Acoustic - Structure Interaction Studies of Fiber Optic Mandrel Hydrophone using COMSOL Multiphysics

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Abstract: The field of underwater acoustics requires sensing solutions having high sensitivity and low noise. Several technologies are used in sensing various properties of the sub-marine environment, of which hydrophones are the most commonly used. Fiber optic hydrophones bring in more reliability and operational advantages to the underwater acoustic sensing market. For efficient performance of a fiber optic hydrophone, it is essential to consider the parameters like sensitivity and acoustic receiving bandwidth. Optimization of the performance parameters of fiber optic hydrophone is the major aim of this research work. To achieve an optimum design, FEM analysis using COMSOL Multiphysics® was used. The design was optimized using structural mechanics module. Finally, hydrophone with the optimized design was studied using the acoustic module. An acoustic sensitivity of -151.5 dB re V/µPa was achieved at 1 kHz with the present simulation.

Keywords: Fiber optic hydrophone, Acoustic sensitivity, Frequency response.

1. Introduction

Hydrophones are acoustic receivers, which are used for listening underwater sound produced from marine life, ships, submarines and from other sound sources in the sea. Commonly used hydrophones are based on piezo-ceramic transducer materials. With the introduction of fiber optic mandrel hydrophones, many drawbacks seen in piezo-ceramic hydrophones can be eliminated. The hydrophone research area is a challenging field, in which extreme sensitivity is required to meet very low acoustic detection levels in the presence of a very large hydrostatic pressure [Ref. 1]. Fiber optic mandrel hydrophones have been developed since early 1980s, started with bare fiber wrapped over solid plastic mandrels and later with different high compliance materials like Teflon or Nylon for higher sensitivities. Subsequently, air backed mandrels were used for further increase in the sensitivity. These hydrophones demonstrated promising sensitivity and low noise suitable for deep sea state sensing applications [Ref. 2-3] and also for high energy hadrons detection in underwater environment [Ref. 4]. Analytical theory for fiber optic mandrel hydrophone was proposed by Knudsen et al. [Ref. 5] which is valid for small deformations.

The sensitivity of the hydrophone is determined from the radial displacement of the mandrel shell corresponding to acoustic signals. The lowest radial mode vibration of thin cylindrical shell is referred as ‘breathing mode’. M. Anghinolfi et.al. [4], reports that this mode gives the major contribution to length change of fiber in an air-backed mandrel hydrophone. Analytical model of mandrel shell’s radial displacement and phase response are given in Ref. 4 and Ref. 5 respectively. The analytical results from Ref. 4 and numerical simulation results obtained after the present study are compared in this paper.

To predict the response of the hydrophone structure to acoustic pressure, a numerical modeling and simulation work was carried out which forms the theme of this paper. In this study, FEM analysis using acoustic and structural mechanics modules of COMSOL Multiphysics® was used. At first, the hydrophone geometry was created using structural mechanics module and Eigen frequency analysis was done to understand the resonance behaviour of the structure. Then frequency domain analysis was carried out for obtaining its frequency response. From the radial displacement obtained after frequency domain analysis, acoustic sensitivity was calculated using relations given in Ref.6. The details of this work are illustrated in this paper.

2. Fiber Optic Mandrel Hydrophone

One of the successful configurations of fiber optic hydrophones is the mandrel

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hydrophone, wherein few tens of meters of optical fiber is wound over a mandrel, made of a compliant material. When sound impinges on the mandrel shell, it undergoes expansion and contraction, which causes change in length of the fiber wound over it. The change in length is too small to be detected by any conventional methods and therefore special interferometric techniques are used for processing the signals arising from the hydrophone. Fiber optic mandrel type hydrophone consists of a laser source, splitter, two mandrels, coupler, photo detector and phase demodulator as shown in figure 1.

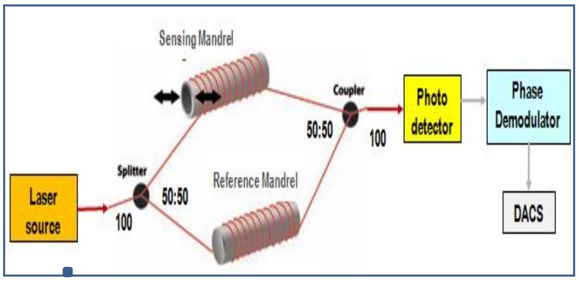


Figure 1. Block diagram of Fiber optic mandrel hydrophone system

Laser beam having low phase noise passes through a splitter and gets splitted into two parts. One part reaches the reference mandrel and other reaches the sensing mandrel which is immersed in water. The light from both the mandrels reaches the second coupler which combines the two beams to form an interferometer. The small acoustic pressure variations in water will change the length of the fiber wound over the sensing mandrel. This in turn introduces a phase shift in the interferometer output. Hence, an interferometer is built within the hydrophone sensor to identify and demodulate the minute phase changes arose due to the acoustic signal.

There are several interferometric configurations that are commonly used in fiber optic sensing applications. The most commonly used configurations are Mach-Zehnder interferometer and Michelson interferometer. Typically, these interferometric sensors achieve high responsivity by winding significant lengths of optical fiber around a compliant mandrel, where mandrel is usually a sealed air-filled metal or plastic tube. Interferometric technique is based on detecting the optical phase change induced as light propagates along the fiber. The two fiber paths recombine at the output of the sensor forming an interference pattern, which is depended on the phase difference between the two paths. A photodetector will convert the interference signal into electrical form. A phase demodulator can process this interference signal and can effectively demodulate the phase changes due to the acoustic signal.

Here, apart from the optical system complexities, the dynamic response of the mandrel shell is very important in getting optimum sensitivity and bandwidth of hydrophone for various applications. In this study, the dynamics of mandrel shell along with support structure was studied using COMSOL Multiphysics and optimum design was arrived.

3. Numerical Model and Simulation

3.1 Eigen frequency and frequency domain analyses using Structural mechanics module

Based on the technical requirements, geometry of the hydrophone was drawn in 2D axi-symmetric platform of COMSOL. Fine structures, grooves, etc. were de-featured and a smooth geometry was subjected to modeling. Free triangular meshing was given to the hydrophone structure as shown in figure 2. A minimum element quality of 0.5 was used and the maximum mesh size (D) used was 1/6th of the shortest wavelength (corresponding to 20 kHz) in the analysis. Using structural mechanics module, Eigen frequency analysis and frequency domain analysis were carried out. The material and dimensions of the mandrel hydrophone were optimized using different iterations of the model.

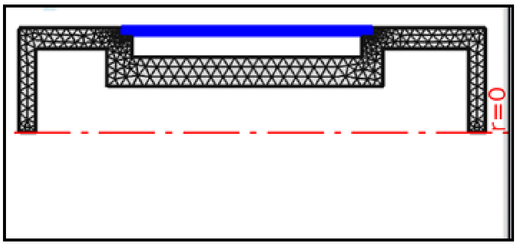
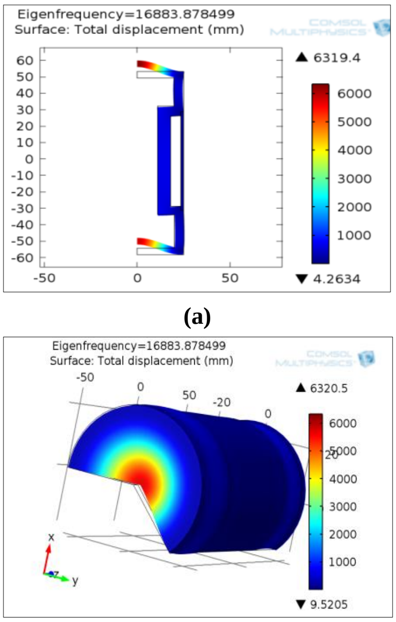


Figure 2. Meshed geometry of the hydrophone design in 2D Axi-symmetric study

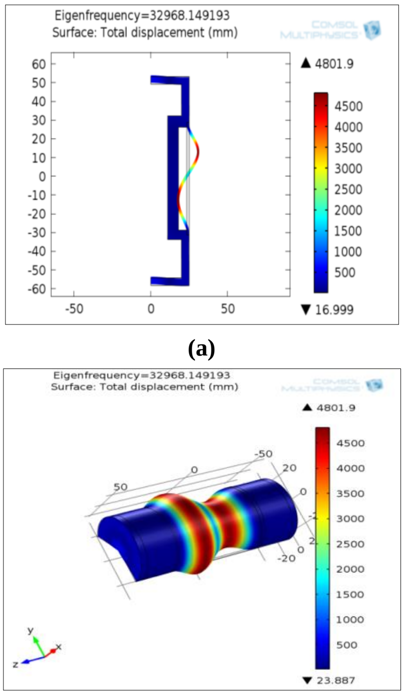
Eigen frequency analysis gave resonance modes of the hydrophone structure. The first prominent modes were found to be bending modes at 16 kHz and 32 kHz. The mode shapes of Eigen frequency analysis in 2D axi-symmetric and the 3D view generated from the 2D analysis are depicted in figures 3 and 4.



(a)

(b)

Figure 3. Prominent resonance mode at 16 kHz
a) 2D view b) 3D view



(a)

(b)

Figure 4. Prominent resonance mode at 32 kHz
a) 2D view b) 3D view

For frequency domain analysis, a harmonic "boundary load" was applied in terms of pressure with 1 Pa amplitude and zero radians initial phase. Then the radial displacement of the mandrel shell was calculated from the frequency domain analysis. With the help of this analysis, dynamic frequency response of the structure was understood and the result is given in figure 5.

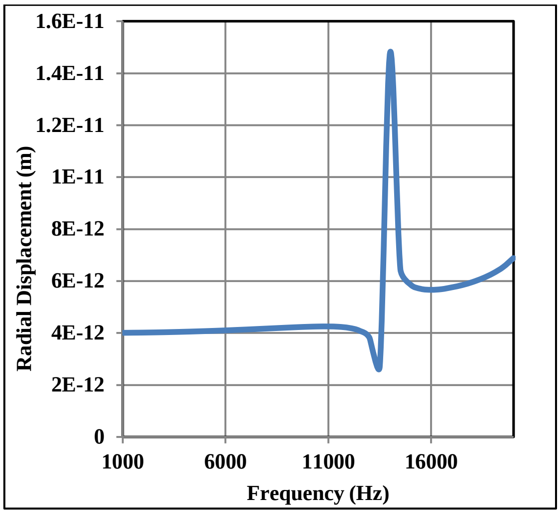


Figure 5. Radial displacement after frequency domain analysis in structural mechanics module

3.2 Acoustic-Structure Interaction study

Using the Acoustic- Structure Interaction Multiphysics coupling, the hydrophone structure was placed in a water domain. The "Pressure acoustics, frequency domain" tool was used to compute the pressure variations when modeling the propagation of acoustic waves in fluids. The frequency domain or time harmonic formulation uses the following inhomogeneous Helmholtz equation:

$$\nabla.\left(\frac{1}{\rho_c}(\nabla p - \boldsymbol{q})\right) - \frac{\omega^2 p}{\rho_c c_2^2} = Q \qquad (1)$$

Here p= p(x,ω), ρ_c and c_c are complex valued quantities. The water acoustic domain is truncated as a sphere with a reasonably large diameter. The diameter (d) of the spherical domain is set as equal to the largest wavelength of interest (Here 1 kHz was set as lowest frequency and hence wavelength is 1.5 m, where speed of sound in water is 1500 m/s). Hence, the diameter of the spherical water domain is set as 1.5 m. Another spherical layer located outside the water domain will act as a perfectly matched layer (PML). The perfectly matched layer (PML) is used as a non-reflecting and absorbing boundary to avoid standing wave formation. PML thickness is fixed as 375 mm. However PML thickness was varied and studied upto 7.5 m and no variation was observed for radial displacement results within a bandwidth of 10 kHz. For the PML, swept mesh containing 6 elements was used. Meshed geometry of the hydrophone in water domain with PML is given in figure 6.

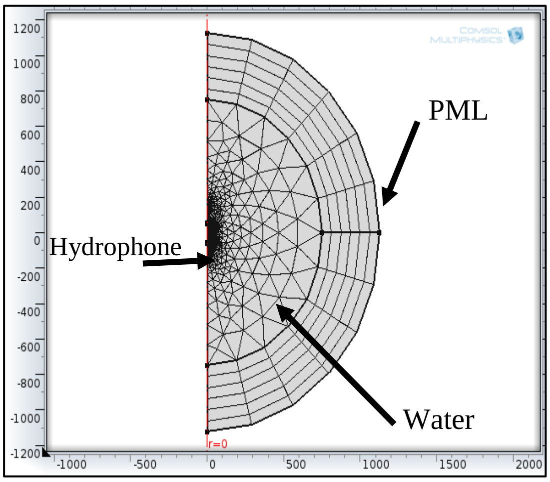


Figure 6. Meshed geometry for Acoustic – Structure interaction study

Acoustic pressure in the form of a plane harmonic wave of 1 Pa maximum amplitude was applied with a maximum frequency of 20 kHz to the water domain surface using "background pressure field" option in COMSOL. This pressure will be propagated inside water domain and will be impinged on the hydrophone structure as a sound wave to ensure continuity in pressure. Here free triangular meshing is given to the hydrophone structure with a minimum element quality of 0.5 and the maximum mesh size (D) is calculated as:

$$D = \frac{\lambda}{6} = \frac{c}{6 \times \upsilon} \qquad (2)$$

Where, υ is the frequency corresponding to shorter wavelength i.e., higher frequency of interest (20 kHz). Using this analysis, resonant frequency and acoustic sensitivity of the hydrophone structure was computed when the sensor was in water domain.

4. Simulation Results and Discussion

After acoustic – structure interaction study, the radial displacement of the hydrophone in water domain with different fixed constraint conditions are shown in figure 7. From the frequency domain analysis, it reveals that there exists a flat response of ±3 dB within a range of 4 kHz bandwidth. The first resonance frequency of mandrel shell was found as 10.5 kHz. The acoustic sensitivity is calculated from the radial displacement using relations given in Ref. 6 and its frequency response is depicted in figure 8, where a sensitivity of -151.5 dB re 1V/µPa at 1 kHz was obtained. These results are close to the analytical model given in Ref. 4.

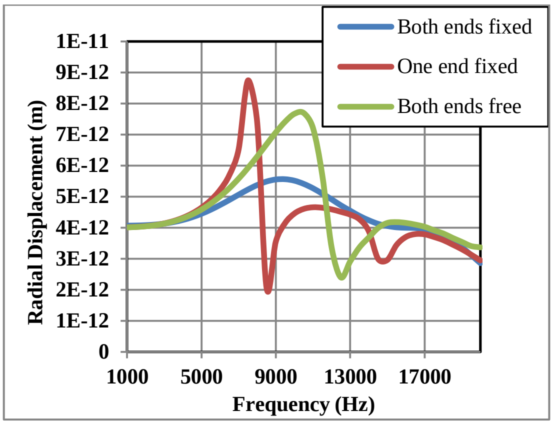


Figure 7. Radial displacement of the hydrophone for different conditions

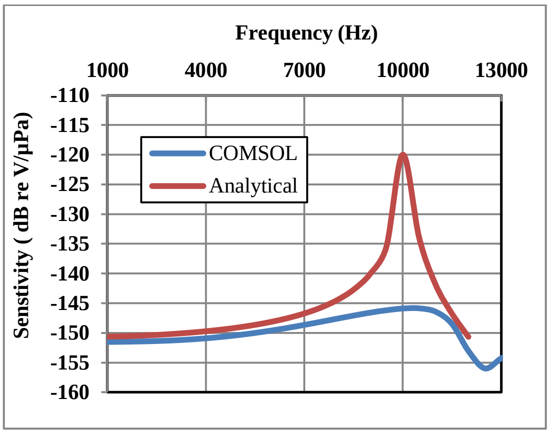


Figure 8. Comparison of Analytical and COMSOL results of the hydrophone's frequency response

The resonance frequency is shifted from 13.5 kHz to 10.5 kHz, possibly due to hydrostatic loading. Figure 8 also shows the comparison between analytical and FEM results of acoustic sensitivity in frequency domain when a harmonic plane wave of 1 Pa pressure is applied. It can be seen that the analytical model result generally agrees well with numerical solution from COMSOL Multiphysics within a frequency range of 1 - 13 kHz. The acoustic sensitivity (blue curve) in figure 8 was calculated from FEM results of radial displacement with both ends free condition.

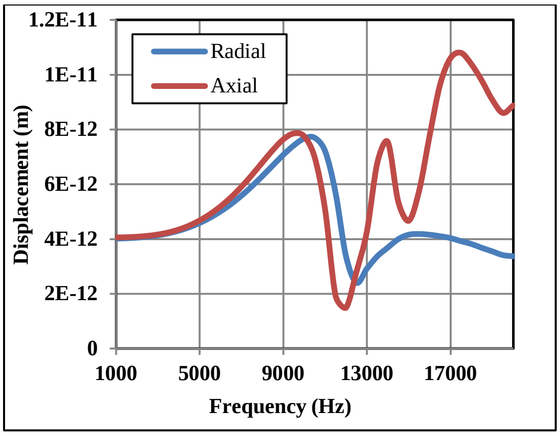


Figure 9. Axial displacement and radial displacement of mandrel hydrophone

Further, axial displacement obtained from FEM results of the hydrophone is plotted in figure 9 along with radial displacement, in both ends free condition. It can be deduced that, after the first resonance frequency, axial displacement for mandrel shell is predominant rather than radial displacement. However, in low frequency range, radial displacement only needs to be considered.

5. Conclusions

Design of a fiber optic mandrel hydrophone was analyzed using 2D axi-symmetric modeling in COMSOL Multiphysics and the design was optimized for required performance parameters. Eigen frequency and frequency domain analyses were carried out in structural mechanics module and the design was optimized such that first resonance frequency is 13.5 kHz. Dynamic acoustic response was modeled using the Acoustic-Structure interaction feature. The optimized structural design was placed in a spherical water domain encircled with PML and acoustic – structure interaction study was carried out. At 1 kHz, a radial displacement of 4 pm was obtained which corresponds to an acoustic sensitivity of -151.5 dB re 1V/µPa, when the structure was analyzed with 1 Pa plane acoustic pressure wave. With the help of COMSOL Multiphysics, we were able to analyze the performance of fiber optic mandrel hydrophones for different dimensions and materials without fabricating the structure. This will be helpful in design optimization of various mandrel hydrophones with required sensitivity and band width.

6. References

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