Finite Element Modeling and Simulation of Fiber Optical based Load Cell (FOLC) sensor.

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ABSTRACT

Optical techniques have played an important role in telecommunication, industrial instrumentation and the sensors fields. In telecommunication field, the fiber optic technology is now firmly established for voice and data transfer. Wider bandwidth, low attenuation and mechanical properties of the fiber, are among the major advantages of optical fiber systems, even in the presence of various extreme and hazardous environmental conditions. The applications of optical fibers in the field of sensors are well established. This paper reports on development, modeling and simulation of fiber optic load cell (FOLC) sensor. The sensor basically consists of a fiber optic micro-displacement sensor probe and a load sensing diaphragm which also acts as a reflector. A pan is used for keeping the weights, the load of which is transferred to the diaphragm by a pin. The geometrical information of developed sensor is translated into a 3-D model. The stresses and deformations generated in the diaphragm are calculated using finite element method. Results for loading conditions ranging from low (mg) to high (100s of kg) levels and diaphragm parameters like thickness, diameter, Young's modulus and tensile strength are obtained. The fiber optic micro displacement sensor then senses the resulting deformations. A Ray Tracing module is used to study the relation between received intensity and position of fiber probe. The simulation results match well with the experimental results. The sensor dimensional parameters, geometry and material parameters of the diaphragm are optimized and are reported in the paper. It is hoped that this non-contact Load Cell sensor will offer several benefits over the conventional strain gauge based load cells.

1. INTRODUCTION

The applications of optical fibers in the field of sensors are well established. Optical techniques have played an important role in telecommunication, industrial instrumentation and the sensors fields [1-4]. Wide bandwidth, low attenuation, flexibility and mechanical properties of the fiber, and the immunity towards EMI are among the major advantages of optical fiber systems. Load cells, used in the weight as well as stress measurement, are important sensors in variety of applications of industrial and commercial importance. Conventionally the load cell sensors use a dome shaped diaphragm in contact with a resistive strain gauge bridge or a Piezo. Due to the contact type operation, there is a wear and tear and aging effect. Secondly the sensor deals with electrical voltage, and thus is a likely source of hazard in inflammable gas/ liquid environment.

This paper reports development, modeling and simulation of fiber optic load cell (FOLC) sensor. The FOLC sensor basically consists of a fiber optic micro-displacement sensor probe [5] and a load-sensing diaphragm, which also acts as a reflector. A pan is used for keeping the weights, the load of which is transferred to the diaphragm by a pin. Fiber optic load cell (FOLC) sensor uses non contact intensity modulated extrinsic fiber optic sensor, to convert the load induced deformation of the diaphragm to electrical voltage.

The geometrical information of developed sensor is translated into a 3-D model. The shape deformation of the diaphragm under given load conditions and constraints is analyzed using ANSYS, with appropriate material constants and boundary conditions. A ray tracing program developed in C takes this deformation information and estimates the intensity variations at the output of the receiving fiber. The sensor behavior is studied by varying diaphragm thickness, pin contact area and material elasticity constants. Optimization of these parameters for best linear performance over largest operating range is reported in this paper.

2. STRUCTURE OF FIBER OPTIC LOAD CELL

The FOLC basically consists of a weighing pan, load sensing diaphragm or reflector and a fiber optic micro-displacement sensor probe. The fiber optic sensor probe consisting of two multimode fibers (transmitting and receiving) arranged in a particular way, is used to measure the effective displacement of a diaphragm attached to the weighing pan. Whole assembly is placed in a compact box such that the relative position of the sensor probe and diaphragm is fixed. Figure 1 (a), (b) and (c) shows the constructional details of the FOLC.

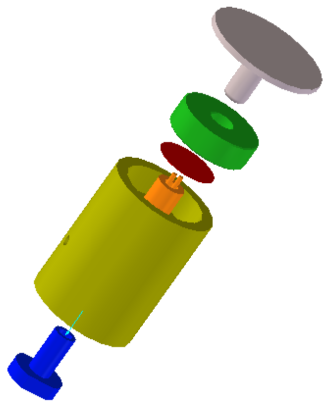


Fig. 1 (a)
Exploded View

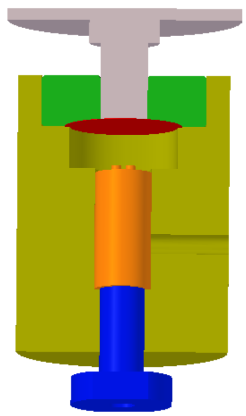


Fig. 1 (b)
Sectional View

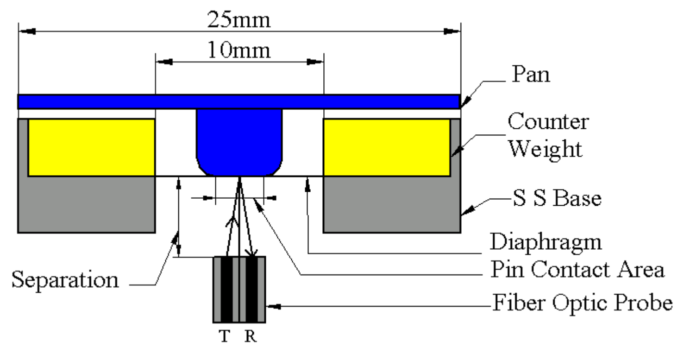


Fig. 1 (c)
Geometrical Arrangement

3. FINITE ELEMENT MODELING

Create finite element model of diaphragm:

Diaphragm is critical part in the whole structure of fiber optic load cell (FLOC), so we decided to model diaphragm and calculate deflection of diaphragm using ANSYS. First, nodes are created along positive X axis and these nodes are circularly patterned. Elements are created from nodes in the same fashion. Figure 2 shows the models created. The geometrical information and material parameters used are given in Table 1.

Table 1 : Geometrical and Material properties used in the model

Geometric properties	**Material properties**
1. Outer diameter of diaphragm is 25 mm 2. Counter weight on Area from diameter 10 mm to 25 mm.	A) Spring steel 1. Young's Modulus (E) is 2.1 x 10^5 N/ mm^2 2. Poisons ratio (μ) is 0.30. B) Aluminum 1. Young's Modulus (E) is 0.7 x 10^5 N/ mm^2 2. Poisons ratio (μ) is 0.35.
Element used: - **Shell 63** Real Constant: - **Thickness** Element size : - **0.25 mm** Surface Load: - **Pressure** Degree of freedom: - **Displacement**	**Variable parameter:** 1. Contact area of pin: - from 0.5 mm to 9.0mm pin diameter 2. Weight on diaphragm: - from 1mg to 1kg 3. Thickness of diaphragm: - from 0.05 mm to 0.5 mm 4. Material: - Spring steel and Aluminum.

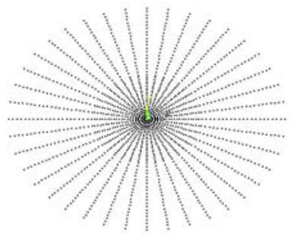


Fig. 2(a)
Model with nodes

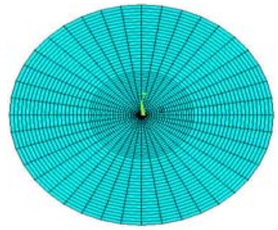


Fig. 2(b)
Mesh model

Apply Boundary Conditions

Boundary conditions are pressure as a surface load and zero degree of freedom on the area on which counter weight is placed. For applying pressure, we defined parameter like radius of pin and press1 as pressure on diaphragm. We select nodes of given pin radius & apply surface load. Figure 3 shows the FEA model with pressure and nodes fixed as per constraints.

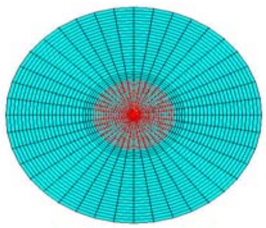


Fig. 3(a)
FEA model with pressure

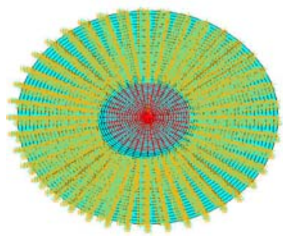


Fig. 3(b)
FEA model with pressure & fixed nodes

The deflection profiles are computed and stored for further use by specially developed ray tracing program described in the next section.

4. RAY TRACING

Ray tracing technique is used to obtain the output for the optical fiber sensor probe. The principle of ray tracing is based on laws of optics. The program assumes that the transmitting and receiving fibers are placed at a proper distance from a diaphragm, which is used as a reflector. The coordinates of the deformed diaphragm as obtained from the ANSYS program are used here to define the shape of the reflector upon loading under different conditions. A conical fan beam of rays emerges out of the transmitting fiber and the points of intersection for each of the rays is computed and after estimating the direction of the normal to the deformed surface at that point, the reflected ray direction is calculated. If this ray in turn enters into the receiving fiber core area, duly positioned, then it would add to the received power else it is considered lost. The overall power received is thus estimated as integration of the power contributions by all the rays incident on the receiving fiber core. Results obtained for various experimental conditions are then stored
The algorithm for simulation of load cell is given below.

1. Draw the initial position of the diaphragm from the coordinates obtained from ANSYS. Draw counter weights at its boarder.
2. Place the fibers at proper position from the diaphragm.
3. Using the value of numerical aperture of the transmitting fiber the ray is traced up to the diaphragm where the point of intersection is calculated.
4. Calculate the slope of normal at the point of intersection.

5. Draw the reflected ray up to the receiving fiber.
6. Repeat the process for all rays emerging from transmitting fiber.
7. Integrate the power contributions from the ray's which falls within the acceptance angle of the receiving fiber.
8. Record the total power output for different distance between source and reflector.
9. Repeat the process by using the data obtained for adding the weights into the weighing pan.
10. Store the result in the file.

5. RESULTS AND DISCUSSION

Table 2

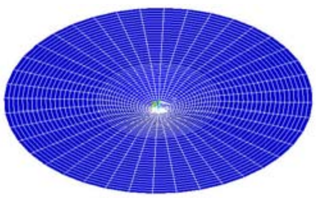
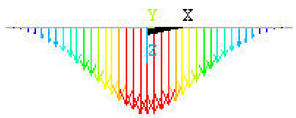
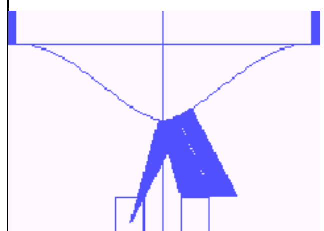
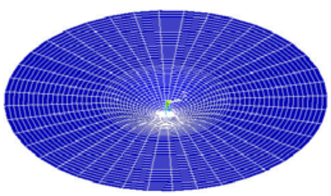
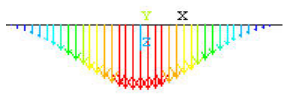
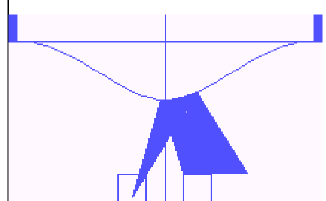
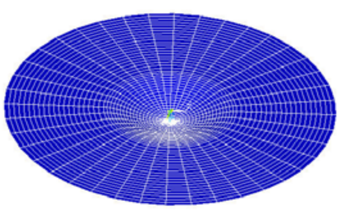
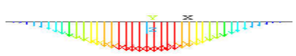
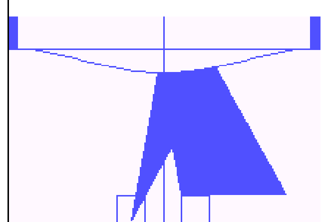
Deformed diaphragm	Cross sectional Profile	Ray tracing for FO sensor probe	Comment
	**Pin Contact diameter = 0.50 mm** 		Small Contact area: Deflection shows a sharp peak May create marks & permanent deformation. High Sensitivity and Smaller operation range.
	**Pin Contact diameter = 3.00 mm** 		Medium Contact area: shape broad and more uniform. Sensitivity reduces, but operation range increases.
	**Pin Contact diameter = 9.00 mm** 		Large Contact area: shape flattens. Sensitivity reduces further without much improvement of operation range.

Table 2 shows the results obtained for different representative conditions for 1 kg load on a 300 micron Aluminum diaphragm. The same procedure was followed for studying the effect of varying contact area, varying thickness and different materials under different loading conditions of 0-1 kg weight.

Figure 4 shows the effect of the variation in the sensor output with applied weight for different placements of the fiber probe with respect to the undeformed diaphragm. It is seen from the figure that for smaller distances the sensor output shows a sharp fall leading to total insensitivity. This is due to the fact that the reflected cone from the undeformed partially covers the receiving fiber core, and after adding weights the cone shrinks further so that the light power coupled keeps on reducing. For large enough weights (over 400 g for distance = 2mm) the power coupled to the receiving fiber reduces to zero. As the distance is increased to 3 mm, a region with positive slope starts appearing, which however continues only for a while and again for loads over 400g there is a fall in the sensor output. The linear (positive slope) range thus increases with the distance between the diaphragm and the fiber probe. Figure 5 shows this effect.

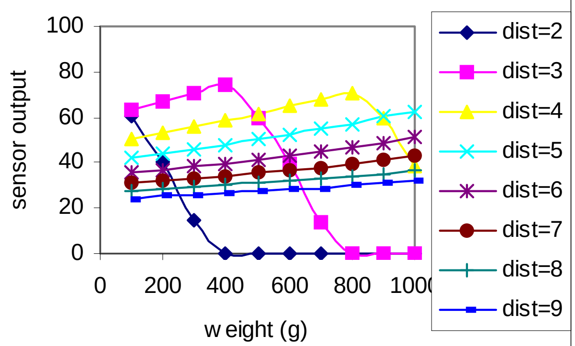


Fig.4: Fiber sensor output variation w ith applied w eight for different separations

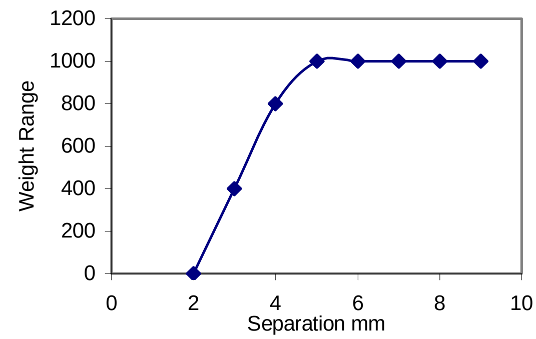


Fig. 5: Variation of linear range of weight with separation

Fig. 4

Fig. 5

Figure 6 shows the sensitivity variation with contact diameter for different probe separation. It is seen that sensitivity is almost constant up to contact diameter of 3 mm, but with further increase in contact area sensitivity decreases. Thus a primary conclusion emerges that the pin diameter should be restricted to a maximum of 3 mm. For lower diameter there is a likelihood of denting and permanent deformation so the pin diameter is optimized to be 3 mm. It is seen from the figure that with increase in probe separation the sensitivity decreases. This is shown in Figure 7. Considering results of Figure 5 and Figure 7 together another geometry parameter, the diaphragm-probe separation gets optimized at 4 mm.

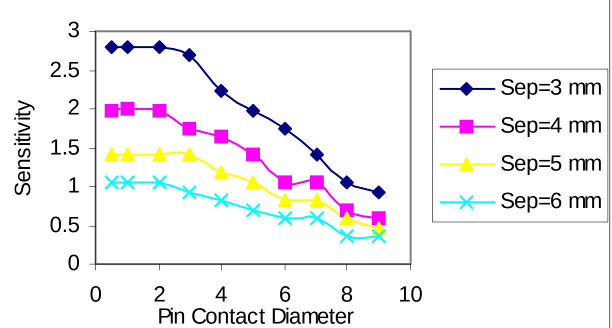


Fig.6: Sensitivity variation w ith pin contact diameter for different probe seperation

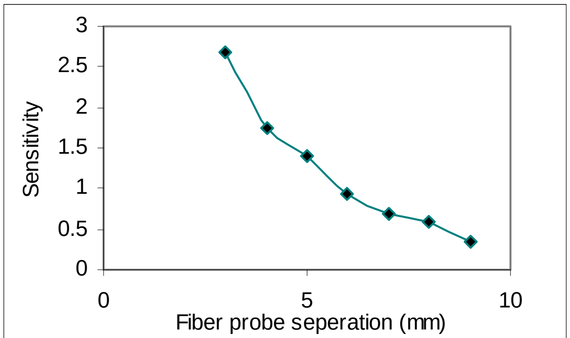


Fig.7: Sensitivity variation w ith diaphragm to fiber probe separation at 3 mm contact dia

Fig. 6

Fig. 7

The same procedure was followed for studying the effect of varying thickness of diaphragms made of different materials under different loading conditions of 0-1 kg weight. It was observed that as the thickness increases, the deformation reduces leading to lesser sensitivity for load. This is in compliance with well known formula for a bending diaphragm, which gives inverse dependence of bending on cube of thickness. The same formula suggests reciprocal dependence of bending on Young's modulus. This indeed was observed when the deformations and thus the sensitivity were estimated for Aluminum (Al) and Spring Steel (SS) diaphragms. The Al diaphragm shows higher sensitivity than the SS, but the linear weight range is seen to be reduced. Moreover, the breaking strength of Aluminum is much less than that of Spring Steel.

6. CONCLUSIONS

The FEM studies on the bending diaphragm followed by ray tracing to model the performance of the FOLC lead to following conclusions. The approach described in this paper yields good understanding of the behavior of FOLC. It is observed that as the pin contact diameter increases the sensitivity remains almost constant up to 3mm and reduces for higher contact diameters. Further, for the same contact diameter, there is a reduction in sensitivity with diaphragm-probe separation. Increasing range of linear operation with positive slope, however, counterbalances this. A separation of 4 mm is thus optimized. The diaphragm material and its thickness also show effect on sensitivity, which is in accordance with well known theory.

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