Performance Analysis of Fiber Optic Sensing Mandrel for Underwater Acoustic Signal with ANSYS

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***Abstract*-The proposed paper outlines the design and development of fiber optic sensor using principle of interferometry. In the design, optical light waves are used to extract information. Two parallel mandrels are used where one is the sensing mandrel and another is the anti-sensing mandrel. The mandrel is designed underwater to detect acoustic pressure. Sensing mandrel is referred to as hydrophone which detects the sound underwater. The optical hydrophone is made up of different materials. The different materials used are elastic foam layer, polyurethane, aluminum and nylon. The hydrophone is suspended 200 meters below water surface. The physical properties of the sensing mandrel are varied to select the design that gives optimum minimal sensitivity. The hydrophone is also referred to as fiber optic mandrel since optical fiber is wound on the mandrel. The design is made using ANSYS 12.0, EDA tool. The sensitivity obtained is -64.92 dB for a pressure of 2 MPa.**

Keywords— Interferometry, Mandrel, Hydrophone, ANSYS, EDA Tool, MZI.

1. Introduction

Fiber optic sensing is a subject that has attracted considerable interest in recent years. A finite element analysis of an interferometric optical fiber hydrophone for underwater acoustic sensing was included in a previous work. However; the hydrophone outlined in the previous work was only a simple format, consisting of an optical fiber coil wounded in a homogeneous solid cylindrical mandrel with a thin polymer layer to protect the fiber. Interaction with acoustic wave effects the deformation in the mandrel, resulting in a change in the optical length of the fiber coil which is subsequently detected as a phase variation induced in the light passing through the fiber winding. Also this design has the benefit of simplicity, reliability, and compactness, its intrinsic sensitivity to acoustic fields is relatively low. Accordingly, this paper describes a concentric composite mandrel-type optical fiber sensor that can produce a better performance to the basic cylindrical mandrel sensor. The mandrel should be as compliant as possible to enhance the interaction with the acoustic fields. However, a solid mandrel must also support the weight of whole sensor; thus, for the sake of stability it cannot be too wider. To solve these drawbacks, several attempts have been made to make the mandrel appear easier in its overall properties. Therefore a concentric composite structured mandrel is proposed as an alternative that can improve sensitivity while maintaining structural stability. A mixed composite mandrel consists of double layers (a thin foaming layer on top of a base layer) and a center hole. The center hollow space is a commonly employed method for enlarging the deformation of the mandrel. The originality of proposed design is the addition of a compliant foaming layer. The foaming layer also called as soft rubber is more flexible than the base layer, and is expected to radically improve the acoustic sensitivity of the sensing mandrel due to its uniform compliance.

2. Architecture of Sensing Mandrel

The direct view of optical fiber wounded on a composite concentric mandrel using MZI [1-2] principle is as shown in Fig. 2. It consists of total five layers which are made up of different materials having different young modulus and bulk modulus, the first layer from Nylon material which is the inner diameter of the mandrel with a thickness of 0.25cm, the second layer is made of Aluminum (Al) metal which acts as a supporting structure for the entire mandrel, the thickness of Al layer is 2cm, the third layer is made up of foam material i.e., the foaming layer (Soft Elastic), the thickness of foaming layer is 1cm, this acts as flexible material supporting the optical fiber deformations or molding, the optical fiber is coveted between foaming layer and the Polyurethane coating of 1cm thickness. So when an acoustic event impinges on the effective length Leff of sensor, the pressure exerted by the acoustic wave on the sensor is influenced by the elastic polyurethane coating and this makes an efficient impact of stress & strain on the optical fiber which causes some slight deformation on the fiber, Consequently there is a change in length and diameter of the optical fiber, this in turn causes change in optical path and changes the phase of the light emitted from Laser. The change in phase after the exerted pressure can be found out by a technique known as Mach-Zehnder Interferometry. Fig. 1 shows the Mach-Zehnder Interferometer (MZI) principle. The input light signal is split by splitter and passed into optical fiber wounded sensing and reference arm, when pressure is applied on sensing arm, phase changes in light happen due to changes in light path. Output of sensing arm and reference arm are taken and passed through coupler where phase changes in light can be evaluated by suitable mechanism.

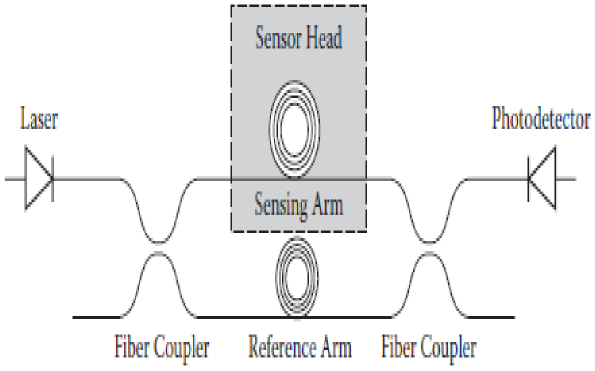

Figure 1. Mach-Zehnder Interferometer Principle

In a composite fiber wounded mandrel of MZI Sensor, a thin jacket fiber is typically wrapped around a compliant mandrel and thin elastic polyurethane is coated over the fiber as protection during operation. The optical fiber measures the acoustic pressure-induced strain in the mandrel and protecting layer. Mandrel sensors are important because they are easy to produce and they exhibit a high sensitivity and amenability to spatial shading. Fig. 3 shows the schematic cross sectional view of novel MZI optical fiber wounded concentric composite mandrel.

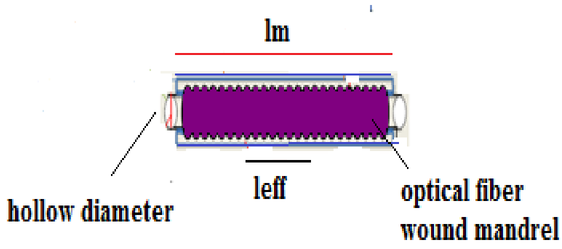

Figure 2. Direct view of the concentric Composite Mandrel

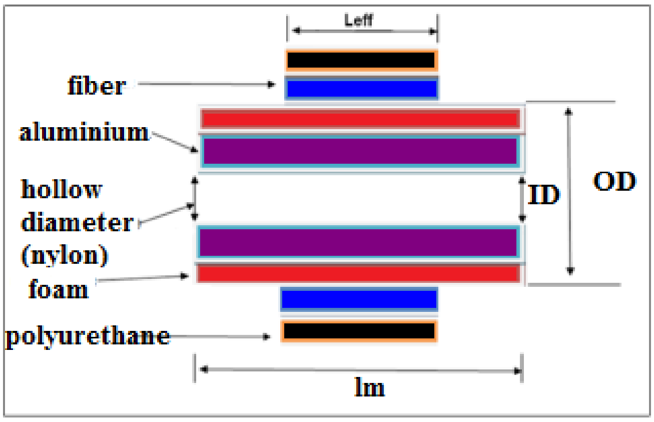

Figure 3. Cross sectional view of Novel MZI optical fiber wounded concentric composite mandrel

Fig. 3 shows the designed fiber optic sensing mandrel, with direct view of concentric structure. The next chapter discussed the mathematical design constrain with complete structural and material analysis.

3. Design Consideration

The layout and design of above design mandrel has significant changes, i.e. as we know from the basic concepts of the molecular physics that as area increases pressure exerted decreases and as area decreases pressure exerted increases, in the above mandrel the polyurethane and optical fiber layers have been specifically placed at the center of the overall length of the mandrel and its design is restricted for the effective length Leff so that whenever an acoustic even has occurred the acoustic pressure exerted by the wave will hammer the (Leff) effective length of the mandrel , so we get a good acoustic sensitivity underwater as compared to the other designs where in the polyurethane polymer layer and optical fiber are spread across the overall length of the mandrel. A pressure P striking with the fiber induces a change in phase $\Delta\phi/P$ and is given by

$$\nabla\phi/P = kn\Delta L + Lk\Delta n \quad (1)$$

Where the first term corresponds to the change in the length of the fiber means optical path length and the second term corresponds to the photo elastic effect i.e. refractive index. This photo elastic effect describes the relevance between the mechanical strain [3] in the fiber and the resulting change in the refractive index of the fiber core. Therefore, the pressure sensitivity of the fiber optic sensor per unit of air pressure becomes

$$\nabla\phi/\phi = z - n^2/2\ [(P_{11} + P_{12)\ r} + P_{12}\ z \quad (2)$$

Equation (2) indicates that the phase change of the sensing mandrel can be found, as we find the appropriate strain distribution in relation to the unit of applied pressure, which then leads to the analysis of the fiber optic sensor performance.

4. Theoretical Pressure Sensitivity Calculation

The sensing mandrel is made up from the fiber optic winding with polyurethane coating, to calculate the no. of turns required to get optimum sensitivity as follows:

From the formula:

$$l = 2\pi RN \quad (3)$$

Where, *R* - Distance from the center of the mandrel to modified fiber wrapped on it.

N – No. of turns of winding fiber on the mandrel

l – Total length of fiber wrapped around the mandrel

Length of the mandrel = 6cm

Effective length of the fiber winding = 3cm

Hollow radius of the mandrel= 1cm

Radial thickness of the nylon= 0.15cm

Radial thickness of the aluminum= 1cm

Radial thickness of the foam= 2cm

Radial thickness of the fiber= 0.5cm

So, Assume total length of fiber (*l*) = 150 meters.

Radius of the mandrel (R) = $4.15*10^{-2}$ meters.

From Equation (1):

150 = 2*3.14*4.15*N

N= 150 /6.28*4.15*10^-2 = 575.55 Turns.

Phase induced in fiber is given by,

$$\Phi = nk_0 l = n * \frac{2\Pi}{\lambda} * l \quad (4)$$

Where, n – Refractive index of the core = 1.46

λ - Wavelength of the light propagating through the light = 1550nano meters

l - Length of the fiber wrapped around the mandrel = 150 meters

$\phi = 1.46 * 2*3.14*150 / 1550*10^{-09}$

$\phi = 887*10^6$ degrees.

To convert into degrees, multiply by $\pi/180$.

$\phi = 1.548*10^7$ Radians

$\nabla\phi / \phi = \; _{Z} - (n^2/2 [(P_{11} + P_{12}) €r_{+} P_{12} €z)]$ (5)

where, $€z = 7.10*10^{-3}$, $€r = 1.82*10^{-3}$

$\nabla\phi / \phi = 7.10*10^{-03} - (1.46)^2/2 [(0.121+0.27)* 1.82*10^{-3} + (0.27*7.10*10^{-03})]$

$\phi / 1.548*10^7 = 4.30*10^{-03}$

$\phi = 66650$ Degrees

To convert into degrees, multiply by $\pi/180$

$\phi = 1161$ Radians.

$Sm = \Delta\phi/P$ (6)

Assume P= Pressure (2 Mega Pascal)

$Sm = 1161/2*10^6$

$Sm = 5.805*10^{-04}$

Sensitivity =20 log (Sm/Sr) (7)

Sr = 1radian/Micro Pascal

S (dB) = 20 log ($5.805*10^{-04}$/ Micro Pascal)

So, Pressure Sensitivity = -64.72 dB

The design and performance analysis of hydrophone is done using ANSYS 12.0, EDA software [6].

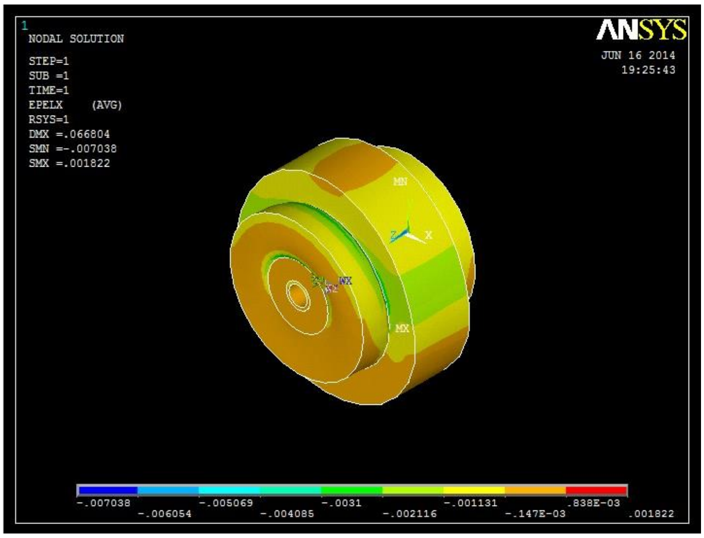

Figure 4. ANSYS Simulation of Radial strain

We perform the static analysis using a fundamental resonance frequency of 15 KHz with a depth of 200 meters underwater and applying a basic pressure of 2MPa. The deformation changes in mandrel causes the axial and radial strain values of optical fiber. From the Fig. 4 and 5, we can see the deformation changes in mandrel which affects the radial strain and axial strain in optical fiber. Fig. 4 & 5 are the snap shots of the designed sensing mandrel in the ANSYS Cad tool, the simulation results of both axial strain and radial strain were obtained in ANSYS 12.0

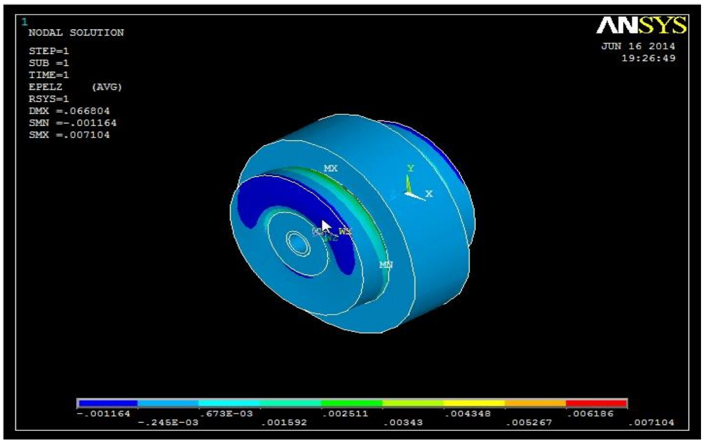

Figure 5. ANSYS Simulation of Axial Strain

By the above analysis, we achieved an improved sensitivity near about 9dB. The foaming layer [3-7] is more flexible than the base layer Al, by sandwiching the optical fiber in between the foaming layer and the outer polyurethane elastic polymer layer improved the radial pressure sensitivity due to its superior compliance [8].

5. Results & Discussion

In this paper, various performance evaluation parameters such as material parameter like diameter, young modulus, bulk modulus etc and structural parameter like, thickness, length etc. with respect to pressure sensitivity are studied and simulated the performance parameters include such as length of Mandrel, Wavelength, and Young Modulus (E) [7-8] of foaming layer for radial pressure. This analysis and simulation report give the evidence for highest possible value of sensitivity of optical fiber based on interferometer principle which shows the optimized performance of the mandrel w.r.t Young modulus of the foaming layer. In this study, the mandrel hydrophone was required to have a fundamental resonance frequency of 15 kHz and the optical fiber was required to maintain a constant length of 150rn. Before conducting a detailed analysis of the hydro- phone response a preliminary modal analysis was performed so that the range of the main calculations could be established beforehand, even though a rough estimate.

Table 1 shows the iteration process of calculation of acoustic pressure sensitivity for different polyurethane coating thickness. It shows that for a material having a length of 6cm, fiber thickness of 0.5cm and polymer thickness of 1cm gives a higher sensitivity of -64.72dB.

Table 1. Iteration for thickness of Polyurethane

Pressure (P)	Length	Fiber Thickness	Thickness of polyurethane	Sensitivity (dB)
2	6	0.5	0.1	-65.43
2	6	0.5	0.2	-65.21
2	6	0.5	0.3	-65.05
2	6	0.5	0.4	-64.93
2	6	0.5	0.5	-64.85
2	6	0.5	0.8	-64.73
2	6	0.5	1	**-64.72**

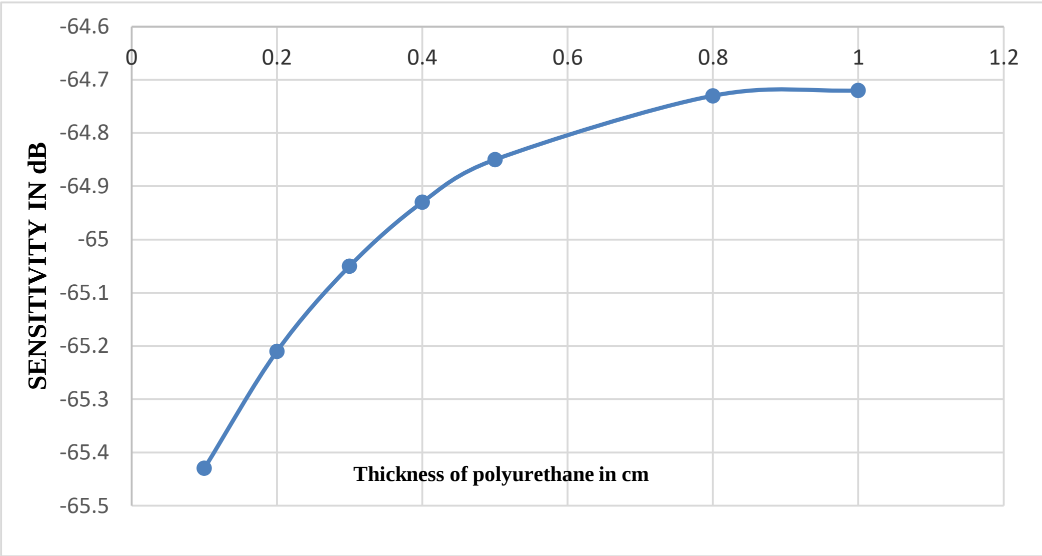

Figure 6. Thickness of Polyurethane versus Sensitivity

Figure 6 shows the graph of sensitivity versus different polyurethane coating thickness, which indicates as the polymer thickness decreases, acoustic pressure sensitivity gets affected.

	A	B	C	D	E	F
14						
15				Thickness of fiber	0.5	cm
16				Hollow Diameter	1	cm
17				Thickness of Aluminium	1	cm
18				Thickness of Teflon	0.15	cm
19				Hollow Radius	0.5	cm
20				OD of the Foam	2	cm
21				Leff of the fiber	0.03	m
22				Radius of Mandrel	0.0415	m
23				No. of turns of fiber	575.55061	
24				Refractive index , n	1.46	
25				wavelength of light, λ	1.55E-06	nm
26				length of the fiber, l	150	m
27				Elastoopic constants, p_{11}	0.121	
28				Elastoopic constants, p_{12}	0.27	
29				Radial Strain, ε_r	1.82E-03	
30				Axial Strain, ε_z	7.10E-03	
31				n square by 2	1.0658	
32				Phase induced, ϕ	1.548E+07	
33				Δϕ/ϕ	4.30E-03	
34				Δϕ	1161	rad
35				Pressure, p	2.00E+06	MPa
36				S_m	0.00058059	
37				Pressure Sensitivity	-64.72	

Figure 7. Snapshot of excel sheet used for sensitivity calculation

Above Fig. 7 shows excel sheet status of performance of acoustic pressure sensitivity calculation with various material and structural properties of fiber optic sensing mandrel. The maximum allowable dimension of the mandrel was determined when its fundamental resonance frequency reached 15 kHz. However, the optical fiber cannot be wound as a single layer onto the mandrel surface due to its extended length; therefore, it is stacked as multiple layers. Since the fiber has a higher stiffness than the foaming or molding layers, a higher number of fiber layers around the mandrel strengthen the stiffening effect from the optical fiber, which decreases the sensitivity of the hydrophone . Consequently, a lower number of fiber layers are more desirable

6. Conclusion

The novel improved design of fiber optic sensing mandrel is obtained with dimensions of aluminum (1cm), hollow empty diameter (1cm), fiber thickness (0.5 cm), Polyurethane (1 cm), foaming layer (2 cm), length of mandrel (6 cm) and effective length (3 cm). The design gives a sensitivity of -64.72 after running various iterations. The designs can be improved by using different materials and performing various iterations to get the optimum sensitivity. Instead of aluminum layer on the mandrel, steel or any material with similar property can be used; Foaming layer can be replaced by any other elastic material like rubber. Similarly, various materials can be used and simulated for better results.

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