Remote vibration sensor using fiber optic fused 2x2 coupler

Dantala Dinakar*, Putha Kishore, Kamineni Srimannarayana and Pachava Vengal Rao
National Institute of Technology, Department of Physics, Warangal, A.P., India.
*Corresponding mail: dinakar.anu@gmail.com

Abstract: A simple geometrical fiber optic vibration sensor is designed and demonstrated using fiber optic fused 2x2 coupler that utilizes the principle of reflection intensity modulation. The rational output is used to avoid the effects of source signal power fluctuations and fiber bending losses. The calibrated 1mm linear region of the displacement characteristic curve of the sensor having high sensitivity of 2.1 mV/mm (0.36 a.u. /mm) is considered for vibration measurement. The experimental results show that the sensor is capable to measure the frequency up to 3500 Hz with ~0.03μm resolution of vibration amplitude over a dynamic range of 0-1mm. The SNR of the rational output is also improved with respect to the sensing signal. In comparison with dual-fiber and bifurcated-bundle fiber, this sensor eliminates the dark region and front slope which facilitates the easy alignment. The simplicity of design, non-contact measurement, high degree of sensitivity, economical along with advantages of fiber optic sensors are attractive attributes of the designed sensor that lend to real time monitoring and embedded applications.

Keywords: Optical Fiber, fused 2x2 Coupler, displacement, vibration, sensor.

1. INTRODUCTION:

Vibration monitoring is carried out on important machines such as power station turbines and generators to give an early warning of impending conditions which may develop and lead to complete failure and destruction of the components in machines [1-2]. Continuous monitoring of vibration reduces not only the maintenance and operating costs but also avoids frequent interruptions of undesirable engine working [3]. In general vibration is measured by electro-mechanical devices, such as piezoelectric, piezoresistive, or capacitive accelerometers. Such types of measurements require physical contact with the vibrating object. However some non-contact vibration measurement techniques have been developed with optical interferometric and fiber optics. Especially such non-contact sensors made with optical fibers have already established and playing key role in sensing several physical parameters like vibration, displacement and pressure [4]. So that the fiber optic sensors are replacing to the conventional sensors and also due to their advantages like Immune to EMI, small size, flexible length of the fiber, remotable, high accuracy, secure data transmission, potentially easy to install, and noncorrosive[5-8]. Reported fiber optic vibration sensors are in general divided into two types according to their working principle of phase or intensity modulation. The phase modulation fiber optic interferometric techniques such as Fabry-Perot [9], Michelson or Mach-Zehnder [10], self-mixing [11] and Doppler vibrometry [12-13] were deployed for vibration measurements. These sensors are much more accurate than intensity modulated sensors and can be used over large dynamic range. However, they are often much more expensive, low degree of stability and critical alignment. Consequently, these sensors are not suitable to industrial applications [14]. However, the second one i.e. intensity modulated technique takes the advantage of change in intensity with the vibration using simple fiber optic geometry [15].

In this paper, we report a simple noncontact intensity modulated fiber optic vibration sensor designed with fiber optic fused 2x2 coupler. It consists of four ports, one port for the coupling of source, second port act as a sensing probe, third port is connected to the sensing photo-detector and fourth one also connected to

Optomechanical Engineering 2013, edited by Alson E. Hatheway, Proc. of SPIE Vol. 8836,
883605 · © 2013 SPIE · CCC code: 0277-786X/13/$18 · doi: 10.1117/12.2023462

another photo-detector to act as a reference. Here the single fiber alone guides the light, to incident on the reflected surface glued on sensing part of the vibrating object and to receive the reflected light[16]. It consist only single slope than the two slopes, so the alignment of the sensor is very simple. It is one of the advantages of the proposed sensor in comparison with the dual-fiber and bifurcated bundle fiber vibration sensors by removing the dark region and disappear the front slope [17-18]. Another one is rational output between the sensing and reference minimizes both effect of source fluctuations and bending losses at the source end [19].

2. Design of the Sensor:

In general, the required major quantity to measure the vibration is displacement. The velocity and acceleration can be measured from the displacement, because these parameters are related to each other. The non-contact fiber optic vibration sensor is working based on the reflection intensity modulation with respect to displacement between sensing fiber probe to reflecting surface. The schematic experimental setup of the working principle of the vibration measurement is shown in figure 1. It consists, a multimode plastic fiber 2x2 fused coupler (IF-541) with splitting ratio of 80:20 as a sensing tool, an LED (IF-E96) of peak wavelength 650 nm is used as a source, a very high sensitivity photodarlington detector (PD) housed in a connector less package (IF-D93) of two number are used to detect the intensity of light at reference and sensing ends. A simple detection circuit is designed to convert the modulated light intensity into its equivalent voltage signal and an NI-DAQ 6016 with LabVIEW software is used to record the time domain signal (TDS) of the reference and sensing signals from which calculated the rational output.

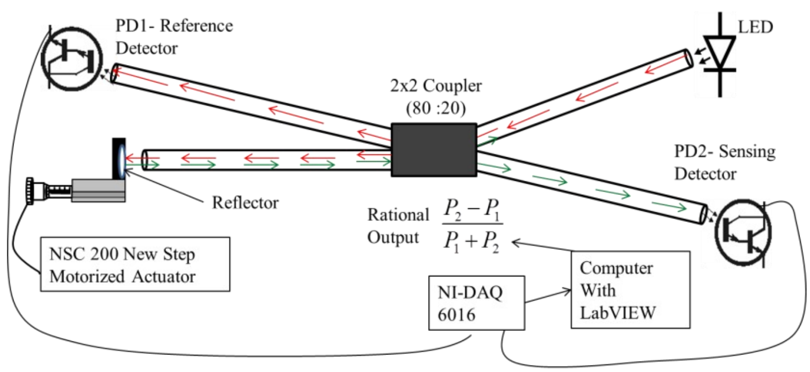

Figure 1. Schematic experimental setup for the displacement response of the sensor.

The fiber optic fused 2x2 coupler is made from Polymethyl Methacrylate (PMMA) having core/cladding diameters of 980/1000 μm has 100cm in length with splitting ratio of 80:20. All the four ports of the coupler are used for the vibration detection. The LED light is coupled to the port A, the coupled light is split (80:20) and a part of light is transmitted through the port C acts a sensing probe and other part is directed to PD1 through port D used as a reference. The light from port C projects onto the vibrating object then the modulated reflected light is recoupled into the same fiber (port C) and directed to incident on the PD2 through port B and port D. The rational output of PD1 and PD2 is used to avoid the effect of source signal power fluctuations and fiber bending losses. A suitable calibration has taken from the displacement characteristic curve of the sensor as shown in figure 2 for the measurement of amplitude of vibration. New Step Motorized Actuator NSC200 along with NSA12 micrometer replacement actuator and NewStep-Util software 303A are used to move the reflector attached to the micrometer to and fro from the sensing probe with a step size of 1μm for the dynamic range of 4mm.The curve shows the linear region of about 1mm with high sensitive of

2.1mV/µm where as in the rational output curve the sensitivity is found to be 0.36 a.u /mm, which is considered for vibration measurement..

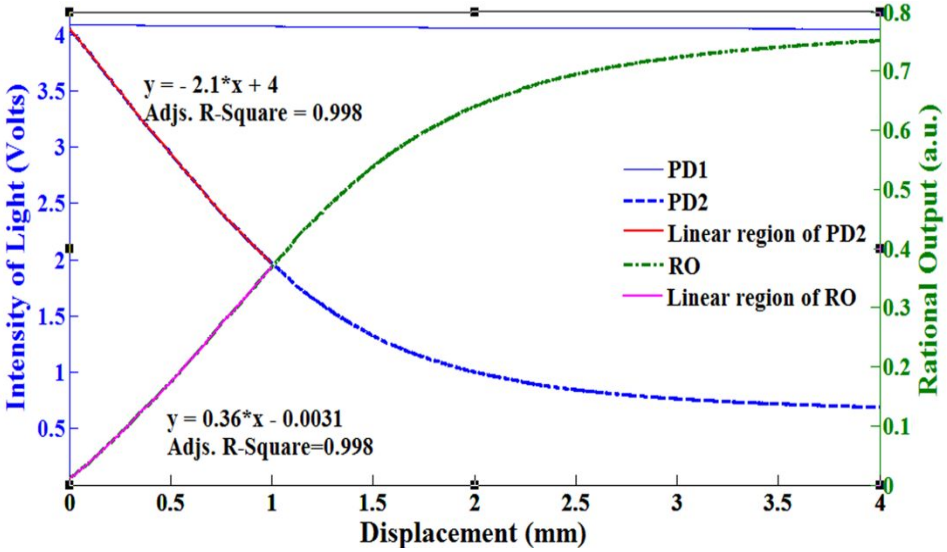

Figure 2. Displacement characteristic curve of the sensor.

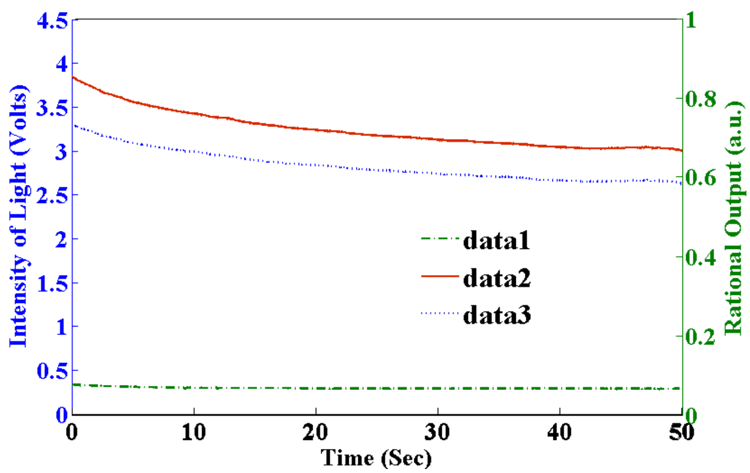

Figure 3. Effect of source fluctuation on PD1, PD2 and RO

Before measuring the real time vibration, the sensor is tested for both source fluctuation and fiber bending at the source end. Figure 3 shows the effect of source fluctuation on the sensing and reference signals. The measured PD1 and PD2 signals are showing a change in intensity of light with respect to the LED light intensity variation by varying the driving voltage. Whereas the rational output of these signals shows insensitive to source fluctuations. It indicates the minimization of the effect of source fluctuation on sensing by the rational output method. To test the fiber bending losses of the sensor, the fiber is bended by using a microbending pressure element. Figure 4 illustrates the no effect of microbending on rational output, even though PD1 and PD2 signals are varying with respect the microbending on the fiber. It concludes the insensitivity of the sensor for fiber bending at source end (port A) using with rational output.

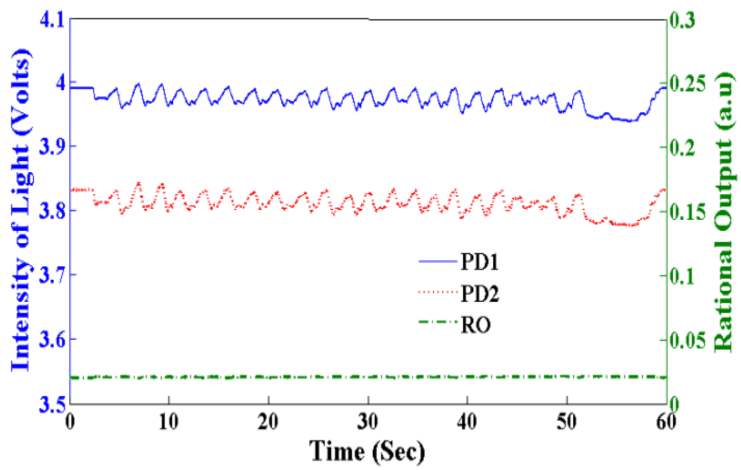

Figure 4. Effect of bending on PD1, PD2 and RO.

3. Experimental Setup:

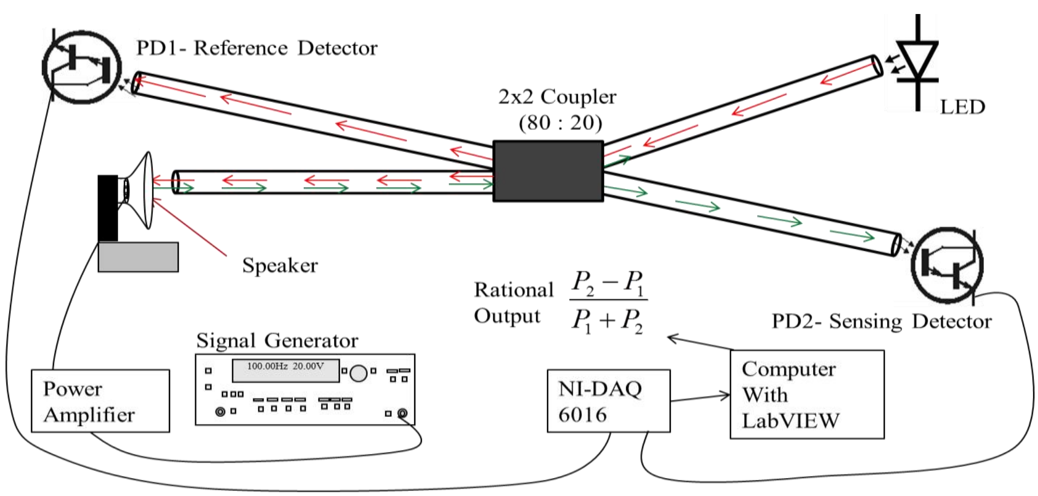

Figure 5. Schematic experimental setup for vibration measurement.

The schematic experimental setup of the vibration sensor is shown in figure 6. The whole setup is mounted on a vibration free table (Newport). A synthesized function generator (HM8130, Scientific) and a commercial speaker with a calibrated reflector attached at the center of it are used to test the sensor response. Record the TDS and monitor the vibrations of the speaker at different known frequencies and amplitudes (driving voltages) by the data acquisition system. Most of the vibrations are in sinusoidal displacement of the vibrating object about its mean position. Generally, this nature of vibrations can be measured by its amplitude and frequency. So, the FFT technique is used to convert the TDS into frequency domain to analyse the vibration in terms of frequency of the vibrating object and also measure the amplitude of vibration. The experiment is repeated for different frequencies of amplitude of vibration to measure the detectable maximum frequency and amplitude resolution of the sensor and also to test the reliability of the sensor.

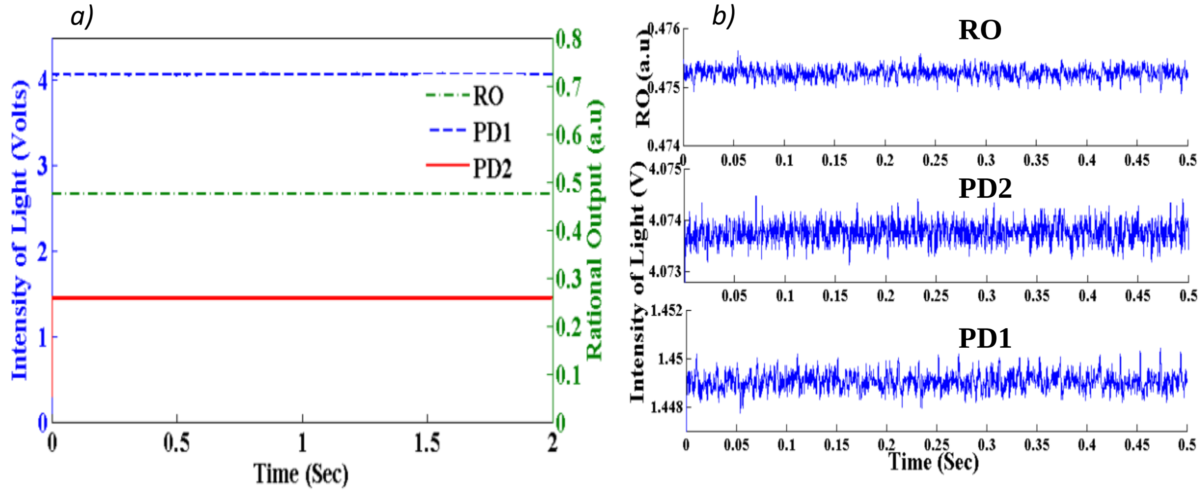

Figure 6. *a)* Stability of the signals, *b)* Noise of the signals.

4. RESULTS AND DISCUSSION:

Figure 6(a) shows the signals of PD1, PD2 and rational output at constant distance from the sensing probe to the reflector attached to the centre of the speaker diaphragm. This reveals the stability of the detected signals. The signal to noise ratio (SNR) is calculated for RO, PD1 and PD2 and found to be 77.51dB, 92.53dB and 74.38dB respectively. The SNR of the RO is improved when compared to PD2 as shown in figure 6(b). The sine wave is applied to the speaker and the TDS response of the sensor is recorded by the NI-DAQ at frequency of 700 Hz is shown in figure 7. The FFT of the signal gives the frequency of the sensed signal and there is a perfect matching in frequencies between applied and sensing signals. The peak to peak voltage of the output signal gives the amplitude of vibration using the slope of the calibration curve which corresponds to displacement amplitude d_p. For a give frequency f_p the peak velocity v_p and peak acceleration a_p can be computed by [20]

$$v_p = (2\pi) f_p d_p \tag{1}$$

$$a_p = (2\pi)^2 f_p^2 d_p \tag{2}$$

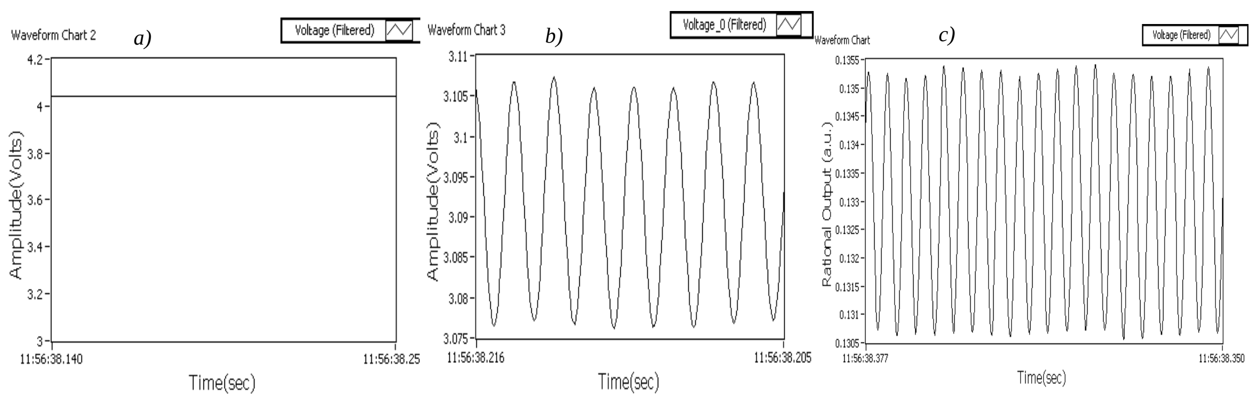

Figure 7. The waveforms of TDS at 700Hz *a)* PD1, *b)* PD2 and *c)* RO

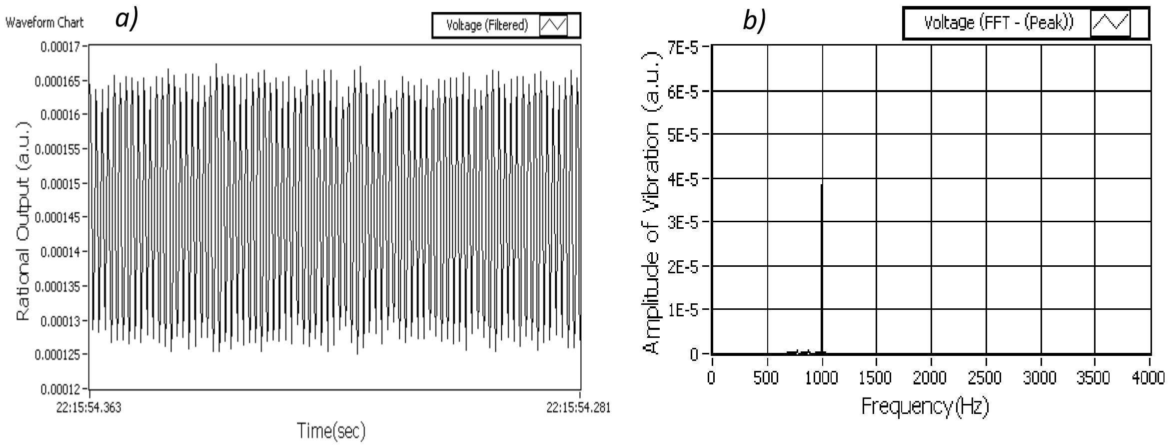

Figure 8. *a)* TDS waveform of RO Sensing signal and *b)* spectrum of FFT at 1 kHz.

The sensed TDS waveform is recorded by the DAQ and corresponding FFT spectrum for 1 kHz is shown in figure 8. Figure 9 illustrates the relation between the frequency applied and frequency measured by the sensor. At constant amplitude of vibration i.e., at constant driving voltage, the frequency range of 0-3500 Hz applied to the speaker and corresponding frequency is measured by the sensor. The obtained results shows, up to 3500 Hz there is a perfect matching between the frequencies applied and measured by the sensor output. In between 3500 Hz to 4000Hz, the sensor exhibits an error of ±5 Hz in its vibration measurements because the noise in the sensing signal is dominating and beyond 1400 Hz there is no response of sensing from the sensor, producing only dc output.

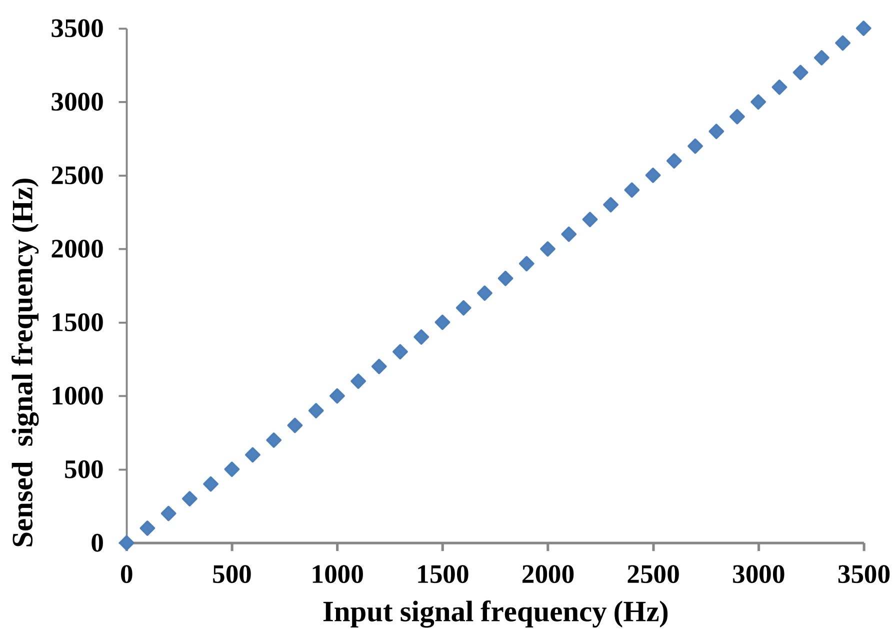

Figure 9. Frequency response of the vibration sensor.

Figure 10 shows the sensor output at a constant frequency of 100Hz for varying amplitude of vibration. The amplitude response of the sensor between the driving voltage to the speaker and FFT peak

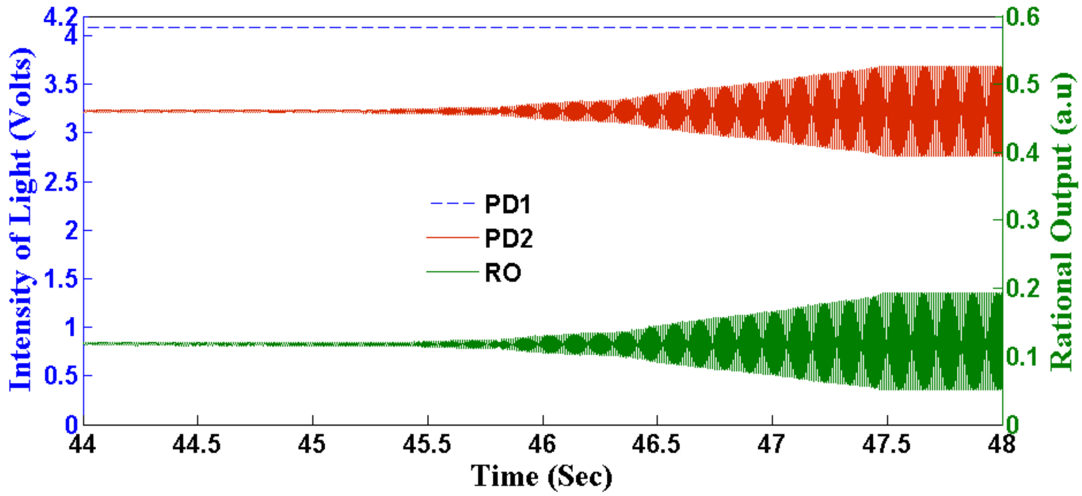

Figure 10. TDS spectra from the sensor for continuous varying amplitude of vibration at 100 HZ.

voltage of output signal at different frequencies are plotted in figure 11. It is observed that the amplitude of vibration is linear with correlation coefficient of 0.99, in response to the driving voltage to the speaker. The resolution of the sensor is calculated from the minimum amplitude of vibration detected by the sensor at maximum frequency. The sensitivity of the vibration sensor is found to be 0.36 a.u. /mm (2.1mV/µm) for a dynamic range of 1mm from the slope of the displacement characteristic curve. Experimentally the minimum amplitude resolvable by the sensor is 1E-5 a.u., which corresponds to the resolution of 0.028µm. The experiment is repeated to test the reliability and response of the sensor system and which is found to be consistent.

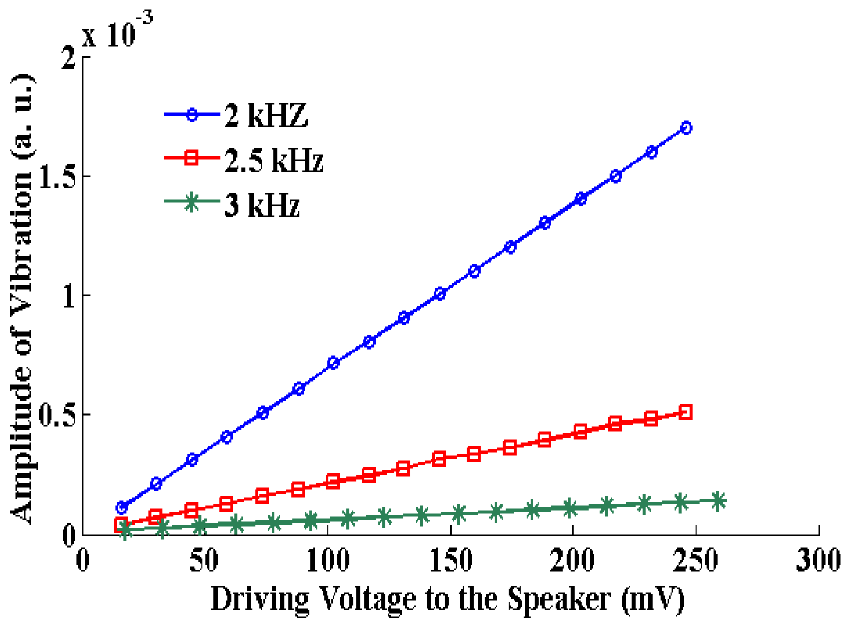

Figure 11. Amplitude response of the sensor at different frequencies.

In general, the possibilities of error might be occurred in non-contact intensity modulated measurements are fluctuation in the source of light, the stray light effect and dust formation on the mirrors. A hollow cylindrical protection tool is arranged surrounding of the reflector so that the stray light cannot interfere with the source light and to avoid formation of dirt on the mirror. The sensor is positioned very close within the sensing linear region to the vibrating target and not requires special optics are especially useful for sensing applications in embedded situations.

5. CONCLUSIONS:

In this paper, a simple geometrical intensity modulated non-contact vibration sensor has been presented using 2x2 fiber optic fused coupler. A single fiber is used as sensing probe and it consists only one slope with high sensitivity of 2.1mV/µm for a dynamic range of 1mm linear region facilitates the easy alignment and accurate measurement. Minimized the effect of source signal fluctuations and fiber bending losses by adopting rational output technique. The experimental results show that the sensor is capable to measure the frequency up to 3500 Hz with ~0.03µm resolution of vibration amplitude over a dynamic range of 0-1mm. It is also observed that the SNR of rational output is improved with respect to sensing signal. In comparison with dual-fiber and bifurcated-bundle fiber, this sensor eliminates the dark region and front slope which facilitates the easy alignment. The simple in design, non-contact measurement, high degree of sensitivity, economical along with advantages of fiber optic sensors are attractive attributes of the designed sensor that lend to real time monitoring and embedded applications.

References

[1] David Zook, J., William, R., Herb, Bassett, C., J., Terry Stark, Jeff N., Schoess, and Mark, L. Wilson. 2000. Fiber Optic Vibration sensor based on frequency modulation of light –excited oscillators. *Sensors and Actuators* 83: 270-27.

[2] Slavic, J., Cermelj, P., Babnik, A., Rejec, J., Mozina, J., and Boltezar, M. 2002. Measurement of the bending vibration frequencies of a rotating turbo wheel using an optical fiber reflective sensor. *Meas. Sci. Technol.* 13: 477-482.

[3] Bela G Liptac, "Instrument Engineer's Hand Book: Process Measurement and analysis", published by CRC Press, Fourth edition, Vol. I, pp. 1102-1117, 2003.

[4] D. A. Krohn, "Fiber Optic Sensors: Fundamentals and Applications", published by Instrument Society of Americal, USA, Second Edition, 1992.

[5] Culshaw Brain and John Dakin, "Optical fiber Sensors: Applications, analysis, and future trends", Artech House Inc., Boston, London, Vol. 4., 1997.

[6] Alayli, Y., Topcu, S., Wang, D., Dib, R., and Chassagne, L. 2004. Applications of a high accuracy optical fiber displacement sensor to vibrometry and profilometry. *Sensors and Actuators* A 116: 85-90.

[7] Maria Luisa Casalicchio, Guido Perrone, and Alberto Vallan. 2009. A Fiber Optic Sensor for Displacement and Acceleration Measurements in Vibration Tests. *I2MTC2009*, Singapore, May, pp. 5-7.

[8] M.R. Saad, Dr. M. Rehman and Dr. Othman Siddiqui, "Development of Linear Fiber Optic Pressure sensor", IEEE LTIMC2004, Palisades, New York, USA, 2004.

[9] N. Sathitanon, and S. Pullteap, "A Fiber Optic Interferometric Sensor for Dynamic Measurement", International Journal of Computer Science and Engineering 2;2 2008, pp.63-66.

[10] Donati, S. 2004. Electro- optical instrumentation: sensing and measuring with Lasers. *Upper Saddle River:* Prentice Hall,.

[11] Giuliani, G., Norgia, M., Donati, S., Bosch, T., 2002. Laser diode self-mixinTechnique for sensing applications", *J. Opt. A: Pure Appl. Opt.* 4: S283-S294.

[12] Castellini, P., Martarelli, M., Tomasini, E, P. 2006. Laser Doppler Vibrometry: Development of advanced solutions answering to technology's needs. *Mechanical System and Signal Processing* 20: 1265-1285.

[13] Chijioke, A., Lawall, J. 2008. Laser Doppler vibrometer employing active Frequency feedback", *Appl. Opt.* 47: 4952-4958.

[14] Chang, J., Wang, Q., Zhang, X., Huo, D., Ma, L., Liu, X., Liu, T. and Wang, C. 2009. A Fiber Bragg Grating Acceleration Sensor Interrogated by a DFB Laser Diode. *Laser Physics,* 19(1) : 134–137.

[15] Binu, S., Kochunarayanan, K., MahadevanPillai, V., P., and Chandrasekaran, N. 2010 PMMA (Polymethyl Methacrylate) Fiber Optic Probe as a Noncontact Liquid Level Sensor. *Microwave and optical technology letters* 52(9): 2114-2118.
[16] Vijay K. Kurkarni, Anandkumar, S., Lalasangi, I., Pattanashetti, I., and Raikar, U., S. 2006. Fiber optic micro-displacement sensor using coupler. *Journal of optoelectronics and advanced materials* 8(4): 1610-1612, 2006.
[17] Kishore, P., Dinakar, D., Sengupta, D., Saidi Reddy, P., Sai Shankar, M., and Srimannarayana, K. 2012. Fiber Optic Vibration sensor Using PMMA Fiber for Real Time Monitoring. *Sensors & Transducers Journal* 136(1): 50-58.
[18] Kishore, P., Dinakar, D., Sai Shankar, M., Srimannarayana, K., VengalRao, P. and Sengupta, D. 2012. Non-Contact Vibration Sensor Using Bifurcated Bundle Fiber for Real Time Monitoring of Diesel Engine. *International Journal of Optoelectronic Engineering* 2(1): 4-9.
[19] Jun Chang, Liangzhu M, Tongyu Liu, Hongchun Wang, Dianheng Huo, Jiasheng Ni and Zhidong Shi, 2007 "Fiber Optic Vibration Sensor Based on Over-coupled Fused Coupler", Proc. of SPIE Vol. 6595, pp.65954C-1-65954C-6.
[20] http://www.spaceagecontrol.com/calcsinm.htm .