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Structural and Material Analysis of Acousto-Optic Sensing Mandrel Using FEA Technique for Higher Sensitivity

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***Abstract* - This paper frameworks the design of Acousto-optic Hydrophone by using the finite element solver COMSOL Multiphysics tool. An optical fiber wound hydrophone intended for studying the effect of underwater acoustic pressure on the effective refractive index ($n$eff) of single mode light and obtain a better sensitivity occurring inside a frequency range. The optical fiber wound hydrophone composite of a coil of fiber wound on mandrel for extracting the information by probing the phase variation of light passing through the coil due to variant in both the length and refractive index of the optical fiber as pressure is applied to mandrel. The optimal structure is used to determine the influence of both the geometrical parameters of the mandrel and material properties of frothing layer. The geometrical parameters included diameter of the mandrel and the analysis was further carried out to determine the influence of frothing layer on the performance of hydrophone. The analysis results indicated that for a higher sensitivity, a hydrophone requires larger diameter possible for mandrel and afrothing layer coating. The sensitivity obtained for a mandrel diameter of 4cm, without frothing layer is -82.22 dB and with frothing layer is -77.15 dB, thus obtaining a sensitivity of 5dB higher with frothing layer marks its efficiency.**

***Keywords:* (Acousto-optic Hydrophone, mandrel, Acoustic sensitivity, frothing layer)**

I. INTRODUCTION

An optic fiber hydrophone finds enormous application in underwater acoustic sensing since the late 1970's; because of

low cost, reduced weight and low power consumption as a result there is a growing interest in research areas to develop a productive and profitable hydrophone for military purposes. The paper proposes to introduce an acousto- optic hydrophone that provides improvedsensitivity.

The fibre optic hydrophone was first developed in 1977 subsequently significant efforts in discovering first operational optic fibre sonar systems for military purposes were taken during the 1980s and 90s. By 2004, large aperture fibre optic planar hull array was deployed in submarines by US Navy [1], and further the research is continued to develop miniaturized hydrophones to incorporate in large arrays of sensors. The impact of structural parameters on the enactment of an optical fiber twisted mandrel hydrophone is investigated by means of Finite Element Method (FEM). A hydrophone should possess highest probable sensitivity, the broadest possible flat frequency response and an Omni-directional sensitivity pattern insidea frequency range [2]. Nevertheless, in the previous works only a basic form of hydrophone was discussed in-spite of having the advantage ofreliability; simplicity and robustness, its sensitivity to acoustic fields are low. Thus in [3], a concentric composite mandrel twisted with optical fiber is proposed which is composed of double layers, a thin foaming layer on top of a base layer and a centre hole. The frothing layer is more flexible than the base layer, thus radically improving the sensitivity of the sensor due to its superior compliance.

In this paper the authors have analysed two different structures of optic-fiber hydrophone to improve the sensitivity; one which has a mandrel with optical fiber twisted around it and second has a mandrel coated with foaming layer to improve the sensitivity of the acoustic sensor. In both the cases the geometrical parameters of the mandrel are varied to analyse if it improves the sensitivity. The geometrical

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parameters of the mandrel include its diameter. The use of this tactic opens up abundant design possibilities that have not been stated before. The improvement in the sensitivity is observed with consideration of the underwater parameters. The second section of this paper gives the design and implementation details of the hydrophone, followed by mathematical validation of the structures in the third section. The fourth section gives a detailed analysis of the simulation results.

II. DESIGN AND IMPLEMENTATION

A comprehensive description of design and implementation of two different structures of optical fiber wound hydrophone is discussed. Models were designed and simulated using COMSOL MULTIPHYSICS Tool. Performance factor such as acoustic sensitivity was analysed.

2.1. Optical fiber wound hydrophone without frothing layer

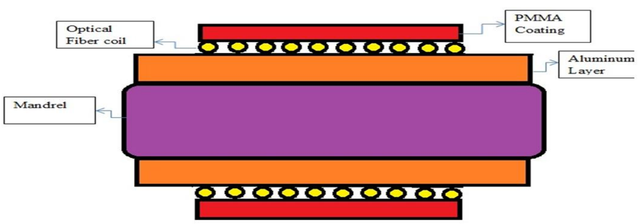

Fig. 1. Optical fiber wound hydrophone without frothing layer.

The mandrel designed acts as a major part of the hydrophone which is suspended at100m below the water surface for detecting the acoustic pressure. It is in cylindrical shape with height of 8cm, material used is Nylon surrounded by Aluminium layer of 2cm diameter for mandrel protection then an optical fiber of 10 turns is wound on the mandrel and PMMA material of 1cm is coated on fiber for protection in case of severe stress applied. The structure in fig 1 is the basic design of hydrophone constructed with the required acoustic parameters in consideration.

2.2. Optical fiber wound hydrophone with frothing layer

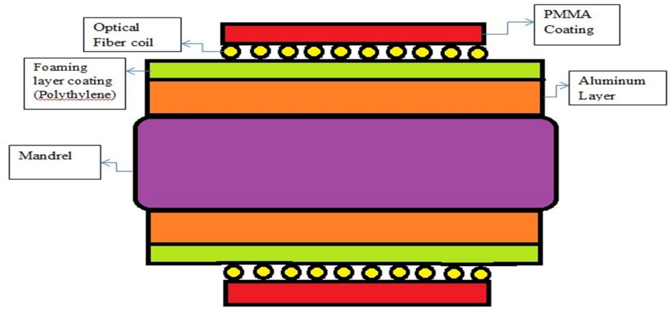

Fig. 2. Optical fiber wound hydrophone with frothing layer.

The model in fig 1 has been varied in order to obtain improved sensitivity as shown in fig 2. A layer of frothing material such as Polyethylene of 1cm diameter is coated on top of aluminium layer. It is observed that as frothing layer is more flexible than base layer there is improvement in sensitivity. The properties of different materials used in the analysis of Hydrophone are listed in Table 1.

Table 1
Material properties

	Material	*E*(Pa)	Density	Poisson's ratio
Mandrel	Nylon	$2x10^9$	1150K g/m^3	0.4
Protection shield	Aluminium	$70x10^9$	2700K g/m^3	0.33
Frothing layer	Polyethylene	$1x10^9$	930K g/m^3	0.4
Fiber Core	Silica-glass	74.8	2.203g/cc	0.19
Fiber protection Shield	PMMA	$3x10^9$	1190K g/m^3	0.4

III. MATHEMATICAL MODELLING

The acoustic pressure sensed by hydrophone depends on the density of the medium, gravitational force and the depth at which the sensor is suspended.

$$P = \boldsymbol{\rho} gh \qquad (1)$$

$\boldsymbol{\rho}$ = density of water = 999.7 $\mathbf{Kg}/\boldsymbol{m^3}$; h = depth = 100m; g = gravitational force = 9.81 N. thus a pressure of 979706 Pascal is applied on the sensor.

The acoustic sensitivity for the mandrel hydrophone can be obtained by considering the phase sensitivity of an optical fiber which is normalized to the total static phase given by,

$$\frac{\Delta\varphi}{\varphi} = \varepsilon_z - \frac{n^2}{2}[(P_{11}+P_{12})\varepsilon_r + P_{12}\varepsilon_z] \qquad (2)$$

$\Delta\varphi$= Change in phase induced by a change in the strain on the fiber; φ = static phase; n = index of refraction; P_{ij} = pockel's coefficients of unclad fiber, (P_{11} = 0.121, P_{12} =

0.27); ε_r = radial strains of optic sensor; ε_z = axial strains of optic sensor.

Thus the acoustic sensitivity per unit of sound pressure is obtained as,

$$S = 20 \log \left({}^{S_m}/_{S_r} \right) \text{ dB} \qquad (3)$$

Where $\mathbf{S_m} = \left(\frac{\Delta\varphi}{P}\right)$; $\mathbf{S_r}$ = 1μ/rad.

IV. RESULTS

The main end results was concentrated on static phase, radial and axial strains, phase sensitivity of optical fiber and acoustic sensitivities for both considered models which are illustrated below. The simulated view of optical fiber wound hydrophone using COMSOL Multiphysics tool is as shown in the figure 3 and comparison of different parameters is provided in table 2.

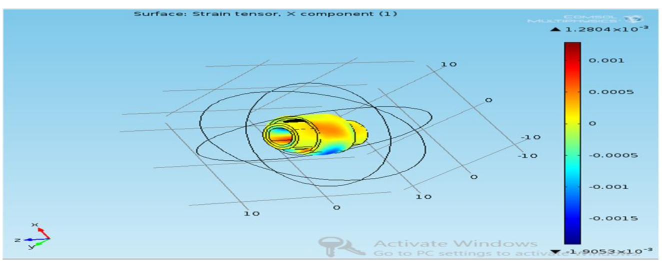

Fig. 3. Simulation result of optical fiber wound hydrophone

Table 2
Comparative study analysis on structural and material properties of hydrophone

Mandrel	Without frothing layer			with frothing layer		
Diameter (cm)	ε_r(m)	ε_z(m)	S (dB)	ε_r(m)	ε_z(m)	S (dB)
4	8.855×10^{-4}	2.5653×10^{-5}	-82.22	1.482×10^{-3}	2.829×10^{-5}	-77.15
3.5	4.562×10^{-4}	4.018×10^{-5}	-90.63	6.982×10^{-4}	1.154×10^{-4}	-86.93
3	2.679×10^{-4}	2.904×10^{-5}	-96.35	3.988×10^{-4}	1.18×10^{-4}	-95.72
2.5	2.564×10^{-4}	3.152×10^{-5}	-97.93	4.355×10^{-4}	1.968×10^{-4}	-102.41
2	2.786×10^{-4}	5.525×10^{-5}	-99.75	4.160×10^{-4}	1.893×10^{-4}	-103.88

V. CONCLUSION

This project outlines the design, simulation and comparative study on structural and material properties of optical fiber wound hydrophone for enhanced sensitivity. An analysis was carried on by varying the structural parameter of hydrophone such as diameter of mandrel and material property by the inclusion of frothing layer Polyethylene. The acoustic sensitivity obtained for a mandrel diameter of 4cm, without frothing layer is -82.22 dBand with frothing layer is **-** 77.15 dB showing an increase of 5dB**.** The sensor exhibits Omni-directional characteristics concentrated within a frequency range up to 5 KHz. Thus the optical hydrophone with higher diameter possible for mandrel and frothing layer coating provides improvement in acoustic sensitivity than the conventional hydrophone.

VI. ACKNOWLWDGEMENT

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