗОНАТОРОВ МОД ШЕПЧУЩЕЙ ГАЛЕРЕИ (ANALYSIS OF WHISPERING GALLERY MODE RESONATORS OPTO-MECHANICAL PROPERTIES)

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Saint Petersburg
2017
TASK FOR THE MASTER’S THESIS

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«___»____________2017 .

Student Барути Бикрам (Baruti Bikram) Group 1580

Topic: Analysis of whispering gallery mode resonators opto-mechanical properties.

Institution: Saint Petersburg Electrotechnical University (ETU)

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The project is inspired by the work named “Effect of angular velocity on sensors based on Morphology dependent resonance. The article is published in the journal Sensors having ISSN 1424-8220.

Contents of the thesis:
It deals with the modelling of micro optical gyroscopes based on Whispering gallery modes. Two types of modelling have been done- Microsphere modeling and toroid modelling. A review of future experimental work is discussed.


Task given on Submitted for defense on

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«___»______________2017.

Student Барути Бикрам (Baruti Bikram) Group 1580
Topic: Analysis of whispering gallery mode resonators opto-mechanical properties

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SUMMARY

Explanatory note 443 p, 28 fig, 2 graphs, 4 tables, 1 appendix.

The subject of the research (development) is: Analysis of whispering gallery mode resonators opto-mechanical properties.

Keywords – Gyroscopes, OOFELIE::Multiphysics, Microsphere, Toroid, Modelling, Whispering gallery modes.

The target of the GQW – The report gives out a discussion about the modelling of the micro optical gyros in OOFELIE Multiphysics Software. The modelling which is based upon previous experiments already in practice based on polymeric micro sphere is being the first step in designing the angular velocity sensors. The report also discusses the various concepts regarding the resonance of electromagnetic waves inside a micro optical sphere. Further on an analytical expression is derived which is based on the change of the radius of the micro sphere when it is subjected to various values of changing angular velocity. The modelling is carried out with the parameters of the analytical expression and coding has been done and executed for a range of angular velocities. On the other side, modelling for a toroid has also been done. Later a preliminary experimental study has been conducted which will be performed near future. The report suggests the possibility of further carrying out the modelling work by making models with different model geometrical shapes. Since, it’s a beginning of designing angular velocity sensors based on whispering gallery modes, the report also discuss the future work in this regard.
АННОТАЦИЯ

Целью данной ВКР является моделирование микрооптических гироскопов на основе резонатора мод шепчущей галереи в программе OOFELIE::Multiphysics. Построение модели полимерной микросферы, основанное на экспериментальных данных, является первым шагом на пути к созданию микрогироскопа. Получено аналитическое выражение, связывающее угловую скорость с изменением длины световой волны в резонаторе. Помимо сферической рассматривается также тороидальная форма резонатора. Кроме того, в работе рассматривается вопрос различных методов ввода оптического излучения в резонатор, а также схема построения экспериментальной установки для испытания микрооптического гироскопа на основе резонатора мод шепчущей галереи.
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DEFINITIONS, DESIGNATIONS AND ABBREVIATIONS

The present explanatory note uses the following abbreviations and designations:

AM- Amplitude Modulated
AR- Anti Reflection
BAW- Bulk Acoustic Wave
CDRH- Center for Devices and Radiological Health
EMC- Electromagnetic Compatibility
EMI- Electromagnetic Interference
ESD- Electrostatic Discharge
FMEA- Failure Mode and Effects Analysis
FMECA- Failure Mode Effects and Criticality Analysis
FTA- Fault Tree Analysis
FM- Frequency Modulated
FTIR- Frustrated Total Internal Reflection
IMU- Inertial Measurement Units
IDT- Interdigital Transducers
IEC- International Electro technical Commission
ISO- International Organization for Standardization
LG- Laser Gyros
MPE- Maximum Permissible Exposure
MTBF- Mean Time Between Failure
MEMS- Micro Electro Mechanical Systems
MDR- Morphology Dependent Resonance
PRR- Passive Ring Resonator
PZT- Piezo Electric Transducers
PDMS- Poly Dimethyl Siloxane
SNR- Signal to Noise Ratio
INTRODUCTION

The advancement of global lifestyle has resulted in the need for equipment with greater ease of use. This has enabled the use of motion sensing technology which extensively uses inertial sensors. This has become a key driving factor in of this market and will play an important role in defining the trend for the next few years. The gyroscope is an important device in many industries like aviation, ships, smartphones, tablets, robotics and much more. It uses the principles of angular momentum to measure and maintain the orientation. It is used in equipment in which orientation plays a decisive role in the proper functioning. The unprecedented rise in unmanned vehicles across various applications in both civilian and defense applications has increased the need for complex navigational systems which include inertial sensors. The rapid advancement in technology has made sensors both accessible and affordable making their use abundant in day-to-day devices. Defense industry takes the major share of the market with applications like missile guidance, control and targeting, precision guided munitions, tank turret stabilization and torpedo guidance. Other primary industries where these systems are used include industrial manufacturing, energy and infrastructure, transportation and aviation. Gyroscopes are devices used in measuring angular rotational movement on one or more axes. The devices find use in accurately measuring complex motion in free space, and help tracking rotation and position of a moving object without the influence of environmental factors such as magnetism or gravity. MEMS gyroscopes are millimeter or micro scaled inertial rate sensors that feature key benefits such as small form factor, higher energy efficiency and lower cost when compared with conventional gyroscopes. Inexpensive vibrating structure gyroscopes manufactured with MEMS technology have become widely available. These are packaged similarly to other integrated circuits and may provide either analog or digital outputs. In many cases, a single part includes gyroscopic sensors for multiple axes. Some parts incorporate multiple gyroscopes and accelerometers (or multiple-axis gyroscopes and accelerometers), to achieve output that has six full degrees of freedom.
These units are called inertial measurement units, or IMUs. Panasonic, Robert Bosch GmbH, InvenSense, Seiko Epson, Sensonor, STMicroelectronics, Freescale Semiconductor, and Analog Devices are major manufacturers. Significant advancements over the years in MEMS technology have encouraged the use of MEMS gyroscopes in various real life applications. Current applications of MEMS gyroscopes includes its use in the enablement of the anti-sliding control features, rollover detection in automobiles, inertial navigation in aircrafts and image stabilization in smartphones.

The global Market for MEMS gyroscope is projected to reach US$ 1.6 billion by 2020, driven by the promised wealth of applications in navigation, smart UI and image stabilization in consumer electronic devices. The latest advances in MEMS inertial sensors for applications where size, weight, power, and cost are key considerations are having profound effects on the market place. MEMS industrial and tactical-grade sensors are the most dynamic technology in the high-performance inertial industry. Yole Development sees the market growing from 381.8M in 2011 to 638.8M in 2017 for single MEMS accelerometers and gyroscopes or assemblies of MEMS accelerometers and gyroscopes [1].

Sensitivities of MEMS sensors to vibrations and temperature that has led to disappointments in recent years because of lower performance and reliability issues. MEMS gyroscopes do not have high shock stability. Other drawbacks of the MEMS gyroscopes includes, such as low precision due to a small vibrating amplitude and very narrow bandwidth [2]. The report discusses the advantages of micro optical gyroscope over MEMS gyroscope.
1 OVERVIEW OF GYROSCOPES

1.1 GYROSCOPE CLASSIFICATION

Gyrosopes can be distributed into two categories:

**Mechanical Gyroscopes.** It is based upon the conservation of momentum. It measures the change in the linear or angular momentum. Following are the different types of Mechanical gyroscopes:

a) **Mechanical Flywheel Gyroscopes.** A rapidly spinning wheel or sphere is with big inertia causes a gyroscopic precession when turned. The rotor is turned with the help of electric motor. The rotor is supported by low friction bearings and is mounted on a gimbal. Both the axis of the gimbal is perpendicular to the rotating axis. The rate of precession is proportional to the torque applied on the body [3].

![Diagram of a Mechanical Flywheel Gyroscope](Figure_1.png)

Figure 1 - A Mechanical Flywheel Gyroscope

b) **Gyrocompass.** It is the special configuration of the flywheel gyroscope. The spinning axis is along the North-South. By adding weight as the gravity reference a two axis instrument will become north seeking instrument [4].

![Diagram of a Gyrocompass](Figure_2.png)

Figure 2 - Diagram of a Gyrocompass
c) **Tuning Fork Gyro.** It is the most popular and low cost gyroscope for land based mobile applications [5].

![Tuning Fork Gyro Diagram](image)

*Figure 3 - A Tuning Fork Gyro*


d) **Systron Donner Gyro Chip.** Chemical etching is used for the tuning fork and support structure on a piezoelectric quartz wafer and used in applications requiring high bandwidth [6].

e) **MEMS Gyroscopes.** They are inexpensive, vibrating structure gyroscopes. They are packaged similarly to the other integrated circuits and may provide either analog or digital outputs. In most of the cases, a single part includes gyroscopic sensor for multiple axes. Some parts include multiple gyroscopes and accelerometers to achieve output that has six full degrees of freedom [7].

![MEMS Gyroscope Diagram](image)

*Figure 4 - Diagram of a Typical MEMS Gyroscope*
Optical Gyroscopes. These are the most promising sensor in the mobile robotics in the near future. Here two laser beams rotates in opposite direction in closed loop. When the beams are combined the rotation rate and direction can be calculated from the interference fringes. Following are the different types of optical gyroscopes:

a) **Ring Laser Gyro.** They have active optical resonator. Resonator is laser itself. If gyro is rotated counter clockwise direction, the counter clockwise beam travels shorter than the opposite beam.[8]

![Figure 5 - A Ring Laser Gyroscope](image)

b) **Fiber optic Gyro.** Senses the change in orientation using the Sagnac effect, thus performing the function of a mechanical gyroscope. However its principle of operation is based on the interference of light which has passed through a coil of optical fiber which can be as long as 5 km. They can be: Open loop interferometric fiber optic gyro, Closed loop interferometric fiber optic gyro, Resonant fiber optic gyros etc.

### 1.2 COMPARISON OF NEW TYPES OF GYROSCOPES

As already mentioned in the introduction part, MEMS gyros in spite of its promise for market growth it suffers lots of disadvantages which make it inappropriate for choosing as the final rotation sensor. There are some other classes of gyroscopes which have an upper edge over MEMS gyros. These are: SAW gyros (Surface Acoustic Wave gyros) and BAW gyros (Bulk acoustic wave gyros).

The surface acoustic wave (SAW) gyroscope was proposed by Lao in 1980 [9]. Several research groups have worked on this concept, and a number of related studies were published between 2000 and 2011 [10]. SAW gyroscopes detect a change in SAW velocity as a function of the angular rate of the medium in which the SAW propagates. When an RF power supply to interdigital transducers (IDT) is deposited on
the surface of a piezoelectric substrate, the IDT generates a SAW. The change in SAW velocity due to rotation is then detected as a phase shift between the generated and detected wave velocities. In comparison with conventional MEMS gyroscopes, SAW gyroscopes are very attractive for these reasons.

As opposed to the MEMS gyroscope, the SAW gyroscope does not need a suspended vibrating mechanical structure. Therefore, it is more resistant to external shocks and vibrations. Frequency matching between the drive- and sense-mode frequencies in the absence of active tuning and feedback control is very easy to achieve. Finally, temperature effects that cause variations in the Young’s modulus and residual stress can be almost completely eliminated easily.

On the other hand, BAW gyroscopes unlike conventional tuning-fork gyroscopes, utilize high-frequency degenerate modes to detect rotation-rate signals. This technology has the following inherent benefits: low drift, wide dynamic range, best in class noise density and immunity to shock and vibrations.

But the report is focused on Micro optical Gyroscopes which are more precise and sensitive than both SAW and BAW gyroscopes. Micro optical gyros are also very stable under harsh environmental conditions. There are two categories of micro optical gyro which are: Passive ring resonator (PRR) based gyroscope and whispering gallery mode (WGM) based gyroscope. PRR has no active element ensuring generation of counter propagating waves. A PRR gyro was first demonstrated and investigated in the late 1970s. It had a mirror configuration and its dimensions were essentially identical to those of the LGs (a usual triangular or square configuration 20–60 cm in perimeter) [11]. In designing the first PRRs, the main purpose was to make an optical gyro similar in sensitivity to the LGs but with no lock-in zone.

It was initially thought that, in the case of PRRs, locking of counter propagating waves was impossible in principle, because there was no lasing and, accordingly, no nonlinear effects. Subsequently, the PRRs were shown to have a lock-in zone, so this PRR configuration found no wide application. A few years later, it became clear that the frequency locking in the PRRs was due to the nonlinear effects arising from the use of feedback loops. However, proper feedback loop designs allow the formation of a
lock-in zone to be avoided [11]. The main focus in the report is on development of a suitable whispering gallery mode based angular velocity sensor.

Whispering gallery modes or waves are specific resonances or (eigen) modes of a wave field (e.g. sound waves, electromagnetic waves) inside a given resonator (a cavity) with smooth edges.

The most interesting from a practical viewpoint are electromagnetic whispering gallery modes, since they possess many unique properties, such as ultra-high Q-factors, low mode volumes, small sizes of resonators supporting them and operation at optical and telecommunication frequencies of light [12]. This combined with the ease of fabrication and on-chip integration of devices using them, makes whispering gallery modes ideally suited for a vast array of applications.

They correspond to waves circling around the cavity, supported by continuous total internal reflection off the cavity surface, that meet the resonance condition (after one roundtrip they return to the same point with the same phase and hence interfere constructively with themselves, forming standing waves). These resonances depend greatly on the geometry of the resonator cavity. In the report microsphere and toroid have been chosen as WGM and also have been modelled. A brief description of possible experimental work has also been discussed.
2 MODELLING

2.1 DESCRIPTION OF WAVE PROPAGATION INSIDE MICROSphere

The wavelength of the light is used to excite the optical modes is much smaller than the size of the optical cavity. In this geometric view, light coupled into the microsphere (for example using a single mode optical fiber) circles the interior of the sphere through total internal reflection as long as the refractive index of the sphere is larger than that of the surrounding medium [12].

![Ray optics description of Resonance in a sphere](image)

Figure 6 - Ray optics description of Resonance in a sphere

The condition for optical resonance is $2\pi Rn=l\lambda$, where $\lambda$ is the vacuum wavelength of the light (supplied by a laser), $l$ is an integer, $R$ is the sphere radius, and $n$ is the sphere refractive index. An external effect applied to the sphere that induces a change in both the radius, $\Delta R$, (mechanical strain) and the refractive index, $\Delta n$, (due to mechanical stress) leads to a shift in the optical resonance as follows:

$$\frac{\Delta R}{R} + \frac{\Delta n}{n} = \frac{\Delta \lambda}{\lambda}.$$

Therefore, any change in the index of refraction and radius of the microsphere induced by the external effect can be sensed by monitoring the change (shift) in the resonance of the microsphere. The general optical arrangement for these sensors is depicted in Figure 7. The optical modes are excited by coupling light from a tunable laser (with nominal power of a few mW) into the sphere using a single mode optical fiber as shown in Figure 7.
Here, we investigate the effect of angular velocity on the MDR shifts of spherical resonators that are used as sensing element as described above. The elastic deformation that is induced in a spinning resonator due to the centrifugal force, may lead to a sufficient shift in the optical resonances and therefore interfering with its desirable operational sensor design [13]. Also this principle could be used for the development of angular photonic sensors. Note that the shift induced in the optical modes by the centrifugal force should not be confused with the Sagnac effect, since the latter requires the interference of two beams traveling in two opposite directions. When a microsphere (sensing element) of radius $a$, and index of refraction $n$ is rotating with an angular velocity $\omega$ (see Figure 8), its morphology (shape and index of refraction) is perturbed due to the centrifugal force acting on the resonator. This in turn induces a shift in its optical resonances.

Figure 7 - Schematic of sensor system

Figure 8 - Geometry of a rotating sphere
Analytical Expression for Resonance shifts induced by the angular velocity $\omega$ is given by-

$$\frac{\Delta \lambda}{\lambda} = \frac{\Delta a}{a} = \frac{a^2(17+(6-5\nu)\nu)\rho\omega^2}{30G(1+\nu)(7+5\nu)},$$

where:

$\Delta \lambda$ – Change in the wavelength of the laser light;

$\lambda$ – Wavelength of the laser light;

$\Delta a$ – Change in the radius of the microsphere;

$a$ – Radius of the microsphere;

$\nu$ – Poisson ratio;

$\rho$ – Density of the material of the microsphere;

$\omega$ – Angular Velocity in rad/s $G$= Shear Modulus.

### 2.2 MODELLING OF MICROSPHERE.

For the purpose of Modelling of the microsphere, OOFELIE::Multiphysics software is used. For this software modelling, the values for the different parameters of the above mentioned equation have been chosen.

<table>
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<tr>
<th>Parameters</th>
<th>Values</th>
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<tr>
<td>Wavelength of laser light, $\lambda$</td>
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<tr>
<td>Radius of the microsphere, $a$</td>
<td>500 $\mu$m</td>
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<tr>
<td>Poisson Ratio, $\nu$</td>
<td>0,49</td>
</tr>
<tr>
<td>Density of the material (PDMS)</td>
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</tr>
<tr>
<td>Angular velocity, $\omega$</td>
<td>5·5 rad/s</td>
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<tr>
<td>Shear Modulus, $G$</td>
<td>1 kPa</td>
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</table>

The main purpose of this modelling is to analyze the effect of changing angular velocity on the microsphere (change in the radius). As from the figure 9 it can be noticed that the microsphere has been installed on an rotating platform. This rotating
platform is meant to provide desirable angular velocities. The microsphere is modelled as similar to the experimental design shown in figure 9.

![Schematic of the Microsphere rotating system](image)

Figure 9 - Schematic of the Microsphere rotating system

In this stage of experiment a universal programming code has been created. The code (appendix A) is designed as to accommodate any range of angular velocities which will further give result as the change of radius of the microsphere. In the experiment angular velocities in the range of -50 rad/s to 50 rad/s has been chosen. As the values of angular velocities change upon executing the code, a list of respective displacement values also comes into picture. It has to be noted that the execution of code can take time if the range of the angular velocity is too large. The execution of the internal command structure of the Software OOFELIE::Multiphysics can take a long time depending upon the complexity of the code and the complexity of the mesh structure of the model. The code has been executed with the predefined angular velocity range and in response of that OOFELIE::MULTIPHYSICS shows the displacement and stress models. The results of the change in radius of the microsphere can be given in the table №2.
Table 2 - List of values of Displacement for change of angular velocity

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<td>-49.5</td>
<td>3.41819e-008</td>
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<tr>
<td>-49</td>
<td>3.34949e-008</td>
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<td>-44.5</td>
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<tr>
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<td>3.4876e-008</td>
</tr>
</tbody>
</table>

Figure 10- Graph for the Angular velocity vs Displacement generated on the microsphere.

2.3 MODELLING RESULTS IN THE OOFELIE::MULTIPHYSICS.

The modelling consists of making a sphere of radius 500 µm and an elastic material has been chosen in the software. The spherical ball is clamped at the bottom to indicate that there is no translation or degree of freedom. Meshing of the spherical ball is done with an average length of the mesh=0.044mm and the mesh type is chosen as Tetrahedron. Proper meshing is key requirement for the best results. As we can see from the modelling results the microsphere suffers centrifugal displacement across the circumference and it gets expanded. With the change of angular velocities from a range...
of -50 rad/s to 50 rad/s exerts a displacement change on the radius of the microsphere which is depicted by the difference of the colors on the microsphere. It has to be noted that the displacement change is mostly concentrated around the center of the microsphere.

Nodal Displacements

Stress Tensor

![Figure 11 - Displacement model top view](image1)

![Figure 12 - Stress Tensor Model](image2)

![Figure 13 - Meshing of the ball](image3)

After getting the values of change of radius for the microsphere, we use the analytical expression for the calculation of change of the wavelength. After this the results have been plotted in the graph.

![Figure 14 - Graph for the rotation of microsphere for a range of angular velocities](image4)
2.4 MODELLING OF TOROID.

For the purpose of Modelling of the toroid, OOFELIE::Multiphysics software is used. A section of rectangle adjoined with a small circle is first created in the model section of the software. The dimensions and the pre toroid model have been shown in the following figure:

![Figure 15 - Pictorial representation of the toroid structure](image)

After the design of the pre toroid model the next stage is to revolve the structure 360 degrees in the revolution section of the modeler and achieve a full toroid. The toroid thus obtained can be meshed and various constraints can be added for the experiment. It needs to be noted that the toroid will be made up of fused quartz. The parameters of the fused quartz are given in tabular form (Table 3).

Table 3- Parameters of Fused Quartz

<table>
<thead>
<tr>
<th>Property</th>
<th>Typical Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>$2,2 \cdot 10^3$ kg/m3</td>
</tr>
<tr>
<td>Hardness</td>
<td>$5.5 - 6.5$ Mohs' Scale 570 KHN 100</td>
</tr>
<tr>
<td>Design Tensile Strength</td>
<td>$4.8 \cdot 10^7$ Pa (N/m2) (7000 psi)</td>
</tr>
<tr>
<td>Design Compressive Strength</td>
<td>Greater than $1.1 \cdot 10^9$ Pa (160,000 psi)</td>
</tr>
<tr>
<td>Bulk Modulus</td>
<td>$3.7 \cdot 10^{10}$ Pa (5.3 $\cdot 10^6$ psi)</td>
</tr>
<tr>
<td>Rigidity Modulus</td>
<td>$3.1 \cdot 10^{10}$ Pa (4.5 $\cdot 10^6$ psi)</td>
</tr>
<tr>
<td>Young's Modulus</td>
<td>$7.2 \cdot 10^{-10}$ Pa (10.5 $\cdot 10^6$ psi)</td>
</tr>
<tr>
<td>Property</td>
<td>Typical Values</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>-----------------------------------------</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td>0,17</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion</td>
<td>$5.5 \cdot 10^{-7} , ^0 \text{C}^{-1} ,(20^\circ \text{C} – 320^\circ \text{C})$</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>$1,4 , \text{W/m} \cdot ^0 \text{C}$</td>
</tr>
<tr>
<td>Index of Refraction</td>
<td>1,4585</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>$670 , \text{J/kg} \cdot ^0 \text{C}$</td>
</tr>
<tr>
<td>Velocity of Sound-Shear Wave</td>
<td>$3,75 \cdot 10^3 , \text{m/s}$</td>
</tr>
</tbody>
</table>

2.5 MODELLING RESULTS OF TOROID IN OOFELIE::MULTIPHYSICS.

The mesh models for the toroid structure have been made by using OOFELIE::Multiphysics software. For this purpose of modelling, two different types of meshes have been applied on the overall mesh structure. One mesh has an average length of 50 micro meters and other and has an average length of 2 micro meters. It has to be mentioned that during modelling of the toroid two separate structures have been created. One is rectangle and other is a circle whose dimensions have been mentioned in the previous notes. These two structures are joined together making it a toroid where the rectangle is used to create a membrane and circle as hollow tube. Coarse meshing is applied to the membrane section whereas fine meshing is applied to the head. Meshing
is a key requirement for achieving a proper output.

From the pictures of the displacement models we achieve three different results for different axes of rotation. When the axis of rotation is along Y axis the displacement or the expansion is quite symmetrical making the overall toroid structure as circular. However for the case of rotation along X axis and Z axis the structure changes to an ellipsoid. As we are interested in determination of the change in the radius of the toroid, we compute the perimeter of the toroid in both the cases. This perimeter computation will also provide us the path length of the wave travelling inside the toroid. Using separate formulae’s for ellipsoid and circle we get following path length of the wave:
- path length of the wave for rotation along Y axis is $45,12 \cdot 10^{-19} \text{m}$;
- path length of the wave for rotation along Z axis is $3,21288 \cdot 10^{-9} \text{m}$.

The displacement models for the toroid modelling are shown in figure 18, 19 and 20

![Figure 18](image1.png)  ![Figure 19](image2.png)  ![Figure 20](image3.png)

Figure 18 - For rotation along X axis  Figure 19 - For rotation along Y axis  Figure 20 - For rotation along Z axis

The Stress/Strain models for the toroid modelling are shown in figures 21, 22 and 23.
Figure 21 - Toroid Rotation along X axis

Figure 22 - Toroid Rotation along Y axis

Figure 23 - Toroid Rotation along Z axis
3 EXPERIMENTAL SETUP DESCRIPTION

3.1 SCHEME OF THE EXPERIMENT

A series of experiments need to be performed to investigate the effect of angular velocity on the MDR shifts of the quartz based microsphere. The probable optoelectronic setup that can be used to excite and monitor the MDR shifts in microsphere is as follows-

Figure 24 - Experimental Setup for the coupling of light inside microsphere

The description of the components to be used in the experimental design is as follows.

a) **Low Noise Tunable Laser.** The Pure Photonics full-band tunable laser solution provides a very narrow linewidth (~10 kHz), significantly reduced low-frequency AM and FM noise and a range of operating modes in this low-noise setting. The product can access any desired frequency set-point in either the C-band or L-band.

Output power can be set as low as 7dBm and as high as 18dBm (optional). The laser and its features are designed for high SNR (Signal-to-Noise-Ratio) applications, such as sensing and T&M (Test and Measurement). The specifications of the laser are as follows.
Table 4 - Parameters of the Low Noise Tunable Laser

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating temperature</td>
<td>°C</td>
<td>-5</td>
<td>75</td>
</tr>
<tr>
<td>Storage temperature</td>
<td>°C</td>
<td>40</td>
<td>85</td>
</tr>
<tr>
<td>Humidity</td>
<td>%DH</td>
<td>5</td>
<td>85</td>
</tr>
<tr>
<td>Voltage +3.3V</td>
<td>V</td>
<td>0</td>
<td>3,6</td>
</tr>
<tr>
<td>Voltage -5.2V</td>
<td>V</td>
<td>-5,5</td>
<td>0,3</td>
</tr>
<tr>
<td>Fiber bend radius</td>
<td>Mm</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Current Source Slew rate</td>
<td>V/msec</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Mounting surface flatness</td>
<td>Micron</td>
<td></td>
<td>25</td>
</tr>
</tbody>
</table>

It has an External Cavity Laser design with tunable filters embedded in the cavity for frequency control. The Cavity consists out of an InP front-facet coated gain chip with back-facet AR coating and a high-reflection end-mirror, mounted on a PZT element. By changing the injection current into the gain-chip and the built-in photodiode tap, the product accurately controls the operating power to the user-defined power target.

![Figure 25 - Low Noise tunable laser](image)

b) **Power Supply.** The power supply is manufactured by the Department of LINS. It can provide a maximum voltage of 3,6 V.
c) *Optical Components (Prism, Lens and Microsphere)*.

d) *Photodetectors*.

e) *Fiber Optic cable*.

### 3.2 PROCEDURE FOR THE EXPERIMENT AND POSSIBLE EXPECTED RESULTS

The light source is coupled to the microsphere with the help of converging lens system and prism. This configuration may lead to fragile coupling between sphere and the fiber; however, the system can be more robust using a planar waveguide coupler [14]. Lens system can be used to focus the laser light coming out of laser diode efficiently into the prism. The prism must be kept very close to the microsphere such that Frustrated Total Internal Reflection (FTIR) is supported. Under ordinary conditions, the evanescent wave transmits zero net energy across the interface. However, if a third medium with a higher refractive index than the low-index second medium is placed within less than several wavelengths distance from the interface.
between the first medium and the second medium, the evanescent wave will be different from the usual one, and it will pass energy across the second into the third medium. This process is called "frustrated" total internal reflection (FTIR) and is very similar to quantum tunneling. The quantum tunneling model is mathematically analogous if one thinks of the electromagnetic field as being the wave function of the photon. The low index medium can be thought of as a potential barrier through which photons can tunnel. The whole system is kept upon a rotating disc/platform to set up desired values of angular velocity. The laser source, optic cable, photodiode need not to be rotated; only the optical system (lens, prism and disc) will be rotated on the platform. The microsphere was mounted on a metallic disk and attached to it using the silica stem. The metallic disk was mechanically coupled to a DC motor. The angular velocity of the disk was changed by varying the voltage that was supplied to the DC motor. The MDR shifts were recorded on a PC. During the experiments the temperature was kept constant. The entire experimental setup was mounted on a floating optical table to reduce noise induced by vibrations. To simulate the presence of angular velocity, the whole experimental setup will be mounted on a centrifuge.

The main objective of the experiment is to achieve dips in the transmission spectrum [Figure 28] (transmission intensity vs wavelength of the laser light). The width of the spectrum $\delta \lambda$ is the key noticeable feature. A key factor that makes this phenomenon attractive for sensor applications is the very large optical quality factors, $Q$, of the optical resonances. The observed line-width, $\delta \lambda$, is related to the optical quality factor as $Q = \lambda / \delta \lambda$. Better the quality factor, better the MDR based angular velocity sensor.

![Figure 28 - Graph for transmission spectrum](image)
4 SPECIAL QUESTIONS IN SAFETY ASSURANCE

4.1 GENERAL REVIEWS ON SAFETY TECHNIQUES

Safety Analysis means that to seem at the work task and considering what's the safest thanks to complete it. It’s the simplest way of turning into alert to the hazards concerned in doing the work associate degrees taking action to stop an injury. Several tasks undertaken square measure done habitually and have in all probability been done an equivalent approach for years – typically safely, typically not. Before beginning a task, it's essential to think about what's the safest and best thanks to be intimate. In different words this comes into the class of Safety Engineering. Safety engineering is associate degree engineering discipline that assures that designed systems give acceptable levels of safety. It’s powerfully associated with industrial engineering/systems engineering, and also the set system safety engineering. Safety engineering assures that a life-critical system behaves as required, even once elements fail. Analysis techniques may be split into 2 categories: qualitative and quantitative ways. Each approaches share the goal of finding causative dependencies between a hazard on system level and failures of individual elements. Qualitative approaches target the question "What should get it wrong, specified a system hazard might occur?", whereas quantitative ways aim at providing estimations concerning possibilities, rates and/or severity of consequences.

Historically, safety analysis techniques swear exclusively on talent and experience of the security engineer. Within the last decade model-based approaches became distinguished. In distinction to ancient ways, model-based techniques attempt to derive relationships between causes and consequences from some type of model of the system.

*Traditional methods for safety analysis*- The two most common fault modeling techniques are called failure mode and effects analysis and fault tree analysis. These techniques are just ways of finding problems and of making plans to cope with failures, as in probabilistic risk assessment. One of the earliest complete studies using this technique on a commercial nuclear plant was the WASH-1400 study, also known as the Reactor Safety Study or the Rasmussen Report.
**Failure modes and effects analysis**- Failure Mode and Effects Analysis (FMEA) is a bottom-up, inductive analytical method which may be performed at either the functional or piece-part level. For functional FMEA, failure modes are identified for each function in a system or equipment item, usually with the help of a functional block diagram. For piece-part FMEA, failure modes are identified for each piece-part component (such as a valve, connector, resistor, or diode). The effects of the failure mode are described, and assigned a probability based on the failure rate and failure mode ratio of the function or component. This quantization is difficult for software – a bug exists or not, and the failure models used for hardware components do not apply. Temperature and age and manufacturing variability affect a resistor; they do not affect software. Failure modes with identical effects can be combined and summarized in a Failure Mode Effects Summary. When combined with criticality analysis, FMEA is known as Failure Mode, Effects, and Criticality Analysis or FMECA, pronounced "fuh-MEE-kuh".

**Fault tree analysis**- Fault tree analysis (FTA) is a top-down, deductive analytical method. In FTA, initiating primary events such as component failures, human errors, and external events are traced through Boolean logic gates to an undesired top event such as an aircraft crash or nuclear reactor core melt. The intent is to identify ways to make top events less probable, and verify that safety goals have been achieved. Fault trees are a logical inverse of success trees, and may be obtained by applying de Morgan's theorem to success trees (which are directly related to reliability block diagrams). FTA may be qualitative or quantitative. When failure and event probabilities are unknown, qualitative fault trees may be analyzed for minimal cut sets. For example, if any minimal cut set contains a single base event, then the top event may be caused by a single failure. Quantitative FTA is used to compute top event probability, and usually requires computer software such as CAFTA from the Electric Power Research Institute or SAPHIRE from the Idaho National Laboratory. Some industries use both fault trees and event trees. An event tree starts from an undesired initiator (loss of critical supply, component failure etc.) and follows possible further system events through to a series of final consequences. As each new event is considered, a new node on the tree is added.
with a split of probabilities of taking either branch. The probabilities of a range of "top events" arising from the initial event can then be seen.

Once a failure mode is identified, it can usually be mitigated by adding extra or redundant equipment to the system. For example, nuclear reactors contain dangerous radiation, and nuclear reactions can cause so much heat that no substance might contain them. Therefore, reactors have emergency core cooling systems to keep the temperature down, shielding to contain the radiation, and engineered barriers (usually several, nested, surmounted by a containment building) to prevent accidental leakage. Safety-critical systems are commonly required to permit no single event or component failure to result in a catastrophic failure mode.

Most biological organisms have a certain amount of redundancy: multiple organs, multiple limbs, etc. For any given failure, a fail-over or redundancy can almost always be designed and incorporated into a system. There are two categories of techniques to reduce the probability of failure: Fault avoidance techniques increase the reliability of individual items (increased design margin, de-rating, etc.). Fault tolerance techniques increase the reliability of the system as a whole (redundancies, barriers, etc.) [15].

**Safety and Reliability:** Safety engineering and reliability engineering have much in common, but safety is not reliability. If a medical device fails, it should fail safely; other alternatives will be available to the surgeon. If the engine on a single-engine aircraft fails, there is no backup. Electrical power grids are designed for both safety and reliability; telephone systems are designed for reliability, which becomes a safety issue when emergency (e.g. US "911") calls are placed.

Probabilistic risk assessment has created a close relationship between safety and reliability. Component reliability, generally defined in terms of component failure rate and external event probability are both used in quantitative safety assessment methods such as FTA. Related probabilistic methods are used to determine system Mean Time between Failure (MTBF), system availability, or probability of mission success or failure. Reliability analysis has a broader scope than safety analysis, in that non-critical failures are considered. On the other hand, higher failure rates are considered acceptable for non-critical systems.
Safety generally cannot be achieved through component reliability alone. Catastrophic failure probabilities of $10^{-9}$ per hour correspond to the failure rates of very simple components such as resistors or capacitors. A complex system containing hundreds or thousands of components might be able to achieve a MTBF of 10,000 to 100,000 hours, meaning it would fail at $10^{-4}$ or $10^{-5}$ per hour. If a system failure is catastrophic, usually the only practical way to achieve $10^{-9}$ per hour failure rate is through redundancy. When adding equipment is impractical (usually because of expense), then the least expensive form of design is often "inherently fail-safe". That is, change the system design so its failure modes are not catastrophic. Inherent fail-safes are common in medical equipment, traffic and railway signals, communications equipment, and safety equipment.

The typical approach is to arrange the system so that ordinary single failures cause the mechanism to shut down in a safe way (for nuclear power plants, this is termed a passively safe design, although more than ordinary failures are covered).

Alternately, if the system contains a hazard source such as a battery or rotor, then it may be possible to remove the hazard from the system so that its failure modes cannot be catastrophic. The U.S. Department of Defense Standard Practice for System Safety (MIL–STD–882) places the highest priority on elimination of hazards through design selection [16].

One of the most common fail-safe systems is the overflow tube in baths and kitchen sinks. If the valve sticks open, rather than causing an overflow and damage, the tank spills into an overflow. Another common example is that in an elevator the cable supporting the car keeps spring-loaded brakes open. If the cable breaks, the brakes grab rails, and the elevator cabin does not fall.

Some systems can never be made fail safe, as continuous availability is needed. For example, loss of engine thrust in flight is dangerous. Redundancy, fault tolerance, or recovery procedures are used for these situations (e.g. multiple independent controlled and fuel fed engines). This also makes the system less sensitive for the reliability prediction errors or quality induced uncertainty for the separate items. On the other hand, failure detection & correction and avoidance of common cause failures
become here increasingly important to ensure system level reliability [17].

**4.2 CATEGORIES OF SAFETY BASED UPON TYPE:**

a) *Electrical Safety*—Electricity can kill or severely injure people and cause damage to property. However, we must take simple precautions when working with or near electricity and electrical equipment to significantly reduce the risk of injury to us, workers and others around us.

The main hazards of working with electricity are:

- electric shock and burns from contact with live parts;
- injury from exposure to arcing, fire from faulty electrical equipment or installations;
- explosion caused by unsuitable electrical apparatus or static electricity igniting flammable vapors or dusts, for example in a spray paint booth;
- electric shocks can also lead to other types of injury, for example by causing a fall from ladders or scaffolds etc.

We must ensure an assessment has been made of any electrical hazards, which covers:

- who could be harmed by them;
- how the level of risk has been established;
- the precautions taken to control that risk.

The risk assessment should take into consideration the type of electrical equipment used, the way in which it is used and the environment that it is used in. We must make sure that the electrical installation and the electrical equipment is:

- suitable for its intended use and the conditions in which it is operated;
- only used for its intended purpose.

In wet surroundings, unsuitable equipment can become live and make its surroundings live too. Fuses, circuit-breakers and other devices must be correctly rated for the circuit they protect. Isolators and fuse-box cases should be kept closed and, if
possible, locked. Cables, plugs, sockets and fittings must be robust enough and adequately protected for the working environment. Ensure that machinery has an accessible switch or isolator to cut off the power quickly in an emergency.

b) **Electromagnetic Compatibility** - EMC means a device is compatible with (i.e., no interference is caused by) its electromagnetic (EM) environment and it does not emit levels of EM energy that cause electromagnetic interference (EMI) in other devices in the vicinity. A medical device can be vulnerable to EMI if the levels of EM energy in its environment exceed the EM immunity (resistance) to which the device was designed and tested. The different forms of EM energy that can cause EMI are conducted, radiated, and electrostatic discharge (ESD). EMI problems with medical devices can be very complex, not only from the technical standpoint but also from the view of public health issues and solutions. The Center for Devices and Radiological Health (CDRH) has regulatory authority over several thousand different kinds of medical devices, with thousands of manufacturers and variations of devices. Because of its concern for the public health and safety, the CDRH part of FDA has been in the vanguard of examining medical device EMI (electromagnetic interference) and providing solutions. Extensive laboratory testing by CDRH, and others, has revealed that many devices can be susceptible to problems caused by EMI. Indeed, CDRH has been investigating incidents of device EMI, and working on solutions (e.g. the 1979 draft EMC standard for medical devices), since the late 1960s, when there was concern for EMI cardiac pacemakers.

c) **Explosion** - Fire can occur when flammable material, oxygen and sufficient ignition energy are available. Explosion depends on an atmosphere of a mixture of flammable material with oxygen. The best approach to prevent fires and explosions is to substitute or minimize the use of flammable material. If that is not possible it is important to avoid effective sources of ignition. Fires and explosions in industrial structures and plants may not only lead to losses and damages but may also hamper the functioning of the economy. In Germany three explosions occur daily on average according to the accident insurance company for the chemical industry and similar sectors, whereby fortunately most of them do not cause bigger problems due to protective measures being in place [18]. Small workshops like garages have a high risk
of fires and explosions because they use highly volatile hydrocarbons for spray painting and cleaning purposes.

In Schleswig-Holstein (Germany) alone four garages experienced large fires between 2009 and 2010 and one had to close down afterwards there is a rapid oxidation of material releasing heat, light and various chemical products. The fire triangle describes the conditions that have to be met in order a fire can start: (1) flammable material, (2) oxygen, (3) energy to ignite the fire. All material capable of an exothermic oxidation reaction has to be considered as flammable. This can be:

- gases such as butane, propane, methane, carbon monoxide, hydrogen;
- liquids such as fuels, solvents, oils, greases, paints and thinners;
- solids such as wood, coal, plastics, metals, food.

Oxygen is usually available in sufficient quantities in our air to get a fire started and to sustain it. Fires may however start much easier and may be more powerful in terms of flame volume and released energy, if the oxygen content of the surrounding atmosphere is increased, e.g. when an oxygen cylinder leaks or bursts or when oxygen releasing substances (e.g. peroxides) are present. The needed ignition energy can be very low (usually with gases) and can be quite high, which is usually the case with solids. Liquids are often somewhere in between. However, the ignition of solids or aerosols depends also on the particle size: fine dusts of e.g. aluminum or flour mixed with air can explode easily. An explosion is a rapid increase in volume and release of energy in an extreme manner, usually with the generation of high temperatures and the release of gases. An explosion creates a shock wave [19]. Does the created shock wave exceed the velocity of sound we talk about a detonation; is the velocity lower the term deflagration is used [20].

d) **Functional Safety** - Freedom from unacceptable risk of physical injury or of damage to the health of people, either directly or indirectly as a result of damage to property or to the environment. Functional safety is the part of the overall safety that depends on a system or equipment operating correctly in response to its inputs. Functional safety is the detection of a potentially dangerous condition resulting in the activation of a protective or corrective device or mechanism to prevent hazardous events arising or
providing mitigation to reduce the consequence of the hazardous event.

Functional safety relies on active systems. The following are two examples of functional safety:

- the detection of smoke by sensors and the ensuing intelligent activation of a fire suppression system or;
- the activation of a level switch in a tank containing a flammable liquid, when a potentially dangerous level has been reached, which causes a valve to be closed to prevent further liquid entering the tank and thereby preventing the liquid in the tank from overflowing.

Safety achieved by measures that rely on passive systems is not functional safety. A fire resistant door or insulation to withstand high temperatures are measures that are passive in nature and can protect against the same hazards as are controlled by functional safety concepts but are not instances of functional safety.

4.3 SAFETY TECHNIQUES INVOLVED IN THE SCIENTIFIC WORK

Following are special Safety requirements for the purpose of fulfilling the experimental design as well as the modelling work done for this report:

a) *Usability of OOFELIE Multiphysics Software according to the International Code ISO 9241*. ISO 9241 is a multi-part standard from the International Organization for Standardization (ISO) covering ergonomics of human-computer interaction. It is managed by the ISO Technical Committee 159. It was originally titled Ergonomic requirements for office work with visual display terminals (VDTs). From 2006 on, the standards were retitled to the more generic Ergonomics of Human System Interaction. So 9241-100:2010 enables users of standards related to software ergonomics to identify ergonomics standards particularly relevant to software development, gain an overview on the content of software-ergonomics standards, understand the role of software-ergonomics standards in specifying user requirements as well as designing and evaluating user interfaces and understand the relationship between the various standards. The software-ergonomics standards are applicable to all those software components of an interactive system affecting usability, including application software.
(including web-based applications), operating systems, embedded software, software development tools and assistive technologies.

The software used in creation of the Modeling works follows the standards of ISO 9241 specifications. It is built in for ease of human and system interaction. This software has its own user guidelines which are based on the ergonomics of ISO system. The Usability and user-centered design standards of OOFELIE can be divided up into 3 main categories:

- product usage characteristics (how well users perform with it, how satisfied they are with it);
- product interface attributes (design of the interface and interaction);
- development process (activities carried out during product development).

b) Safety Measures during Physical Experiment. The experimental setup consists of working with tunable lasers. This tunable laser is of low power; still safety precautions must be followed while working with lasers. The laser guidelines can help the user in working with laser, in spite of being it high power or medium power.

The British Standard quotes Maximum Permissible Exposure (MPE) Levels for laser radiation based on the frequency and duration of exposure. These are the levels of laser radiation which would normally not produce adverse effects. Arrangements for the safe use of lasers should ensure that no one is exposed to laser radiation in excess of these levels. This aim can be achieved by means of three types of safety control:

- engineering controls;
- administrative controls;
- the use of personal protective instrument.

Rules for Specific Classes of Lasers

Class 1 - Low Power Lasers. No formal control measures are required for Class 1 lasers whose outputs are so low that the relevant MPE cannot be exceeded under any viewing conditions [21].

Class 1 - Totally Enclosed Laser Systems. A register must be kept of all such lasers which must bear the correct warning labels. Lasers incorporated in printers, CD-ROM
players and similar devices are excluded.

Class 2 Lasers. A register must be kept of all such lasers which must bear the correct warning labels. Protection from accidental viewing of the beam from a laser in this class is afforded by the natural aversion response to bright lights. However, precautions must be adopted to prevent continuous viewing of the direct beam. The laser beam should be terminated at the end of its useful path by a suitable beam stop and open laser beams at eye level should be avoided.

Class 3A and Class 3B* Lasers. A register must be kept of all such lasers which must bear the correct warning labels. Protection by means of the natural aversion response cannot be relied upon and precautions must be adopted to prevent viewing the direct beam. In particular, optical aids must not be used unless fitted with a filter to ensure that maximum permissible exposure levels at the eye are not exceeded. Control measures are required as follows:

• the beam must be terminated by a suitable beam stop;
• open beam paths at eye level should be avoided and should be enclosed where practicable;
• instruction and training in safe procedures should be given to all users;
• laser warning signs should be displayed at each entrance to areas where such lasers are in use.

Class 3B** and Class 4 Lasers (Including Existing Class 3B Lasers). A register must be kept of all such lasers which must be correctly labelled. These lasers are extremely hazardous and must only be used in a designated laser area i.e. a laboratory or other clearly defined area which can be reserved for the purpose and where the hazards can be effectively controlled. Designated laser areas must be clearly identified with the appropriate signs and notices.

Wherever practicable, a visual signal interlocked to the laser should be mounted at the entrance so that it functions automatically whenever the laser is being operated.

Aspects of Functional safety of designing a device in possible applications:

IEC 61508-2:2010 applies to any safety-related system, as defined by IEC 61508-1 that
contains at least:
- one electrical, electronic or programmable electronic element;
- applies to all elements within an E/E/PE safety-related system;
- specifies how to refine the E/E/PE system safety requirements specification, developed in accordance with IEC 61508-1, into the E/E/PE system design requirements specification;
- specifies the requirements for activities that are to be applied during the design and manufacture of the E/E/PE safety-related systems except software, which is dealt with in IEC 61508-3.

The report deals with the design of microsphere based angular velocity sensors. This sensors or micro optical gyroscope have an abundant range of usage from mobile phones to weapons. Proper working of these gyros is the key desirable feature. Impaired functioning of micro optical gyros can lead to serious safety issues while considering in making weapons and ballistic missiles since error in giving data of direction of rotation can create hazardous safety issues. The micro optical gyros which are currently being designed by our department is being followed by the International functional safety codes.
CONCLUSION

The result shows that polymeric microsphere resonators may experience resonance shift when exposed to an external angular velocity. The curve shows a parabolic relationship between the change of wavelength and the change of radius of microsphere. This confirms the theoretical expression and can give high sensitive angular velocity sensors. The programming coding (appendix 2) helps in selecting the desired angular velocity values. Similarly modelling work has also been done for a toroid. The future work will focus in making mathematical equation for the resonance inside a toroid. An Experiment of MDR shifts for a microsphere needs to be performed to validate the theoretical data with the practical ones. Nevertheless, the analytical solution with the help of the OOFELIE modelling justifies the value of the change of wavelength for the range of angular velocity. These results are also the first step towards the design and development of angular velocity sensors that are based on this principle.


13. Ali, R Amir; Ioppolo, T, Effect of Angular Velocity on sensors based on
APPENDIX A

Source Code for Range of Angular Velocities as Constraint on Microsphere

```cpp
1: Int mn=-50,mx=50,stp=0.5,k=0; int I,j; for(i=mn;i<=mx;i=i+stp) k++;
2: Vector ang_vel(k); double X,Y,Z;
3: //ang vel direction X=1$
4: Y=0$ Z=0$
5: ofstream param("loadParam.e"); param.close(); for(i=0;i<=ang_vel.dim();i++)
6: ang_vel[i+1]=mn+stp*i;
7: Matrix res(ang_vel.dim(),2); res.setToZero();
8: for(i=1;i<=ang_vel.dim();i++)
9: res[i,1]=ang_vel[i]/1;
10: Matrix value;
11: system("%OOFELIEUI_BIN_PATH%\oofelieui.cmd -batch -infile sphererot.sfield -sfile sphererot.e"); for(j=1;j<=ang_vel.dim();j++)
12: ofstream param("loadParam.e");
13: param<<"double ang_value="<<ang_vel(j)<<"\n";
14: param<<"String outputFile="<<"sphererot_"<<floor(ang_vel(j)/1)<<"\n";
15: param<<"double X="<<X<<"\n";
16: param<<"double Y="<<Y<<"\n";
17: param<<"double Z="<<Z<<"\n";
18: system("%OOFELIEUI_BIN_PATH%\oofelieui.cmd -L OOOK_MECHANICAL -L OOKL_PIEZOELECTRICS -autoQuit sphererot.e");
19: value.fromTxtFile("Strain_vMises_current.txt"); res[j,2]=value[1,1]
20: res.toTxtFile("Strain_vonMises_result.txt");
21: cout<<"\n Progress: ""<<j<<"/"<<ang_vel.dim()<<"\n";
22: if(doesFileExist("loadParam.e")) removeFile("loadParam.e");
23: if(doesFileExist("value_vMises_current.txt")) removeFile("value_vMises_current.txt");
24: if(doesFileExist("sphererot_Model.e")) removeFile("sphererot_Model.e");
25: if(doesFileExist("sphererot LinearStatic_Step00000001.oef")) removeFile("AccSq LinearStatic_Step00000001.oef");
26: removeDir("sphererot_files"); exit;
27:/* in UI should be the following:
28: #SECTION_AFTER_MODEL#
29: int isBatch=false;
30: if(doesFileExist("loadParam.e")) isBatch=true; isBatch$
31: if(isBatch) loadParam; if(isBatch)
32: { ang.put(ROTATION_AXIS_ORIGIN,0,0,0); ang.put(ROTATION_AXIS_DIRECTION,X,Y,Z);
33: ang.put(ROTATION_SPEED,ang_value);
34: }
35: #SECTION_AFTER_SOLVER#
36: GeneralPost gp(dom_##);
37: gp.buildStrains3DAtNodes(); // Build the mean strain tensor at nodes
38: dom_##.setStepNumber(1);
39: if(isBatch)
40: { double t,p,v=0;
41: Matrix calc(circle.getNodes()); t=dom_##[TX][calc[1,1]][1];
42: p=dom_##[TY][calc[1,1]][1];
43: v=sqrt(pow(t,2)+pow(p,2)); double i,vMises
44: ofstream result("Strain_vMises_current.txt"); result<<v<<endl;
45: result.close();
46: }
47: #SECTION_PARAM_EXPORT#
48: if(isBatch)
49: { toSF_##.writeResults(outputFile); //to write results in separate folders.
50: NB:Comment it if you have too many values!!!
51: quit;
52: }
53: */
```