FEM Design of Interferometric FBGL Accelerometer for Underwater Applications

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Abstract: An Underwater accelerometer is designed and developed using a Fiber Bragg Grating Laser (FBGL), configured in a cantilever format. For fiber-based accelerometers, high bandwidth is often achieved by a compromise on sensitivity, whereas, the FBGL accelerometer offers high sensitivity with the wide bandwidth together. This is achieved by utilizing a high sensitivity optical interferometer. The accelerometer in the cantilever configuration is modelled using the commercial FEM package COMSOL Multi-physics® (version5.3) for optimizing the geometrical parameters. The results from COMSOL Multi-physics® are validated with analytical results as well as experimental results obtained on a prototype developed.

Keywords: Finite Element Modelling**,** COMSOL FBG Laser, Accelerometer

1. Introduction

Fiber optic sensors have been designed for applications ranging from simple proximity detectors to state-of-the-art inertial navigation systems. Demonstration of Fiber Bragg Grating (FBG) as sensor by D.J Hill *et al*. in 1978 [1], was a breakthrough in the field of fiber optic sensors. More refined approaches for sensing were introduced by Kersey [2], Kersey *et al*. [3], and Berkoff and Kersey [4] during 1991-1996, by replacing FBG with FBG Laser (FBGL) as the sensing element. In these, optically pumped narrow line-width fiber lasers were employed, which, on exposure to the measurand, results in modulations of their emission wavelengths proportional to the amplitudes of the measurand. These modulations are detected as phase shifts in a highly sensitive optical interferometer. In set up, it is possible to realize very high sensitive fiber optic accelerometers with high bandwidth [5-6]. FBGs and FBG lasers have almost the same strain sensitivity, but the latter has the advantage in using high sensitive interferometer and hence yield high sensitivity.

In general, most fiber optic accelerometers are based on cantilever mechanisms and use spring-mass oscillator concepts for strain transduction into the fiber [7-8]. However, the sensitivity and bandwidth of such mechanisms are highly dependent on the geometrical parameters of the mechanical parts and are to be carefully optimized to meet the specific requirements corresponding to each application. Most of the accelerometers are intended for civil construction or structural vibration measurement applications, for which the bandwidth requirement is typically < 100Hz, with sensitivity of 100 to 1000 pm/g [9-10]. FBG sensors with conventional intensity-based interrogation systems are sufficient for such applications [11]. For an accelerometer suitable for underwater applications such as measurement of structural vibrations on underwater vessels like submarines, ships, Autonomous Underwater Vehicles (AUVs) etc., higher bandwidth is sought. Because of the various machineries present in these vessels, and also due to the hydrodynamic flow conditions around these vessels, the bandwidth of interest is generally large, in excess of several hundreds of Hz.

In this work, a FBGL-based accelerometer using cantilever concept has been designed and developed, using the commercial FEM package COMSOL Multi-physics® (version5.3). Since the intended application is under water, stainless steel was chosen as the material for the cantilever structure, although this may be a compromise on mechanical sensitivity. A Distributed Feedback Fiber Bragg Grating Laser (DFB-FBGL) was used in place a simple FBGL, in order to improve the sensitivity of the interferometer. The structure was modelled using COMSOL and the performance was optimized through parametric analysis. A prototype was built and the experimental results were compared with the FEM results, which showed fairly good agreement.

2. Design of the Sensor

The cantilever scheme of the proposed accelerometer is shown in Figure 1, the structure is similar to the one suggested in reference [7].

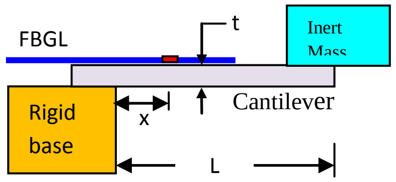


Figure 1. Schematic of the FBGL accelerometer structure

The strain experienced by the FBGL along the surface can be expressed as [2],

$$\varepsilon(x) = \frac{3(0.5d + d_f)(L-x)}{(\omega_0^2 - \omega^2)L^3} \times a \tag{1}$$

Where ω_0 is the natural frequency of the structure, L is the beam length, x is the distance between the centre of grating on fiber laser and the fixed position of cantilever, 'a' is the acceleration. The accelerometer sensitivity (shift in wavelength of FBGL per unit acceleration) is expressed as,

$$S = \frac{\Delta\lambda_L}{a} = \frac{1.2 \times \varepsilon(x)}{a} \tag{2}$$

where $\Delta\lambda_L$ is the shift in wavelength of the FBGL. The factor of 1.2 indicates that strain sensitivity for FBGL's with peak wavelength in C-band regime is about 1.2 $pm/\mu\varepsilon$ in general. In the present case, an interferometer is used to enhance the detection sensitivity by converting the wavelength modulations into corresponding phase modulations which can be interrogated. For the two beam interferometer considered here, with an optical path difference $n\times\Delta L$, the phase sensitivity with respect to wavelength modulation can be expressed (ignoring the temperature and pressure dependent refractive index variations) as,

$$\frac{\delta(\Delta\phi)}{\delta\lambda_L(\omega)} = \frac{2\pi}{\lambda_L^2}(n \times \Delta L) \tag{3}$$

Where $\Delta\phi$ is the initial phase difference between the two arms of the interferometer and λ_L is the wavelength of the fiber laser. 'n' is the refractive index of the material of the fiber.

The cantilever material was chosen by analytically computing the resonance frequencies of the structure, for different materials using the formula given below,

$$\omega_0 = \sqrt{\frac{1}{4}\left(\frac{bd^3E}{ML^3}\right)} \tag{4}$$

Where L×b×d is the cantilever dimension, E is the young's modulus of the material and M is the mass. Frequencies were computed for stainless steel, aluminium, brass, and copper. Stainless steel showed the highest resonant frequency for the preferred dimensions. Therefore, stainless steel was chosen as the material for cantilever as well as the inert mass and aluminium was chosen for the rigid base.

3. Numerical Model and Simulation using COMSOL Multi-physics

The proposed geometry was analyzed using COMSOL Multi-physics (version 5.3a) finite element modelling software. The geometry consists of a stainless steel cantilever of dimensions 40 mm × 20 mm × 1.5 mm with an inert mass of 15 gm attached to it. A polyimide-coated silica fiber of diameter 150 micrometer hosting the FBGL was adhesively bonded on the cantilever surface. The centre of the grating was kept at a distance of 5 mm from the fixing point of the cantilever. The material properties were taken from the COMSOL library.

The 'solid mechanics physics' interface was used and 'linear elastic material' model was assumed for frequency domain analysis. The equations governing the frequency domain study were [COMSOL]

$$\left.\begin{aligned} &-\rho\omega^2 u = \nabla.s + F_v e^{i\phi}, -ik_z = \lambda \\ &s = s_{ad} + c\colon \epsilon_{el}, \epsilon_{el} = \epsilon - \epsilon_{inel} \\ &\epsilon = \frac{1}{2}[(\nabla u)^T + \nabla u] \end{aligned}\right\} \tag{5}$$

Where u is the displacement vector, s is the strain tensor, ϵ is the total strain tensor, F is the force, ω is the angular frequency and ρ is the density. One end of the cantilever was assigned as the fixed point and other boundaries and domains were free. Body load for the structure was applied on the entire structure expect the fixed block. A user-controlled extra fine mesh was used with a minimum element quality of 0.2. The mesh used is shown in Figure 2.

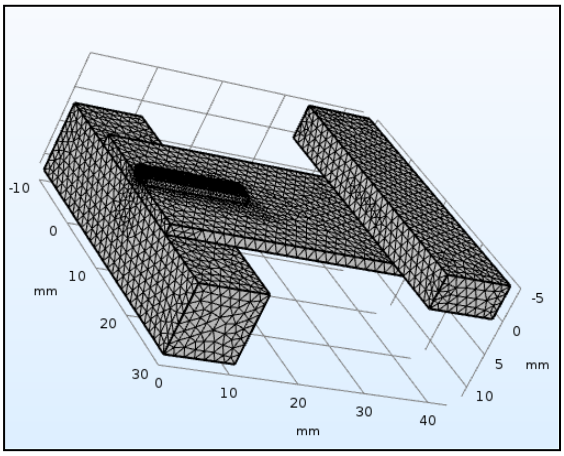
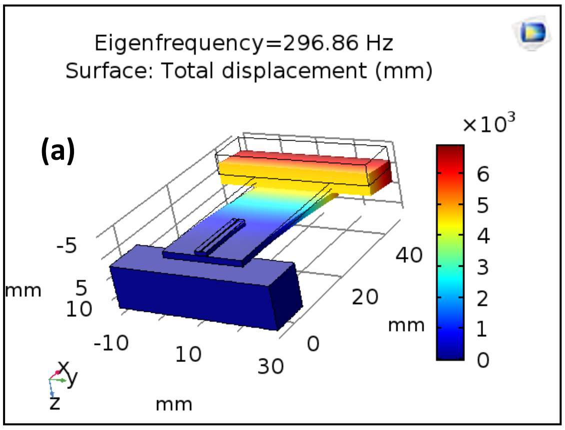


Figure 2. Meshed configuration of the FBGL accelerometer

The Eigen Frequency analysis was carried out for different cantilever dimensions and materials. The material and dimensions of the accelerometer were optimized for improving the resonance frequency. The mode shapes obtained from the Eigen frequency analysis for different cantilever dimensions and materials are shown in Figure 3. For frequency domain analysis, a force equivalent to 1 g was applied on the structure and the response was obtained. From the values of the strain on the fibre, thus obtained, accelerometer sensitivity was calculated using eqns. (2-3).



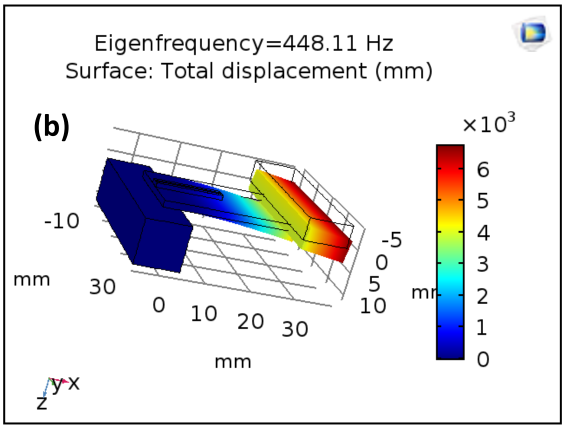


Figure 3. First resonance mode of the accelerometer for stainless steel cantilever with length (a) 40 mm and (b) 30 mm

Figure 4 shows the effect of changing the thickness of the cantilever, keeping other dimensions constant (length, breadth and mass being 40 mm, 20 mm and 15 gm, respectively). It is seen that the resonance frequency shifts upwards, almost three times, when the thickness is doubled.

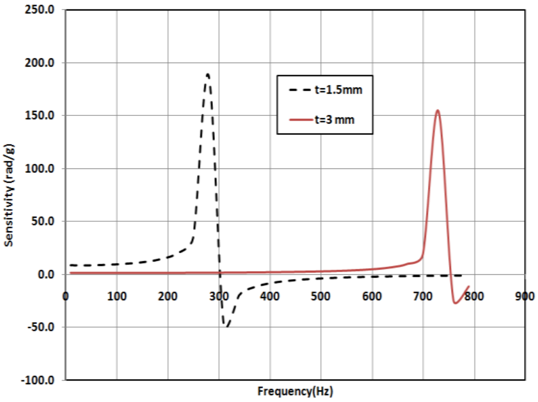


Figure 4. COMSOL results showing dependency of cantilever thickness

4. Experimental Results

The set up used for the experiments is shown in Figure 5. A DFB-FBG laser was used as the sensing element, capable of delivering ~50 µW optical power at 1550 nm when pumped using a 980 nm source with 100 mW optical power. The laser was adhesively bonded on the stainless steel cantilever structure having dimensions 40 mm x 20 mm x 1.5 mm. An inert mass of 15 gm was fixed at the end of the cantilever using cyanoacrylate. The cantilever structure along with mass and DFB-FBG laser was fixed on an aluminium block using given screws. The output of the laser was filtered out using a Wavelength Division Multiplexer (WDM) and fed to a high sensitivity Mach-Zehnder interferometer with Optical Path Difference (OPD) of 10 m.

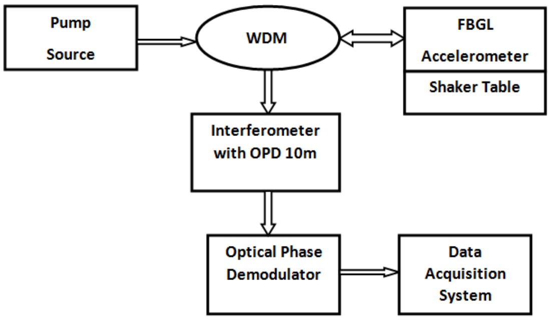


Figure 5. Block diagram setup for acceleration sensitivity measurements

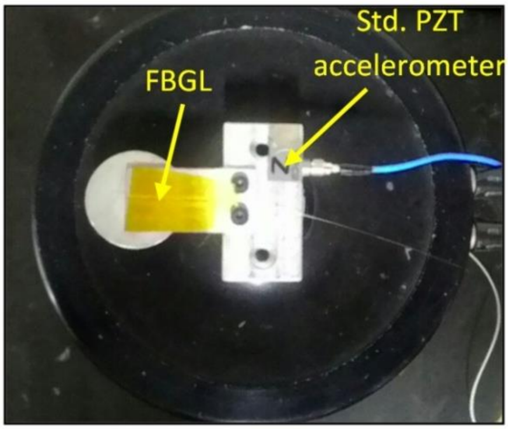


Figure 6. FBGL-based accelerometer and Piezo-electric accelerometers on the shaker.

The modulations in the wavelength of the laser are converted into corresponding phase modulations by the interferometer. A commercial Optical Phase Demodulator (Model OPD 4000 from M/s Optiphase, USA) was used to demodulate these and was stored in a Data Acquisition System. For studying the dynamic characteristics of the FBGL- based accelerometer, shaker table test was carried out, by mounting the accelerometer on a shaker table as shown in Figure 6. Sinusoidal vibrations with fixed amplitude and different frequencies were excited on the shaker table.

A PZT-based standard accelerometer was also pasted using cyanoacrylate on the solid aluminium block, for the purposes of comparison and calibration. The comparison of the FBGL accelerometer output with the analytical and FEM (COMSOL) analysis results is shown in Fig.(7).

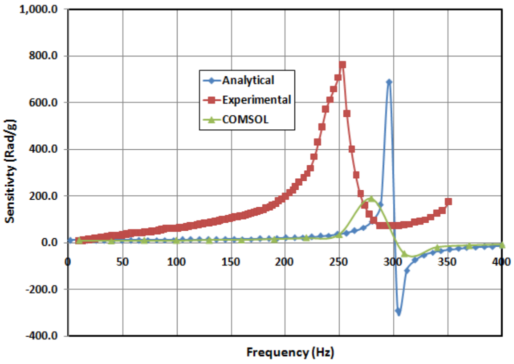


Figure 7. Comparison between COMSOL, analytical and experimental results.

It is observed that the FEM results are in fair agreement with the experimental and analytical results. There exists a flat (within 3 dB) region in the response curve up to 60 Hz. The experimental resonant frequency was observed at 253 Hz which is also close to the analytically and numerically predicted values.

By tailoring the cantilever dimensions we can increase the bandwidth or resonant frequency of the structure. The factors affecting the resonant frequency are Young’s modulus of the selected material, inert mass and cantilever dimensions. In which the change or increase in breadth and width or reduction in the inert mass and length of the cantilever leads to increase in resonant frequency. For a cantilever structure made up of stainless steel with dimension of 30 mm x 20 mm x 4.8 mm will give a resonant frequency of 7000 Hz.

5. Conclusion

FEM modelling of FBGL accelerometer design was carried out along with different cantilever dimensions and materials using COMSOL Multi-physics® (version5.3). Both Eigen frequency and frequency domain analyses were carried out in structural mechanics module for optimizing the design. The COMSOL model was validated using analytical and experimental results using the prototype realized. The COMSOL model results are found to be fairly matching with the analytical and experimental results. The prototype was found to be having a sensitivity of 20 V/g, flat response up to 60 Hz and the first resonance at 253 Hz.

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