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Sensitivity Analysis of MEMS-based four Beam Vector Hydrophone

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Abstract: ***MEMS Vector Hydrophone is a recent advancement in the field of underwater acoustic sensors. The major incentive provided by this hydrophone is that it provides the direction of the incoming source signal. These hydrophones are miniaturized up to the scale of micrometers and hence lightweight which makes them useful for deployment in AUVs and ROVs. This way, this microsensor will help in finding out the precise locations of enemy submarines, underwater drones and warships at times of and thus, improve our defence. Also, this Vector Hydrophone will help in the submarine communication system, sonobuoys, ROV SONAR, pipeline leakage detection, fish tracking, oceanographic surveys and study of marine life. This paper presents design and optimization of MEMS-based four beams Vector Hydrophone and for this, the worldwide research on the vector hydrophones was referred and later on, the design was optimized using parametric analysis. After the modelling of structure, its simulation was carried out using finite element modeling method via ANSYS software. The receiving sensitivity of this vector hydrophone is -196.73 dB (0dB=1V/µPa) and was improved up to -184.68 dB by changing the design parameters.***

Keywords: MEMS Vector Hydrophone, FEA, Harmonic Response, ANSYS, Piezoresistivity

1.Introduction

The development of underwater electro-acoustic transducers expanded rapidly during the twentieth century, and continues to be a growing field of knowledge, with many significant applications, one that combines mechanics, electricity, magnetism, solid state physics and acoustics. Earlier it was possible to detect underwater sound but there was no hint of direction from where it is coming. With high amplification devices and other media it is now possible to trace the exact location as well as direction of underwater sound.

2.MEMS Vector Hydrophone

The MEMS vector hydrophone is designed based on the piezoresistive effect of silicon. The beam microstructure is manufactured by means of a silicon-on-insulator wafer with MEMS technology. Compared with traditional piezoelectric hydrophones, the MEMS vector hydrophone as shown in **Figure1** has the characteristic of a being a single sensor with directional functions. Vector hydrophones can obtain both the acoustic pressure and acoustic particle velocity simultaneously, and therefore can gather more information about a point in the sound field than ordinary acoustic pressure hydrophones.

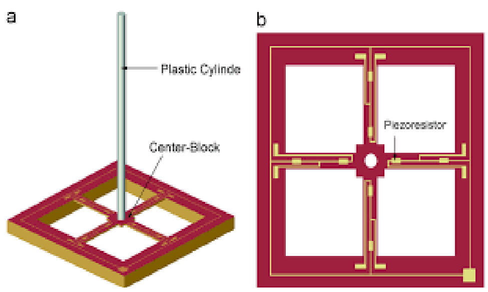


Figure 1: (a) 3-D Model and **(b)** 2-D Top view of the Vector Hydrophone structure **[1]**

Vector hydrophone mimic the behaviour of blind Mexican Cave-fish, which has lost its ability to see underwater and uses a sensing mechanism to swim and make its way underwater. This fish consists of lateral lines which run from the head to the tail of the fish and resemble a towed array with sensing organs along the nerve fiber as shown in **Figure 2**. Each stitch contains several neuromast which comprises up to several hundred mechanosensory hair cells. Hair cell possesses hair bundles consisting of several rows of stereocilia and one kinocilium which protrude from the apical side of the cells. The lateral line is especially sensitive to low frequency fluid motion parallel to the length of the fish.

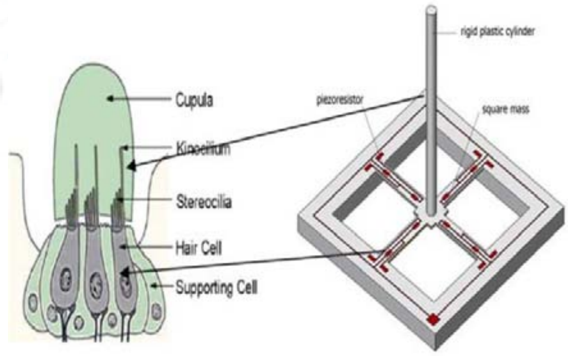


Figure 2: Fish's Neuromast and its simulated structure **[4]**

Afferent nerve fibers are activated by depolarization of hair cell membrane which occurs when the stereocilia are deflected towards the tallest stereocilium. The electric signal originates from impedance changes in cell walls which modulate the flow of K^+ ions. This behaviour of fish under water is mimicked to produce bionic vector hydrophones **[3].**

3.Modeling and Simulation of Four-Beam MEMS Vector Hydrophone

The four beam hydrophone structure consists of a large cuboidal block and another smaller block which is subtracted from it to form a frame with a hollow space. Four cantilever beams are attached to this frame, one on each edge and these beams are inter-connected via center mass. A vertical cylinder is mounted on top of this centre mass. Eight piezoresistors are mounted; two on each cantilever beam to form the four beam Vector Hydrophone.

The final dimensions which were taken for creating the model are mentioned in **Table 1**:

Table 1: Dimensions of various parts of Vector Hydrophone for performing analysis

Part of Vector Hydrophone	Dimensions
Outer Rectangular Block (Silicon)	3000 μm x 3000 μm x 200 μm
Four cantilever Beams (Silicon)	1000 μm x 120 μm x 10 μm
Centre block (Silicon)	500 μm x 500 μm x 10 μm
Cylinder (Acrylic Plastic)	Diameter =200 μm; Height =5000 μm
Piezo-resistive Domains (p-Silicon)	100μm x 40 μm x 5 μm

Element types used for creating model of Vector Hydrophone on ANSYS wereSOLID186 and SOLID187. The properties of materials used for Vector Hydrophone simulation are shown in **Table 2**:

Table 2: Properties of Materials used for Vector Hydrophone Analysis

Material	E (GPa)	μ	ρ (kg/m^3)	Part of Vector Hydrophone
Silicon	169	0.22	2329	Outer block, Beams, Centre block
p-Silicon	169	0.22	2329	Piezoresistors
Acrylic Plastic	3.2	0.35	1190	Cylinder

Here, E is the Modulus of Elasticity, μ is the Poisson's Ratio and ρ is the density of the material. Simulation was done using ANSYS to obtain various results in the form of numerical data and graphs. The steps which were followed in simulation of Vector Hydrophone by FEA methodology using ANSYS are: **(a)** Creating a 3D model of Vector Hydrophone using design modeller in ANSYS Workbench.**(b)** Obtaining stress distribution on cantilever beams using "Static Structural Module" of ANSYS by taking pressure as input and normal stresses on beams as output. **(c)** Performing Modal analysis using "Modal Module" on the four beam structure for determining its vibration characteristics. Modal analysis uses the overall mass and stiffness of the Vector Hydrophone to find the various periods at which it will naturally resonate. Generally, Vector Hydrophone works between 40 Hz to 5 kHz which demands the first resonance frequency greater in order to far away from working frequency but if the working frequency is too far away from the resonance frequency, the sensitivity will be decreased. Therefore, it needs to be considered simultaneously. **(d)** Performing Harmonic response analysis to determine the steady-state response of hydrophone structure to loads that vary harmonically with time. "Peak" responses were then identified on the graph and stresses were reviewed at peak frequencies.**(e)**For sensitivity calculations, two Wheatstone bridges were formed on beams along X-axis and Y-axis respectively. After giving input voltage, and forming couplings to get the Wheatstone bridge on ANSYS, output voltage was obtained as the voltage difference between connections of different piezoresistors.

4.Simulation Results

Following results were obtained after doing simulation on ANSYS Workbench:

(a) The maximum deflection along cylinder was obtained as 0.93172 μm after applying a pressure of 1Pa.

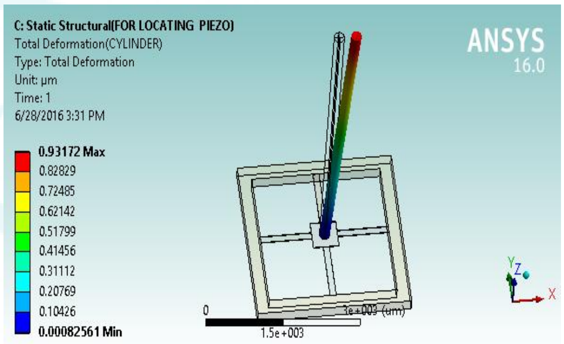


Figure 3: Maximum deflection along the cylinder

(b) The stress distribution on silicon beams was obtained through curves as shown in **Figure 4** to get the optimum distance for locating the piezoresistors.

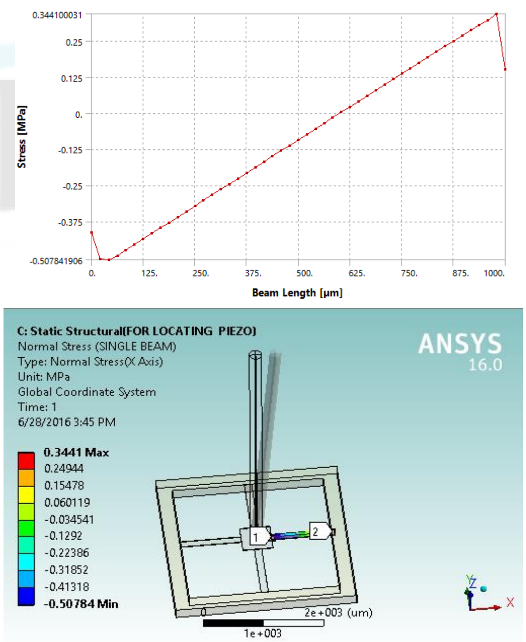


Figure 4: Stress distribution along a single cantilever beam

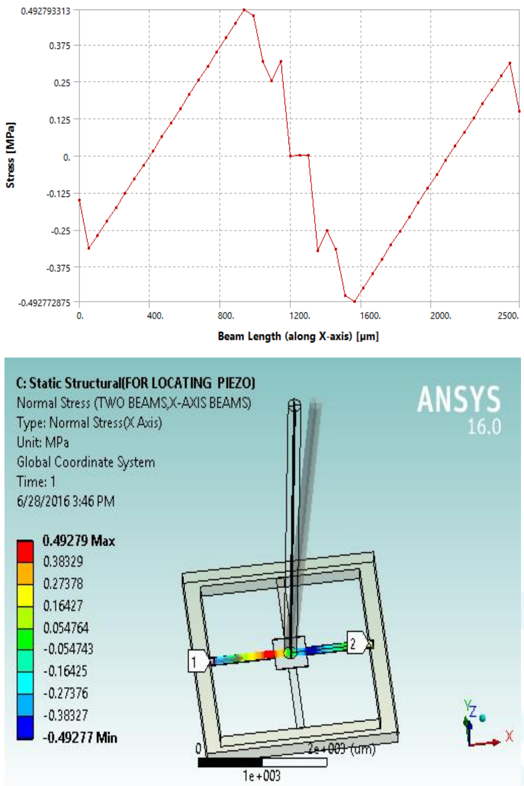
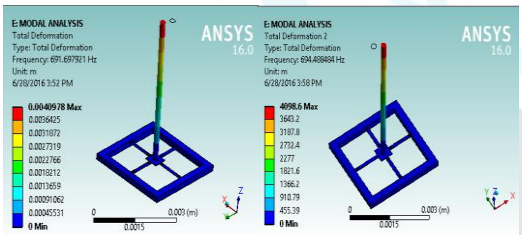


Figure 5: Stress distribution along two beams (X-axis)

Thus, piezoresistors should be located at the maximum stress location, (approximately 25 µm from the end of cantilever beam) so that maximum change in resistance and output voltage can be obtained on piezoresistors.

(c) Various modes of resonant frequency of the MEMS Vector Hydrophone are given below in **Figure 6**:



(a) Mode 1 (b) Mode 2

Mode	Frequency [Hz]
1.	691.697919
2.	694.488484
3.	3425.92508
4.	8301.2005
5.	8305.10354
6.	25996.7727
7.	26003.6399
8.	49585.216
9.	52980.0014
10.	52995.8874

Figure 6: Different Mode shapes and Eigen frequencies of Vector Hydrophone structure

Harmonic response analysis gives for the ability to predict the dynamic behaviour of structures, thus enabling to verify whether or not designs will successfully overcome resonance, fatigue and other harmful effects of forced vibrations **[2]**.

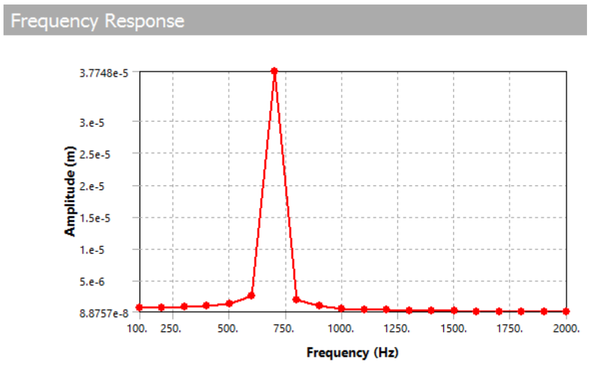


Figure 7: Displacement of the structure in harmonic response analysis in x-axis

The harmonic response analysis results can be shown through curve in **Figure 7** between displacement of cylinder and frequency.

The response is "flat" except at the peak value which is obtained at the resonant frequency (about 700Hz) of microstructure.

For sensitivity analysis, two Wheatstone bridges were formed on beams along X-axis and Y-axis respectively as shown in **Figure 8**. After giving 5V as input voltage, and forming couplings on piezoresistors, an output voltage was obtained as the voltage difference between connections of different piezoresistors.

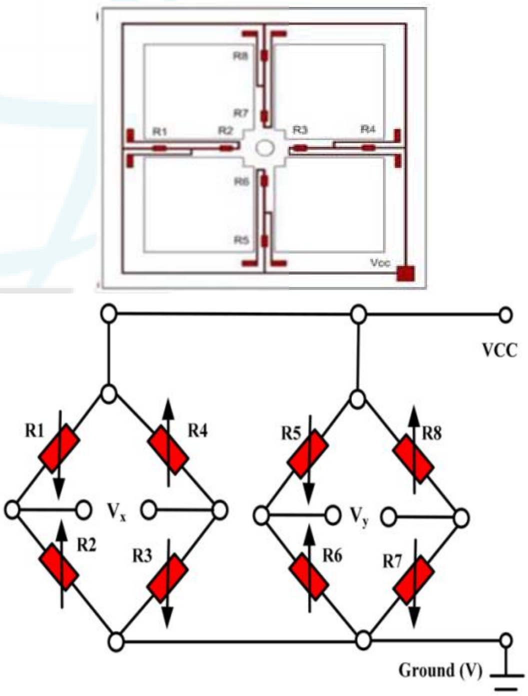
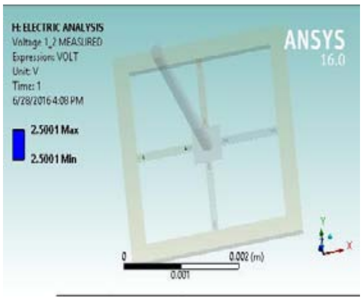
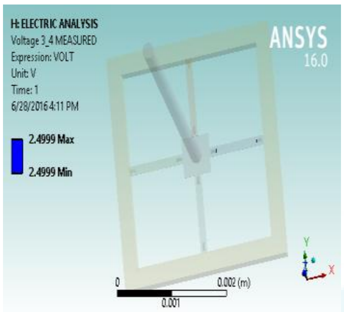


Figure 8: Wheatstone bridge along eight piezoresistors

Piezoresistors R1, R2, R3 and R4 forms the first Wheatstone Bridge and R5, R6, R7 and R8 forms the second Wheatstone Bridge. The input voltage, Vcc is taken as 5V for this analysis. Piezo and MEMS ACT extension of ANSYS was used for accomplishing the electro mechanical analysis part.



(a) Voltage measured along 1-2 coupling



(b) Voltage measured along 3-4 coupling

Figure 9: Electrical results of Piezoresistors Coupling

From the analysis results, it can be seen that measured voltage ($V_{measured1-2}$) along R1 & R2 is2.50007296 V and measured voltage ($V_{measured3-4}$) along R3 & R4 is2.49992728 V. Thus, the voltage output is the difference between these two couplings which is equal to 0.00014567375 V for unit Pascal pressure applied on the cylinder in x-direction.

Sensitivity, S =20 log V/p_0(ref 1V/µPa)
S = 20 log (0.00014567375 V/1e6 µPa)
= -196.73dB

From the calculations, it can be seen that the sensitivity of the MEMS vector Hydrophone is -196.73 dB. Thus, the design was optimized in order to get higher sensitivity. Then, a parametric analysis of Vector Hydrophone structure was performed and for that the following were taken as input parameters: height of cylinder, diameter of cylinder, length of piezoresistors, width of piezoresistors, height of piezoresistors and location of piezoresistors over cantilever beams. The output parameters were voltage output (piezoresistors) and receive sensitivity.

5.Design Optimization using Parametric Analysis on ANSYS

The following tables 3 and 4 show the parametric analysis for optimizing the design of Vector Hydrophone by taking above mentioned input and output parameters. By changing the height and diameter of plastic cylinder and the dimension of piezoresistors, which is the main sensing element of vector hydrophone, an optimized design can be obtained.

Table 3: Parametric Analysis taking Cylinder Diameter and Height

S. No	Diameter (µm)	Height (µm)	Voltage Output, V= V1-2 - V3-4 (Volts)	Sensitivity = 20*log (V/P) ; P=1e6 µPa
1	200	5000	0.00014567375	-196.73
2	210	6000	0.00022029877	-193.13
3	220	7000	0.00031423569	-190.05
4	230	8000	0.00042891502	-187.35
5	240	9000	0.00056672096	-184.93

Table 4: Parametric Analysis taking Piezoresistor Length (L), Width of Piezoresistor (W) & Piezoresistor Thickness (T)

S No.	*L (µm)*	*W (µm)*	*T (µm)*	*Voltage Output, V(Volts)*	*Sensitivity (dB)*
1	100	40	5	0.0001456738	-196.73
2	105	45	5	0.0001378059	-197.21
3	110	45	4	0.0001573563	-196.06
4	115	50	4	0.0001502037	-196.46
5	120	50	4	0.0001499653	-196.48

It can be concluded from the parametric analysis that the design parameters can be changed to improve the sensitivity of device and it can reach upto -184.68 dB when all the design parameters are changed simultaneously i.e.

Cylinder diameter= 240µm,
Cylinder height=9000µm,
Piezoresistor length=120µm,
Piezoresistor width=50µm,
Piezoresistor thickness=4µm.
to get an optimised design which can be used for fabrication.

6.Conclusion

The simulation of MEMS based four beam vector hydrophone has been presented in this paper. The measured resonance frequency is 691.69 Hz. The sensitivity was obtained on FEA software ANSYS is up to -196.73dB (ref 1V/µPa) in a bandwidth of range 20Hz to 2kHz and can be improved to -184.68 dB by optimizing the design parameters. Further research can be carried out for getting more optimized Vector Hydrophone structure with higher sensitivity with a wider bandwidth.

References

[1] Chenyang Xue, Shang Chen, Wendong Zhang, Binzhen Zhang, Guojun Zhang, Hui Qiao, "Design fabrication and preliminary characterization of a novel MEMS bionic Vector hydrophone," Microelectronics Journal 38 (2007),pp 1021 – 1026.
[2] Shang Chen, Chenyang Xue, Binzhen Zhang, Bin Xie and Hui Qiao, "A Novel MEMS Based Piezoresistive Vector Hydrophone for Low Frequency Detection", Proceedings of the IEEE 2007, pp 1839 – 1844.
[3] Binzhen Zhang, Hui Qiao, Shang Chen, Jun Liu, Wendong Zhang, Jijun Xiong, Chenyang Xue, Guojun Zhang, "Modeling and Characterization of a micromachined artificial hair cell vector hydrophone"

Microsyst Technol (2008), 13 March 2008, Vol 14, pp 821 – 828.

[4] Wen Dong Zhang, Ling Gang Guan, Guojun Zhang, Chen Yang Xue, Kai Rui Zhang and Jian Ping Wang, "Research of DOA estimation based on single MEMS vector hydrophone," Sensors, Vol 9, No. 9, pp 6823 – 6834 Aug, 2009.

[5] Guojun Zhang, Peng Zhao, Wendong Zhang, "Resonant freqnency of the silicon micro-structure of MEMS vector hydrophone in fluid structure interaction," AIP Advances, 2015, Vol 5, 041316 – 1-8

[6] Chenyang Xue, Zhaomin Tong, Binzhen Zhang and Wendong Zhang, "A Novel Vector hydrophone based on the piezoresistive effect of resonant tunneling diode", IEEE sensors, Vol 8, No. 4 April 2008, pp. 401 – 402.

[7] Tan Shizhe, "Underwater artificial lateral line flow sensors" Microsystem Technologies,(Dec 2014) Vol 20,Issue 12, pp 2123-2136.

[8] Guojun Zhang, Zhen Li, Shu-Juan Wu, Chen-Yang Xue, Shi-e Yang, Wendong Zhang, "A bionic fish cilia median low frequency three dimensional piezoresistive MEMS vector Hydrophone" Nano-micro Letters, Vol .6, No. 2, March 2014, pp. 136 – 142.

[9] Ling gang Guan, Guojun Zhang, Chenyang Xue, Wendong Zhang, Jijun Xiong, Jiao Xu, "Design of T-shape vector hydrophone based on MEMS" IEEE Transducers' 11 Beijing, China June 5 – 9, 2011, pp 20 – 23.

[10] Thomas Ramotowski, "NUWC XP-1 Polyurethane – Urea: A New "Acoustically Transparent encapsulant for underwater transducers and hydrophones" Transducer materials Branch, NUWC Division Newport (CODE 2132), Sep. 2003, pp 227 – 230.

[11] H Kitsunai, T Suzuki, M Ishikawa, N Kawashima, E. Ohdaira, M. Kurosawa and S Takenchi, "Development of miniature hydrophone with PZT film deposited by hydrothermal method" Ultrasonics symposium, 2004 IEEE, Vol 3, 23 – 27 August 2004, pp 2201 – 2205.

[12] YingYing Wang and Chang Wang, "Simulation of high-sensitivity hydrophone based on ANSYS, "Proceedings of 2012 International conference on Mechanical Engineering and Material Science (MEMS 2012), pp. 697 – 699.

[13] Linxian Liu, Wendong Zhang, Guojun Zhang, Chenyang Xue, "Package optimization of the cilium-type MEMS bionic vector hydrophone" IEEE Sensors, Vol 14, No 4 April 2014.

[14] Smitha G Prabhu, S Nagabhushana, "Design and Simulation of Underwater Acoustic MEMS sensor", Proceedings of the 2015 COMSOL conference.

[15] MN Mat Nawi, A Abd Manaf, M R Arshad and O Sidek, "Development of biomimetic flow sensor based on artificial lateral line flow sensor for underwater applications" Indian Journal of Geo-Marine Sciences, Vol 41(6), December 2012 pp. 527-532