Finite Element Analysis of Fiber Optic Concentric Composite Mandrel Hydrophone for Underwater Condition

Prashil M. Junghare, Cyril Prasanna Raj and T. Srinivas

Abstract An Interferometric fiber optic hydrophone is designed in this work with a composite concentric structure. The structure is made of different layers having a variable material and structural properties. The mandrel is designed to withstand a natural frequency ranges from 0.2 to 2.5 kHz. The objective of the work is to design the mandrel which is placed at a distance ranging from 20 to 200 m underwater with varying boundary conditions. Boundary conditions specified are innermost layer of the mandrel is fixed and pressure is applied to the outermost layer of the mandrel. The design is feasible with two optic fiber layers which are wound over the center of the length of the mandrel. Preprocessing of design is made using Hyper Mesh; analysis is performed in ABAQUS 6.10 CAE tool and visualization of results in hyper view. Whenever the pressure is applied to the mandrel, the phase change of light happens which can be to calculate sensitivity mathematically.

Keywords Interferometric · Concentric structure · Hyper mesh
Hyper view · ABAQUS CAE · Preprocessing

P. M. Junghare (✉)
Centre for Research & Development, PRIST University, Thanjavur, India
e-mail: prashiljunghare3@gmail.com

C. P. Raj
Electronics & Communication Department, MSEC, Bangalore, India
e-mail: cyrilprasanna007@gmail.com

T. Srinivas
Department of Photonics, Indian Institute of Science, Bangalore, India
e-mail: tsrinu@ece.iisc.ernet.in

A. Mishra et al. (eds.), *Silicon Photonics & High Performance Computing*,
Advances in Intelligent Systems and Computing 718,
https://doi.org/10.1007/978-981-10-7656-5_14

1 Introduction

In present days, sensor technology has become a vast concept and is grabbing the world's attention toward it. A number of innovative terminologies related to the field of sensors is evolving day to day. The updating of terminologies in sensor technology is leading to modify the existing design; many dissertation works are carried under reputed research and development centers, universities. These canters are providing a platform for research scholars in the field of sensor technology. Flexible designs are evolving with the technology improvement.

Interferometry with a medium of electromagnetic waves is considered and superimposed for extracting the information about waves. The optical fiber is a device that uses the effect of interference [1]. Here an input beam is split into two with the use of beam splitter and some of these beams are exposed to external influences such as length change or refractive index change in the transparent medium [2]. The beams are recombined by a beam coupler. In the design two mandrels are used, one is considered as reference mandrel which provides results under ideal conditions and another is a sensing mandrel, whose output is to be measured. Reference mandrel is designed such that, it does not respond to any of the environmental changes. But sensing mandrel will respond to changes that are occurred naturally. Sensing mandrel is designed to be placed in underwater; hence, it is called as hydrophone [3] (Fig. 1).

The purpose of placing sensing mandrel in underwater is to detect the pressure variations known as acoustic pressure [4]. Different materials are considered in designing hydrophone they are Nylon, Aluminum, Polystyrene, Optic fiber, and Polyurethane. The design has to be feasible to suspend the hydrophone under the water at a depth of 200 m. Depending on requirements the depth may be varied [5].

The final output required from the hydrophone is sensitivity which is expressed in terms of decibels. To get the optimum sensitivity dimensional parameters are varied; such as effective length, diameter, and thickness. Finite element analysis [6] of hydrophone is performed to know the preferable design. Light form source is passed through an optic fiber that is wound in between Polystyrene and Polyurethane layers. While light is propagating through optic fiber the pressure load is applied to the sensor, change in phase is obtained. Change in the phase of both

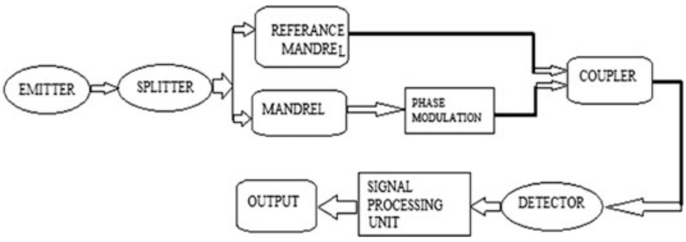


Fig. 1 Block diagram of phase change detection process

reference mandrel and sensing mandrel are coupled using a coupler and passed to the detector, where the output is converted into electrical signal and is processed in the signal processing unit [7]. Here, phase change is detected by comparing the output of both reference mandrel and sensing mandrel.

2 Mach–Zehnder Interferometric Principle

Mach–Zehnder interferometer [8] is shown in Fig. 2 Configuration of this kind represents a typical transmissive type fiber optic hydrophone. It can be used to build a transmission-type sensor array. Here, laser light is split into two beams by the first fiber beam splitter, one is entering sensing arm and the other is entering reference arm. In a single sensor case, the sensor head in the sensing arm is placed in the sensing environment. The reference arm provides the phase under the ideal condition and it can stay with all other components of the system at the "dry" end. Near the output end of the second fiber coupler, the two beams are sent to a photodetector in a combined manner, which produces an electrical signal resulting from the interference of the signals of sensing and reference beams at the receiver circuit.

3 Basics of Finite Element Analysis

Eventually, each and every phenomenon in nature related to biological, geological or mathematical can be defined with aid of laws of physics. Historical background related aspects are required for the mathematical formulation of the physical process. Formulation results in form of mathematical statements [9], often differential equations relating quantities of interest in understanding and design of the physical process. Assumptions related to proceedings of work carried are needed for the development of the physical process. Derivation of governing equation for a complex problem is not so difficult [10]. Finding their solution by exact analysis is a time-consuming job. The value of desired unknown quantities at any location in a

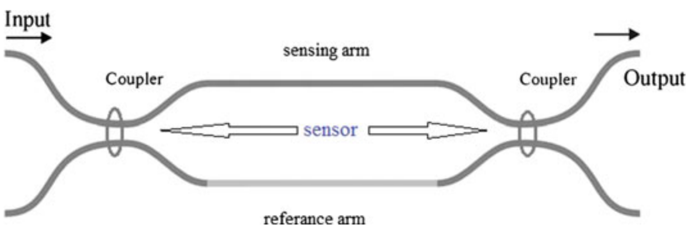


Fig. 2 Fiber optic hydrophone based on the principle of Mach–Zehnder interferometer

body can be found using analytical solution which is in the form of mathematical expression. For idealized and simplified situations analytical solution can be easily obtained.

4 Modeling and Design

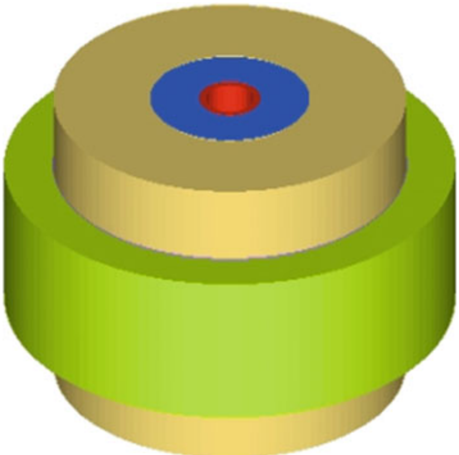
1. Preparation of CAD model using CATIA V5 R20.
2. Meshing the model by using Altair's HYPERMESH 12.
3. DECK prepared by using Altair's HYPERMESH 12.
4. Analysis is performed in ABAQUS CAE 6.10 solver.
5. Required output such as strain values can be viewed either using Altair's HYPERVIEW or ABAQUS CAE 6.10.

The optic fiber used is made of silica glass having diameter 125 micrometers which is wound around the polystyrene layer of the hydrophone. Material, total number of elements used, thickness of elements, and area occupied by these elements is shown in Table 1 (Figs. 3 and 4).

Table 1 Material, Elements, Area, and Thickness of layers

Sl/no	Material	Number of elements	Area occupied (mm^2)	Thickness (mm)
1	Nylon	744	4430.123	1.5
2	Aluminum	6138	10102.437	10
3	Polystyrene	26784	26635.680	20
4	Optic fiber	3600	13901.519	0.25
5	Polyurethane	9000	20966.297	10
Total assembly		46266	31117.624	

Fig. 3 CAD assembly of hydrophone 3



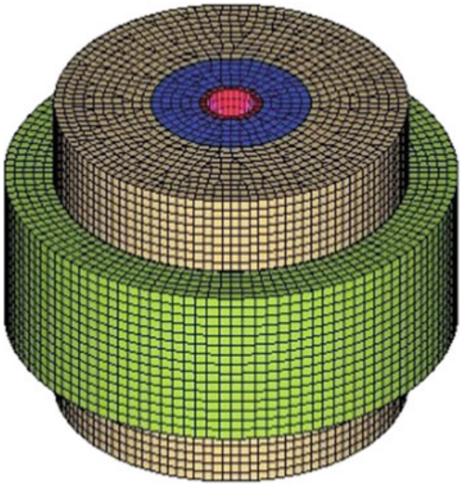


Fig. 4 Meshed model of hydrophone

5 Results and Discussion

5.1 Static Analysis of Sensing Mandrel

Static analysis is performed to know the variations in the sensing mandrel when it at rest with constant pressure loads on the outermost part of sensing mandrel. When the mandrel is placed in underwater condition at a depth of 200 m, it is assumed that a constant hydraulic pressure of 2 Mpa is applied. Results considered in this model are displacement model, axial strain model, radial strain model, and stresses in the model.

$$P = \rho g h,$$

where,

P density of medium = 1000 kg/m^2
g Gravitational force = 9.81 N
h Depth, = 200 m

P = 1000 × 9.81 × 200 = 1,962,000 = 1.962 Mpa

$$P = \sim \mathbf{2\,Mpa}$$

Sensitivity of hydrophone can be found using the following relations, where φ is the phase of light propagating, P is externally applied acoustic pressure, also S_r = 1 rad/µPa, n is the refractive index of fiber core and ε_r **is** radial strain acting on the surface, ε_z is the axial strain resulting the externally applied acoustic pressure.

$$\Delta\varphi/\varphi = \varepsilon_r + \varepsilon_z - n^2/2 \cdot [(p_{11} + p_{12}) \cdot \varepsilon_{\mathbf{r}} + p_{12}\, \varepsilon_z],$$

where

$\boldsymbol{\varepsilon_r}$ = 1.648×10^{-3},
$\boldsymbol{\varepsilon_z}$ = 5.954×10^{-4},
P_{11} = 0.121,
P_{12} = 0.27,

$$S_m = \Delta\varphi/p$$

Sensitivity of hydrophone is given by, $S = 20 \log (S_m/S_r)$, where $S_r = 1\mu$/rad

$$S = 20 \log (S_m).$$

5.2 *Influence of Geometric Properties on Sensitivity of Hydrophone*

Geometry of hydrophone affects the sensitivity with the following parameters

- Inner to outer diameter ratio
- Outer diameter
- Thickness of foaming layer
- Optic fiber length

The below shown figure gives the brief idea that how sensitivity is affected. Here, when the hallow diameter is for hydrophone is taken as zero or no hallow diameter sensitivity was seen comparatively less. Whereas with a hallow diameter sensitivity was seen to be improved. When the inner to outer diameter ratio was varied with the variable length of optic fiber increase in sensitivity was achieved. Variation is shown in the below figure. Constant improvement in sensitivity was achieved till inner to outer diameter ratio of 65%, above the sensitivity improvement is but this improvement is because of variable length of the optic fiber.

Fiber optic length is directly in relation with the phase change of light (φ), so that change in optic fiber length results in a change in sensitivity. The figure shown below indicates that, as the length of optic fiber increases sensitivity increases. But it is not possible to consider the higher length of the optic fiber, because with an increase in the length of the optic fiber effective length of mandrel increases and which affects the light propagation through optic fiber (Figs. 5, 6, 7 and 8).

Outer diameter is also a parameter that affects the sensitivity of hydrophone. Without considering inner (hallow) diameter sensitivity produced is comparatively less. But when inner hallow diameter considered increase in sensitivity is achieved. Even with the increase in outer diameter, length of optic fiber wound around the outer diameter increases which in turn increase sensitivity.

Fig. 5 Sensitivity versus inner to outer diameter ratio

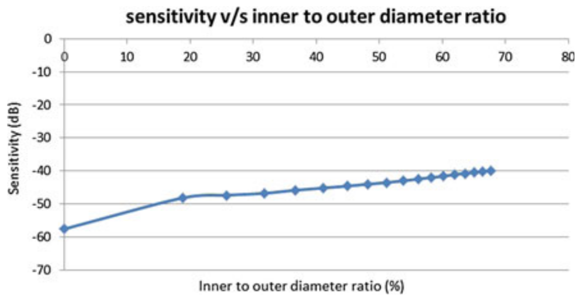


Fig. 6 Length of optic fiber versus sensitivity

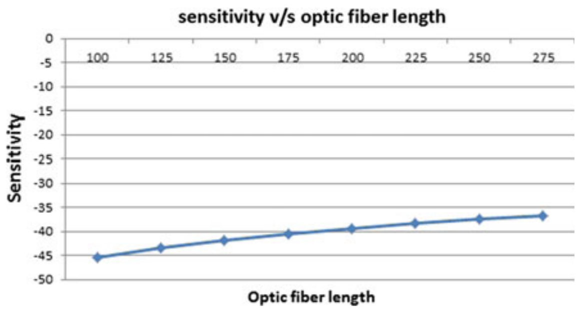


Fig. 7 Sensitivity versus outer diameter

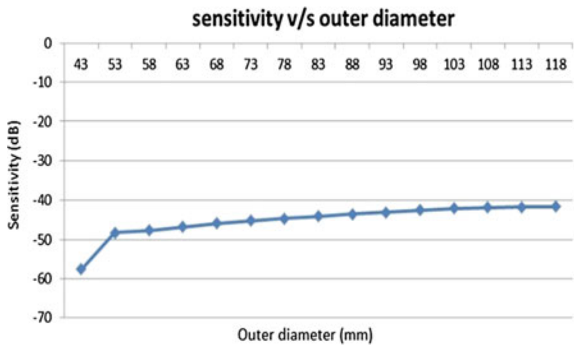
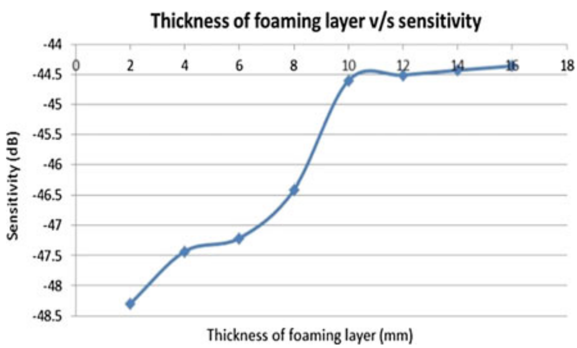


Fig. 8 Sensitivity versus thickness of foaming layer



Similarly, when the polystyrene material is used that allows the optic fiber to flexibly move (stretch), and thus, it can sense the acoustical pressure applied. As the thickness of foaming layer increases sensitivity also increases till it reaches (thickness of aluminum to thickness of polystyrene) 1:1 ratio. Even after that sensitivity increases slightly this is because of increase in outer diameter of sensing mandrel.

Also material properties have an influence on the sensitivity of hydrophone.

- Young's modulus,
- Poisson's ratio,
- Type of material (ductile or brittle).

Material properties also affect the sensitivity of hydrophone. Materials which are flexible in nature will tend to behave as ductile, which means they deform elastically. The materials which are having lowest young's modulus can stretch with small loads. Hence, the layer between optic fiber and aluminum must have lowest young's modulus. So many materials are there which have lowest young's modulus; among them, some of them are used to find sensitivity. Polystyrene is one which gives more sensitivity about −43.56 dB. Poisson's of individual material will not affect the sensitivity, but there will be slight variation about 1–2 dB.

Sometimes variation in sensitivity is too small that can be neglected. If the material used is ductile material then strain is produced, whereas when the brittle material is used more acoustical pressure load is required to produce strain (Figs. 9 and 10).

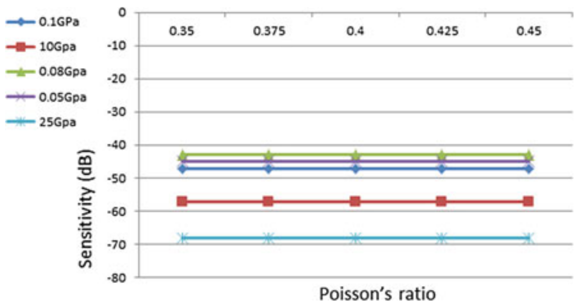


Fig. 9 Sensitivity versus Poisson's ratio

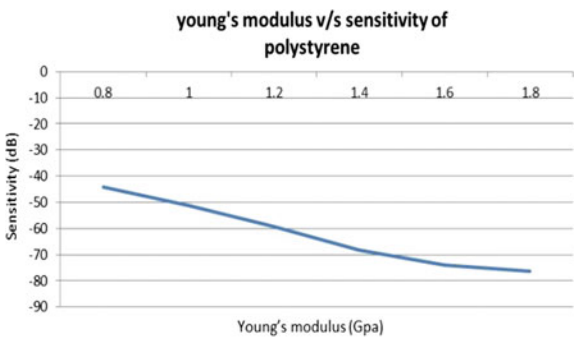


Fig. 10 Young's modulus versus sensitivity

6 Conclusion

This project outlines the finite element analysis of Mach–Zehnder fiber optic Hydrophone. Design indicates the structure of concentric composite mandrel. The foaming layer of polystyrene is used with base material as Aluminum. The hydrophone is designed to have fundamental natural frequency over 2.5 kHz was achieved from the subsequent analytical test. Better sensitivity was achieved when it is underwater at a depth of 200 m. While designing hydrophone the parameters considered are material properties of Polystyrene layer, Aluminum layer, Optic fiber, and Polyurethane layers along with the geometry of hydrophone. By viewing and analyzing the results, it is found that sensitivity has drastically improved. During the design properties of the material used showed that, Polystyrene (foaming layer) of the mandrel is having lowest young's modulus with respective Poisson's ratio.

In the design, by varying effective length and thickness of optic fiber considerable change in sensitivity was obtained. The mandrel is designed for resonance frequency about 15 kHz with the optimal design of concentric composite mandrel, the sensitivity of −43.27 dB is obtained with respect to $S_r = 1$ rad/μPa for the applied pressure load of 2 Mpa. The results shown have 20 dB increased sensitivity over conventional hollow cylindrical mandrel type hydrophone.

Acknowledgements We, acknowledge Vision Group on Science & Technology (VGST), Govt. of Karnataka for providing research fund to carry out the work presented in this paper.

References

1. Africk S, Burton T, Jameson P, Ordubadi A (1981) Design studies for fiber optic hydrophones. Report No. 4658. Bolt, Beranek & Newman, Inc., Cambridge, Mass
2. Hughes R, Jarzynski J (1980) Static pressure sensitivity amplification in interferometric fiber optic hydrophones. Appl Optics 19(1):1
3. Im J-i, Roh Y (1999) A finite element analysis of an Interferometric optical fiber hydrophone. Am J Eng Res
4. Hocker GB (1979) Fiber optic sensing of pressure and temperature. Appl Opt 18(9):1445
5. Wang Z, Hu Y, Meng Z, Ni M, Luo H (2010) College of Photoelectric Science and Engineering, National University of Defense Technology, 410073, P. R. China
6. Stockbridge N (2007) Fiber optic hydrophones. Winfrith Technology Centre, Winfrith Newburgh, Dorchester, vol 6619, 661907-2
7. Shahrieel M, Aras M, Mazni M, Hairi H, Jamaluddin MH (2010) Development of hydrophone sensor system for autonomous underwater vehicle application. In: Second international conference on engineering and ICT
8. Mach-Zehnder Interferometer sensor for acoustic detection with optimal performance. IOSR J Electron Commun Eng (IOSRJECE) 2(5):29–33, ISSN: 2278–2834 (2012)
9. Arshad MR (2009) Indian J Mar Sci 38:267–273
10. Lagakos AN, Hickman TR, Ehrenfeuchter P, Bucaro JA (1991) Planar flexible fiber-optic acoustic sensors. In: Proceedings of the 34th midwest symposium on circuits and systems, vol 56, pp 666–671