ANSYS Simulation Study of MEMS Tuning Fork Gyroscope

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Abstract— **This paper presents a MEMS based Tuning Fork Gyroscope (TFG) design by using ANSYS software. The designing of the Tuning Fork Gyroscope is based on the architecture and the parameter that been chosen from the previous studies. The structure of TFG is focus on the capacitance at the comb's structure and the chosen parameter are based on which factor that makes greater effect on the sensing when it is variance and the parameter is using Taguchi method to determine the mathematical formulation of the design of experiments. From the simulation results, it can be conclude that the best design of Tuning Fork Gyroscope based on capacitance which had the values of 260 µm for comb finger length, 30 µm for comb finger width, 80 µm comb finger thickness and lastly capacitance gap of 3 µm.**

Keywords-component; **Micro Electro Mechanical Systems (MEMS), Tuning Fork, Gyroscope (TFG), ANSYS**

I. Introduction

Micro machined gyroscopes have been develop and undergo rapid progress since it was created and numerous MEMS gyroscopes have been commercialized and applied in electronics appliances, health care, space and even defense [3]. The need for gyroscopes with high performance is demanding. In order to realize high performance gyroscopes, proper drive and sense mechanisms and architecture must be selected except improved device fabrication, interface and control circuits design. Capacitive drive and sense gyroscope with a tuning fork structure, namely capacitive TFG, is one of the most successful MEMS gyroscopes.

A. Micro Electro Mechanical System (MEMS)

Micro Electro Mechanical System or MEMS on the other hand is a technology that use both electronic and mechanical in micro size. MEMS are made up of component in between 1 to 1000 micrometer in size and generally the device's size is in the range from several micrometers to several millimeters.

MEMS based technology has been widely used because of its improved accuracy and reliability and gyroscope that develops based on MEMS is one of them because nowadays it has gained its popularity due to their cheap cost and small sized compared to traditional gyroscopes [1].

B. Tuning Fork Gyroscope

The main focus of this gyroscope is the capacitance of the tuning fork or in some research paper it called comb capacitor. For that, the structure of the tuning fork gyroscope must be identified and choose the one that easier to design and simulate.

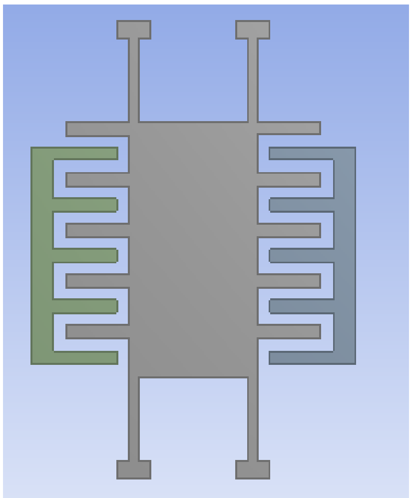

Figure 1. Simple tuning fork gyroscope

In the reported capacitive TFGs, only gap-variable mechanism [8] [9] or only area-changing mechanism [10] [11] is adopted for sensing capacitors. Area changing capacitors normally have good linearity for a wide measurement range but the fabrication imperfections may deteriorate the linearity especially for vertical motion sensing [12].

After choosing the suitable structure, then the parameter for the capacitance also need to be identified. This parameter likes for example width, thickness, length or diameter of the comb is varied to see the changes at the gyroscope during simulation. The software that been used for the designing is ANSYS because it can handle MEMS micro technology.

C. Taguchi Method

The MEMS tuning fork gyroscope are designed as a sensor to detect the direction of the device motions. Because of that, we need to identify the parameters for the designs to be more sensitive towards the momentum of motion.

Taguchi Method is a method that can determine the best of parameter which can give the optimum result in frequency that had been simulate using ANSYS software. For the parameters, the experiments were testing the variations value of comb finger length, comb finger width, comb finger thickness and capacitance gap between two finger combs.

II. METHODOLOGY

The structure and parameters of the tuning fork gyroscope must be identified and determined so that we can do the simulation afterward. The structure that been selected must be related to the capacitance structure and from there the parameters like the width, height, thickness, and length of the comb or the fork or the gaps between both finger comb must be identified to get the data of the structure. After that, Taguchi method was applied for the parameters so that it can be used for the simulation.

A. Tuning Fork Gyroscope Design

The operating principle of the device is based upon a normal tuning fork's reaction toward rotation. Between all types of MEMS gyroscopes, capacitance sensing micro gyroscope is a very attractive class [11] [12]. These gyroscopes use electrostatic comb drive to trigger the device in X direction. If there is an angular velocity along Y direction, the mass will vibrate along Z direction due to Carioles force [10].

To prove the capability of the comb capacitor, a general finite-element simulating tool ANSYS is used to simulate the capacitance of the comb capacitor. For simplicity, only one pair of comb fingers with unit length is modeled with a 2-D electrostatic element. The height, h of the movable finger and the width w and gap g of all fingers were stated respectively and been simulated [3].

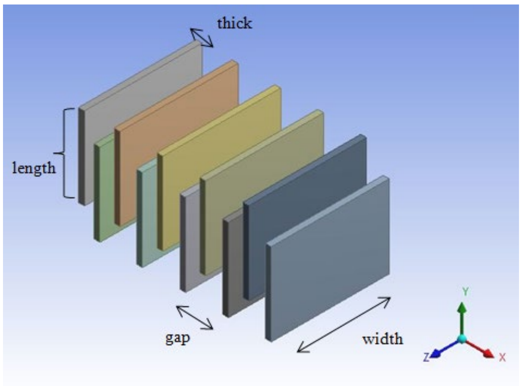

Figure 2. Comb finger of tuning fork

In the design of tuning fork gyro, finding the structure of drive mass, the sense mass and the drive electrode of the gyro are the priority ones. This will become the starting point to achieve the main objective of this experiment.

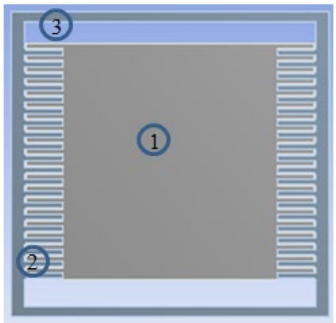

Figure 3. Full body design 1.Drive mass 2. Sense mass 3. Drive electrode

This vibrated deflection is very small and can be detected from the change in the electrostatic capacitance of the gap between the resonator and the substrate. The gap was designed to be more than 3µm less than 6µm to detect the change with high sensitivity [12]. Besides that, the thicknesses of the structure also play roles in the sensitivity of the TFG.

With small gaps, the gap-varying capacitors can have a high sensitivity. At the same time, small gaps also dramatically increase the air damping and so most gyroscope with gap-varying capacitors requires vacuum packaging to acquire a high sensitivity, which increases the costs of the device [12].

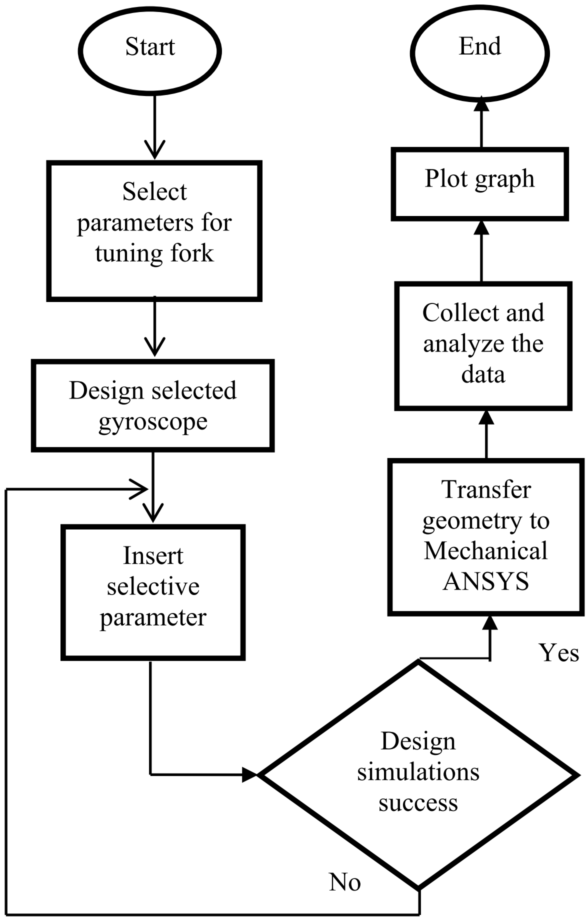

Figure 4. Flow Chart of

B. *Taguchi Design of Experiment*

The Taguchi experimental design was employed to determine the best combination of thickness parameter for the Tuning Fork Gyroscope to obtain optimum value of frequency when we focus the design on its capacitance. [16]

Orthogonal array is used in this experimental design for the purpose of reducing the number of experiment. Four control factors were considered which are Comb Finger Length (A), Comb Finger Width (B), Comb Finger Thickness (C), and Capacitance Gap (D).

The experiment was conducted by using different values of parameters, for example the comb finger length are in the range of 230µm to 260µm, comb finger width from 30µm to 45µm, comb finger thickness 80µm to 110µm and lastly the capacitance gap are from 3µm to 6µm. These four parameters will be optimized based on the combinational of experiment as tabulated in Table 1 and since there are four factors with four levels, thus the suitable orthogonal array that can be used is L16[15].

TABLE I. CONTROL FACTORS AND THEIR LEVEL

Symbol	A	B	C	D
Parameter	**Comb Finger Length (µm)**	**Comb Finger Width (µm)**	**Comb Finger Thickness (µm)**	**Capacitance Gap (µm)**
Level 1	230um	30um	80um	3um
Level 2	240um	35um	90um	4um
Level 3	250um	40um	100um	5um
Level 4	260um	45um	110um	6um

The experimental arrangement using L'16 orthogonal array table is shown in Table 2. These four control factors were assigned to four columns so that 16 combinations of control factor levels can be obtained. Each combination comes out only once in the array.

The parameters were chosen based on the research which variety will give higher or lower frequency when the structure been vibrated using the ANSYS Mechanical software. For example we focus on the highest and the lowest values in each of the parameters.

TABLE II. L'16 ORTHOGONAL ARRAY

	Factors			
Designation	**A**	**B**	**C**	**D**
Level 1	A1	B2	C4	D4
Level 2	A2	B1	C1	D1
Level 3	A4	B3	C2	D2
Level 4	A1	B4	C4	D3
Level 5	A3	B3	C4	D4
Level 6	A1	B1	C1	D3
Level 7	A2	B3	C2	D4
Level 8	A3	B2	C1	D1
Level 9	A4	B2	C1	D4
Level 10	A2	B4	C4	D4
Level 11	A3	B1	C4	D2
Level 12	A4	B1	C1	D1
Level 13	A1	B3	C2	D2
Level 14	A2	B2	C2	D3
Level 15	A4	B3	C3	D2
Level 16	A3	B1	C4	D4

C. *Device Simulations*

Random vibration test standards and specifications usually provide spectra showing desired vibration intensity as Power Spectral Density (PSD) or as Acceleration Spectral Density (ASD) in rather strange units of g2/Hz vs. frequency in hertz or Hz[11].

(PSD) is a statistical measure defined as the limiting mean-square value of a random variable. It is used in random vibration analyses in which the instantaneous magnitudes of the response can be specified only by probability distribution functions that show the probability of the magnitude taking a particular value.

By using ANSYS software, TFG structure can be designed and simulated manually or automatically by inserting the analysis system and input or parameter that we want. In this experiment, firstly from the ANSYS Workbench analysis system, select the Modal option where all the design can be create and adjust there.

Second is, after design the structure in Modal, drag and insert the Random Vibration option into Modal's solutions. By doing that, the Geometry data in the Modal analysis system is been transfer to the Random Vibration in order for the structure's vibration to take place.

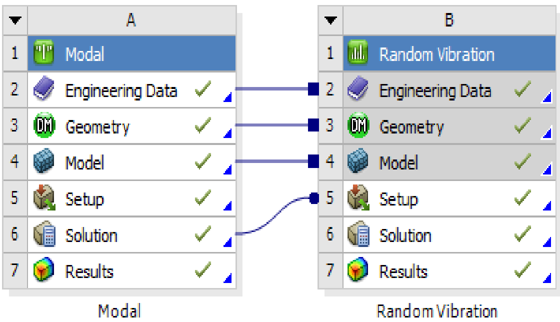

Figure 5. Project Schematics

Before experiment the vibration, Mesh needed to create first in geometry as it was one of the most critical aspects of engineering simulation in Finite Element. Too many cells may result in long solver runs, and too few may lead to inaccurate results. For this experiment, the range of the Mesh sizing is in between 0.008m to 0.01m. If we choose too fine mesh analysis, some of the structure part cannot vibrate thus giving inaccurate result and reading.

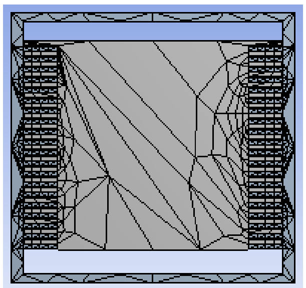

Figure 6. The mesh of the structure.

Based on the Mesh structure, the part that been focused for the experiment were at the comb finger. That is why the meshing was fine at the comb and less fine at the center of the drive mass.

After the Mesh has been generated, next step is to create the Fixed Support for the structure or geometry. But if we do not want to create the fixed support, it also does not affect the result because the fixed support is only to test the structure properties. This is because, the structures that been vibrate the software itself. Usually from the research and analysis, a lot of TFG designs have static mass where during vibration, it does not vibrate that as if it playing a role as haft for the structure.

Then, apply the PSD Acceleration for the structure to generate the natural frequency. The generated frequencies were determined by the design of the structure. Some of experimental structures give lower frequency and some of them give the higher frequency. These frequencies were obtained together with the mode. For each of the experiment, we fix the tabular data for Frequency (Hz) and Acceleration [$(m/s^2)^2$/Hz] input. This PSD Acceleration is calculating by using Fourier Transform technique [7].

TABLE III. TABULAR DATA INPUT

No	Frequency (Hz)	Acceleration [$(m/s^2)^2$/Hz]
1	10	10
2	20	15
3	30	20
4	40	25
5	50	30
6	60	35

The types of solution that can be applied to the random vibration analysis include:

- Deformation
- Strain
- Stress
- Energy
- Linearized stress

The solutions that were used in this experiment are total deformations, normal elastic strain and equivalent stress. The first two of the solution that were used contains directional orientation that allows user to test vibrate the structure according to desire orientation.

Each of the experiment have their own structure properties due to different parameter been used when designing them. These properties are generating from the ANSYS Multiphysics system. The material that been used in this experiment were structural steel as it was the default structure for each of the experiment.

TABLE IV. PROPERTIES STRUCTURE FOR EXPERIMENT 1

Properties		
Structure	**Drive mass**	**Sense mass**
Volume	3.0569e-010 m³	1.1249e-010 m³
Mass	2.3996e-006 kg	8.8303e-007 kg
Centroid X	-7.3967e-004 m	-7.3747e-004 m
Centroid Y	-7.2821e-004 m	-7.4935e-004 m
Centroid Z	5.5e-005 m	
Moment of Inertia Ip1	5.3908e-013 kg·m²	4.5587e-013 kg·m²
Moment of Inertia Ip2	6.0951e-013 kg·m²	6.839e-013 kg·m²
Moment of Inertia Ip3	1.1438e-012 kg·m²	1.138e-012 kg·m²

III. RESULT AND DISCUSSION

A. Simulation Analysis

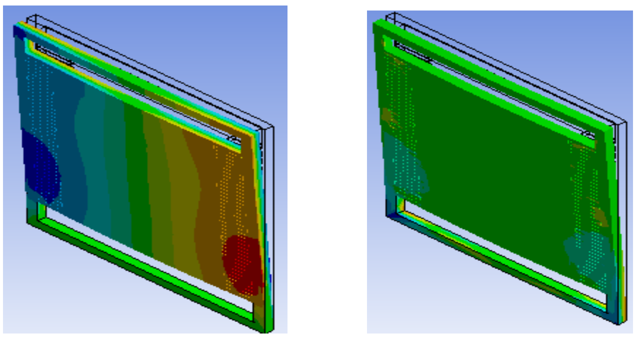

Figure 7. Total deformations and normal elestic strain

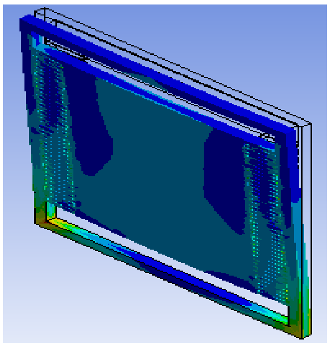

Figure 8. Equivalent stress

In each of the experiment, the data that been generate and analysis are natural frequency. Natural frequency is defined as the rate at which an object vibrates when it is not disturbed by an outside force. In other word, the higher the frequency, the faster the object tends to vibrate.

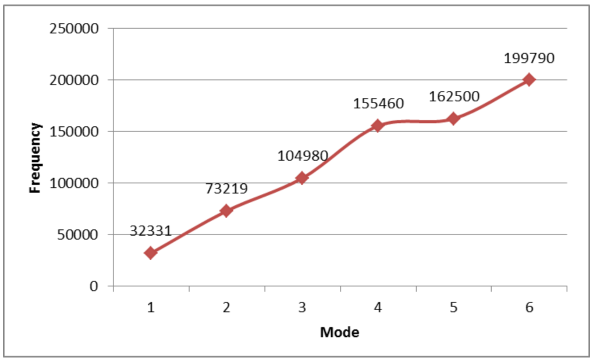

Figure 9. Frequency versus Mode graph for experiment 1

For the graph, the natural frequency that been generate at Mode 1 is 32331 Hz and for every Mode it increasing vertically and the last frequency that ben generate is 199790 Hz. All the generated natural frequencies are produced by the ANSYS software and the user does not need to enter any calculations that are necessary.

The parameters for the first experiments are; comb finger length 230(µm), comb finger width 35 (µm), comb finger thickness 110 (µm) and lastly capacitance gap 6 (µm). The gap between sense comb and drive comb are not too large, but this situation will lead to difficulty when the structure are been fabricates [10].

B. Taguchi Method Analysis

TABLE V. FREQUENCY FOR EACH EXPERIMENTS

Exp	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
1	32331	73219	104980	155460	162500	199790
2	28757	60247	78946	122630	143000	169240
3	18001	47786	72522	121150	139850	144890
4	20165	53539	75536	98021	100110	110790
5	27379	63233	84465	94524	101740	111690
6	35146	72849	90998	128710	169040	174250
7	28477	64423	90785	141570	144000	174910
8	25193	53252	72985	117770	131100	156570
9	30600	62487	73895	92567	101220	106430
10	25974	62528	91108	136790	152960	177640
11	33036	74049	100610	152480	167220	188050
12	40974	81129	95485	128940	168090	176360
13	19338	49592	77088	125330	142330	148180
14	26100	59271	76553	95894	100410	108640
15	18454	50879	80655	135400	146560	155390
16	40264	81806	93160	95133	115350	128020

From the table 5, all the data were been plot Frequency (Hz) versus Experiment. From the graph, all the information were analyzed according to the parameters and objective that been stated earlier.

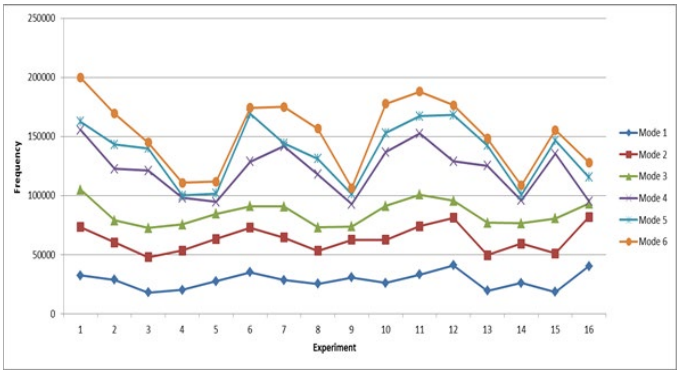

Figure 10. Frequency versus experiment graph

From the analysis of the graph on Mode 1, 2 and 3 only, the frequency that higher when majorities of the parameter at capacitance gap are larger. For example, in experiment 1, 5, 6, 7, 9 and 16 all the parameters are the larger; 3 µm and 4 µm. Vice versa, in the smaller gap of capacitance, the frequency obtain were smaller compare to the bigger one.

Before the result from each of experiment can state which combinations of parameter are the best using Taguchi's Method, ones must consider what parameter that make the gyroscope become more sensitive. For vibrating gyroscopes, decreasing the mismatch between the resonant frequencies of the driving and detection modes is important to attain high detection sensitivity of the gyroscope [6]. In some journals also state that, in general, sensitivity can be enhanced by increasing the drive mode amplitude and by lowering the natural frequencies ω_x and ω_y. To do that, the sense mass must be bulker. But as the mismatch decreases, the mechanical coupling between the two modes makes operation more and more unstable [6].

These also depend on what type of design that been used for the TFG. For these experiments, it has bulker sense mass which is one of the criteria to maximize the sensitivity of the gyroscope. Besides, because of the structure of the TFG is quite large, it will produce higher natural frequency and resonant frequency and also based from the Mesh sizing.

It's easier to do the experiment on the TFG when it has been fabricate rather that do the analysis base on the software alone. This is because, the software is quite limited and not all the function that we need to used are available.

Therefore based on the analysis and the research on the journals, it clearly that on the Mode 1's frequency, the best combinations using Taguchi Method are on Experiment 12 because it have the largest frequency generated compare to the others. The combinations for the structure are A4B1C1D1 and the nature frequency obtain is 40974 Hz. This value is not too large compare to some of analysis that has all most the same volume of structure as this experiment but it giving higher frequency then the structure in Experiment 12.

IV. CONCLUSION

As a conclusion, capacitance on the Tuning Fork Gyroscope plays important role for the sensitivity of the gyroscope. Furthermore, Taguchi's Method has been used to obtain the combinations numbers of experiment to be implemented. The best combination of Tuning Fork Gyroscope based on capacitance is Experiment 12 which had the values of 260 µm for comb finger length, 30 µm for comb finger width, 80 µm comb finger thickness and lastly capacitance gap of 3 µm with combinations of A4B1C1D1. The ANSYS software is good software to be used to simulate micro structure and it also has the vibration option that can vibrate the structure automatically without the structure need to be fabricated first. This will reduce the cost of fabrications because it has the ability to produce results that similar to the actual results. For future this experiment can be improve by combining ANSYS software with other simulations software to get more result and analysis done will give more accurate data.

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