Fiber optic load sensor using microbend-deformer

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Abstract. Monitoring volume in traffic load is necessary in order to manage the increase of traffic load volume. One of the technologies has been used in that case is Weigh-in-Motion (WIM). Conventional load sensors used in WIM technology are piezoelectric, capacitive mats, bending plate, strain gauge, and load cell. However, the sensors have problems such as electromagnetic interference, corrosion, complex installation and high installation costs. In order to solve those problems, an optical fiber load sensor based on microbend using micro-deformer is being proposed. Optical fiber deformer consists of micro grain sand and silicone rubber mixture with certain compositions. The proposed sensor showed promising result with good sensitivity and measure range. The proposed sensor showed the maximum sensitivity performance around 0.0239 mV.N⁻¹, the maximum microbend sensitivity of 0.548 mV.mm⁻¹ and the maximum measurement range of 30000 N that can be applied in WIM system.

1. Introduction
Road damage is one of factors that causes accident in highways. Generally, causal factors of road damage are poor drainage, poor construction materials, unstable land and climate conditions, very thin ossification layer planning, processing work that inappropriate with the specification and increasing traffic load volume [1] . The increasing traffic load volume can be monitored by using Weigh-in-Motion (WIM) technology. With this technology, weight from any vehicles can be measured without stopping the vehicle. In order to measure the weight of the vehicle, load sensor is the most important component in WIM system. Conventional load sensors used in WIM technology are piezoelectric, capacitive mats, bending plate, strain gauge, and load cell. Bending plate and load cell offer high accuracy (± 10% and ± 6%) and long lifetime but suffer high installation costs. On the other hand, the costs of capacitive mats and piezoelectric are lower but they have lower accuracies (5% to 15%) and are unable to function properly at a vehicle speed lower than 20 km/h [2–7] . These conventional sensors additionally have several issues, like corrosion, electromagnetic fields impedance, and complex instalment. To fulfil the requirement of accuracy at reduced costs, optical fiber based WIM sensors have been presented to enhance, supplement or even supplant the ones being used right now.

Research of optical fiber load sensor has been done many years ago. Some of them utilized birefringence effect actuated by pressure in single-mode optical fiber using Sagnac loop interferometer setup [8], Fiber Bragg Grating method [9] and microbend theory [10] . In this paper, an optical fiber load sensor based on microbend theory is proposed. Microbend sensor has been used from 1980s and showed promising result [11] . It has been used in many applications such as strain gauge [12] and load sensor in WIM system [4,13–15] . The work presented here describes development of a novel
configuration in optical fiber load sensor based on microbend theory using sand grains and silicone rubber mixture as microbend deformer.

2. Principle of Operation
The proposed optical fiber load sensor was based on intensity loss of transmission light caused by microbending. The applied force ($\Delta F$) pressed the deformer and caused the periodic bending with periodicity $\Lambda$ in the axial direction of optical fiber. Due to the microbending in fiber optic, the intensity of light transmitted through the fiber decreased. The intensity loss of transmission light can be formulated as

$$T = \left( \frac{\Delta T}{\Delta X} \right) \Delta F \left( k_f + \frac{A_s Y_s}{l_s} \right)^{-1}, \tag{1}$$

where $\Delta F$ is the change of applied force, $\Delta X$ is the change of fiber optic deformation amplitude due to the applied force, $A_s$ is the area, $l_s$ is the thickness of the deformer, $Y_s$ is the Young’s modulus and $k_f$ is the optical fiber bend constant [10].

Some parameters have to be considered in a sensor to determine whether the sensor has an optimum performance or not. One of them is sensitivity. From equation (1), $\left( \frac{\Delta T}{\Delta F} \right)$, the intensity loss of transmitted light caused by the applied force, can be calculated and then the experimental sensor sensitivity can be determined. Other than maximizing sensor sensitivity, it is necessary to maximize the microbending sensitivity in order to optimize the sensor performance. One of the most important parameter to determine microbending sensitivity is the periodicity of the optical fiber deformation. The optical fiber bend constant relates the applied force $\Delta F$ to the change of fiber optic deformation. It depends on these deformer’s geometrical parameter and fiber optic properties. The optical fiber bend constant can be formulated as,

$$k_f = \frac{3\pi Y d^4 \eta}{\Lambda^4}, \tag{2}$$

where $Y$ is the effective Young’s modulus, $d$ is the diameter of the fiber optic, $\eta$ is the number of bend intervals, and $\Lambda$ is the mechanical periodicity of deformer. In this case, the mechanical periodicity of deformer depends on the composition number of sand and sand grain diameter, which can be formulated as,

$$\Lambda = \frac{2a}{b}, \tag{3}$$

where $a$ is the sand grain diameter and $b$ is the composition number of sand.

3. Experimental Methods
A single-mode silica fiber optic was embedded in the deformer mixture. The optical fiber has a core and cladding with diameter of 125 $\mu$m. The micro deformer consists of micro-grain sand and silicone rubber in certain compositions. In order to ensure that the sand grains are uniform, a certain amount of sand has been filtered first. We will vary the sand-grain size and the composition of sand grain in silicone rubber mixture. The sand grains are filtered in 20 mesh and 200 mesh grain size. The composition number of the sand grain are 0.1, 0.3, 0.4, 0.7 and 1. The fabricated fiber optic embedded in microbend-deformer connected to an optical laser source and photodetector. Applied forces to the fiber-optic structure are varied from 0 N to 3000 N. The fiber optic sensor set up is shown in figure 1. The input wavelength of the laser is 1550 nm.
4. Results and Discussion

The embedded microbend optical fiber load sensor was connected to the optical laser source (wavelength of 1550 nm) and the photodetector to measure the voltage output of the transmitted light. The sensor’s response for each variation was shown in figure 2.

Figure 2 showed that the maximum measurement range obtained for both sand grain size was 30000 N. The maximum measurement range obtained at composition number of 0.1. It was probably caused by the solidness of the structure, which depends on the sand grain percentage. The variation of composition and sand grain size determine the mechanical periodicity of deformer and then affect the intensity of transmitted light. The sensitivity of the fiber optic load sensor $\frac{\Delta V}{\Delta F}$ of each mechanical periodicity was shown in figure 3.

Figure 2. Sensor’s response (a) at 20 mesh size of sand grain (b) at 200 mesh size of sand grain.
Figure 3. Experimentally sensitivity response to mechanical periodicity (a) at sand-grain size of 20 meshes (b) at sand-grain size of 200 meshes.

Figure 3(a) shows the maximum sensitivity obtained at 20 meshes of sand grain size was 0.0239 mV.N\(^{-1}\) with composition number of 0.1 and. Meanwhile, at 200 meshes of sand grain size and composition number of 1, the maximum intensity is 0.0072 mV.N\(^{-1}\) . The better sensitivity in 20 meshes case is probably caused by the structure solidness which means that bigger grain size would make the optical fiber can be more sustained. It has been mentioned that in order to obtain the optimum sensitivity, maximizing the microbend sensitivity is necessary. However, observing microbend sensitivity experimentally is difficult. By using Equation 1, the microbend sensitivity can be obtained. Figure 4 showed the microbend sensitivity for each periodicity.

The maximum microbend sensitivity obtained was 0.548 mV.mm\(^{-1}\). Figure 4 showed that the maximum microbend sensitivity obtained at lowest mechanical periodicity, where the mechanical periodicity depends on the sand grain size and the sand grain’s percentage of the mixture. Bigger sand-grain size would have the longer mechanical periodicity and the bigger sand-grain’s percentage of the mixture would have shorter mechanical periodicity. The sand-grain size and the sand percentage were also affected by the difficulty in fabricating load sensor’s structure. It was easier to insert smaller sand

Figure 4. Microbend sensitivity response to mechanical periodicity (a) sand grain size of 20 meshes (b) sand grain size of 200 meshes.
grains and lower grain’s concentration into the mold. The other parameter of sensor that determine its performance is linearity which is showed in Figure 5 below.

Figure 5 showed that the maximum linearity obtained with smaller-sand grain. However, the sand grain percentage of the mixture did not influence the linearity directly. In experimental cases, it is probably influenced by the difficulty in fabrication which varies from time to time. Therefore, further research will be about the effect of variation of sand grain to sensor’s linearity.

5. Conclusions
A single-mode fiber optic was embedded in deformer structure which contained sand grain and silicone rubber mixture. The proposed sensor showed good performance with maximum sensitivity of 0.0239 mV.N⁻¹, maximum microbend sensitivity of 0.548 mV.mm⁻¹ and maximum measurement range of 30000 N. The better linearity showed in sand-grain size of 20 meshes. Therefore, the proposed method showed promising result to be applied in Weigh-In-Motion system.

References
[1] Udiana I M, Saudale A R, and Pah J J S 2014 J. Tek. Sipil. III 13
[2] Batenko A, Grakovski A, Kabashkin I, Petersons E, and Sikerzhicki Y 2011 Int. Conf. Reliability and Statistics in Transportation and Communication 311
[3] Haugen T, Levy J R, Aakre E, and Tello M E P 2016 Transp. Res. Procedia 14 1423
[4] Mimbela L Y, Pate J, and Copeland S 2003 Applications of Fiber Optic Sensors in Weigh-in-Motion (Wim) Systems for Monitoring Truck Weights on Pavements And Structure, New Mexico State University, 2003
[5] Zhang W, Suo C, and Wang Q 2008 Sensors 8 7671
[6] Navarrete M C and E. Bernabeu E 1994 Sensors Actuators A. Phys. 41 110.
[7] Otto G G, Simonin J M, Piau J M, Cottineau L M, Chupin O, Momm L, and Valente A M 2017 Constr. Build. Mater. 156 83
[8] Gan J, Cai H, Geng J, Pan Z Q, Qu R, and Fang Z 2008 1st Asia-Pacific Opt. Fiber Sensors Conf. APOS 2008 6 482
[9] Ile A, Lopez V, Laudati A, Mazzino N, Bocchetti G, Cutolo A, and Cusano A 2016 8th Eur.Work. Struct. Heal. Monit. 8 5
[10] Lagakos N, Cole J H, and Bucar J A 1987 Appl. Opt. 26 11
[11] Ma B and Zou X 2010 Int. Conf. Intell. Comput. Technol. Autom. ICICTA 3 458
[12] Ethonlagi D and Zavrsnik M 1997 Opt. Lett. 22 837
[13] Pandey N K and Yadav B C 2006 Sensors Actuators A Phys. 128 33