

GSJ: Volume 7, Issue 9, September 2019, Online: ISSN 2320-9186 www.globalscientificjournal.com

# EMPIRICAL DETERMINATION OF THE SEVERITY OF VIBRATION SOURCES IN BRIDGES USING A DISTRIBUTED FIBER OPTIC SENSING TECHNIQUE.

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## ABSTRACT

The transient nature of force induced in bridges during vehicular motion requires dynamic analyses of the spectrum of a sensed vibration signal to fully characterize their behavior. This dynamic interaction between the vehicle and bridge induces a vibration in the bridge and this degree of vibrations in the bridge can be sensed using an optical fiber while the spectrum of the vibrations is measured using an Optical Time Domain Reflectometer(OTDR). The OTDR trace shows the various degrees of attenuations across the optical fiber cable. Useful information such as the location of vibration, the severity of vibration, vibration frequency and the vibration modes can be successfully modeled from the recorded OTDR traces. This work focused on measurements and analysis of loss associated with vibration and hence a statistical determination of the vibration severity concerning the dynamic interaction time between the optical fiber and the traversing vehicle as captured on a time series video clip.

## I. INTRODUCTION

Technique for fiber optic sensing is very important since it is cost efficient and non-destructive; for instance, a few dozens of multiplexed optical fiber will replace several thousands of convectional acoustic sensors. The ever-increasing need for sensors that are robust, affordable and durable in environments that are characterized by spurious climatic variations has introduced a paradigm shift in the sensing technology to the use of Optical fiber as sensors. For instance, conventional sensors are prone to damages due to lightning, exposure to harsh environment, wrong calibrations and electromagnetic interference (Anna 2016) which often introduce noise into the measurements. The use of fiber sensing covers the work of several hundreds and thousands of conventional sensors. Sensors are defined as a device that measures a physical quantity due to change in physical stimulus and converts it into a signal which can be read by an observer or by an instrument Zheng-Hua(2010).

Most conventional sensors have limitations with their usage because they are mostly affected by electromagnetic interference Anna(2016) and noise addition during analog/digital conversions Zheng-Hua(2010).

Fiber optic used as sensors are excellent candidates for monitoring environmental changes and they offer many advantages such as easy integration into a wide variety of structures, inability to conduct electric current, immune to electromagnetic interference, High sensitivity. Fiber optics sensing which uses guided light as a probe is the most efficient approach for sensing because it is cost-efficient and employs a nondestructive approach during installations (Wang et al., 2013).

Most notable sensing applications of fiber optics include among others position\vibration sensing, pressure sensing, temperature sensing, pipeline leakage sensing, intrusion/motion sensing, Humidity sensors, strain sensors, Biosensing e.t.c.

Structural health monitoring (SHM) relies on the automatic detection of anomalous behavior of structures because the unpredicted Structural failure may cause catastrophic, economic, and human life loss (Wei Fan and Pizhong Qiao 2013). A reliable and effective study of this dynamic characteristic of the structure is very important since the knowledge of such peculiar characteristics enhances a robust method for quantifying the assurance of their integrity and mechanical health.

(Abdollah et al., 2015) indicates that an accurate experimental knowledge of the natural vibration frequency spectrum of structure can help to predict the risk associated with positioning them close to human existence and the outcome of such analysis could be used to determine the proper time for structure maintenance, reinforcement and possibly a controlled demolition since an analyzed low value of natural vibration (resonant) frequency could mean a quick structural failure in the face of ambient effects. Any crack or localized damage in a structure reduces the stiffness and increases the damping in the structure. Many researchers have used one or more of the above characteristics to determine the severity/ magnitude of vibration sources and also to detect and locate cracks in structures. Optical sensing which uses light as a probe has proven to be one of the most efficient approaches for this purpose since it is cost-efficient and nondestructive.

With the invention of the laser in 1960's, great interest in optical systems for data communications began and several research works have concluded the possibilities for using optical fiber as a sensor for data communications, vibration sensing, pressure sensing, temperature sensing, bio-sensing, and other sensing applications. Fiber optic used as sensors are excellent candidates for monitoring environmental changes and they offer many advantages such as easy integration into a wide variety of structures, inability to conduct electric current, immune to electromagnetic interference and radio frequency, lightweight, more resistant to harsh environments, High sensitivity, multiplexing capability to form sensing networks, remote sensing capability, multifunctional sensing capabilities over conventional electronic sensors.

Vibration measurements have been conducted on varieties of structures and systems using OTDR (Optical Time Domain Reflectometer). Some examples of such OTDR base measurements and analysis include "Dynamic strain measurements in piezoelectric devices". Meiqi et al. (2016) measured the dynamic strain induced by sinusoidal piezoelectric (Lead Zirconate Titanate) vibration signals. These vibration signals produce a direct consequence which manifest as the driving voltages of Lead Zirconate Titanate (PZT) in  $\Phi$ -OTDR, the conclusion of the work asserts that the trace to trace correlation coefficient of an OTDR can be used to analyze system noise which is beneficial to uncertainty measurement.

CHAO et al. (2017) and Hugo (2015) worked on research to study the possibility for remote detection of intrusion and the location of intrusion points over large structures such as national borders, military bases or pipelines using optical fiber as the sensor and their works concluded positively.

The possibility of measuring serious instantaneous and high-speed vibrations to infer structure/machine health using frequency division multiplexed phase-OTDR was investigated (Daisuke et al. 2017). He monitored and measured structure/machine health based on vibration signals received in fiber sensors since vibrations are unavoidable in such mechanical and structural pieces of equipment. These structures are usually built-up from sub-structures coupled together at various interfaces/joints. Each substructure often has quite different vibration properties due to differences in material and geometric properties. Ji et al. (2006) consequently concluded that the vibrations of the whole structure often involve both long- and short-wavelength deformations.

Olsen et al. of the Boeing co. performed a ground vibration test on the mated configuration of the 747 shuttle carrier aircraft and space shuttle orbiter to determine the structure coupled mode to understand the aeroelastic responses

expected in flight and the prediction of flutter stability using fast Fourier analysis of the vibration data.

Due to cost-effectiveness and possibility for large area coverage, fiber sensing is attracting attention and for more than 25 years, phase-sensitive optical time-domain reflectometry has been widely studied and reported in the literature as a result of the potential for fully distributed monitoring of vibration along an optical fiber cable Hugo et al. (2015). H. Taylor proposed this technology by detecting the intensity changes of interferometric light in 1993 as surmised by Yu Wang et al. (20016).

The novel work of Kazuro et al (2006) further confirms the claim of a newly proposed principles and geometrical arrangements of optical fiber for vibration measurement on the premise that the frequency of lightwave transmitted through a bent optical fiber is shifted by vibration at the bent region as concluded (Kageyama et al 2003, 2005 and 2006).

Read et al. (2002) claims that when loads are applied to undamaged structures, the load force is expected to be uniformly distributed across the structure while it would be observed that the stress will be concentrated at some points in the structure when damaged. A sudden redistribution of local stress due to damage/sudden impact releases energy as high-frequency pressure wave (Vibration) which necessitates intensity variation of the interferometry light across the sensing fiber length.

This work aims at determining the severity of vibration sources in bridges based on the magnitude and transit/impact time of the vibration source in optical fiber laid inside the bridge grooves. Bridge vibration is induced by ambient and vehicular effects hence the severity of the vehicular impact is registered on the photons of light propagating inside the fiber optic cables. The vibration impact level is sensed using an OTDR which measures vibration amplitude in a time domain and the corresponding measurement is analyzed using Trace view 5.0 and the corresponding data analyzed and appropriately graphed using Graph Pad Prism 8.0.

# II. DYNAMICAL NATURE OF STRUCTURES

Structural health monitoring (SHM) relies solely on the automatic detection of anomalous structural behavior. SHM using the dynamic response of structures is becoming an increasingly popular part of infrastructure maintenance and management systems. Measurement, analysis, and characterization of this structure require a nondestructive and effective approach; fiber optic sensing gives a prospect for such requirements. For a continuous un-damped structure, the general form of the equation that governed its motion according to Arden (2009) is given as follows:

$$w(x) = \sum_{n} w_n \sigma_n(x)$$
 2.2

 $\sigma_n(x)$  is the n<sup>th</sup> mode shape function and  $w_n$  associated generalized coordinate.

The orthogonal property of  $\rho(x)$  gives

$$\int_{0}^{\nu} \rho(x) \sigma_{n}^{T}(x) \sigma_{m}(x) dx \qquad 2.3$$

$$n \neq m$$

Theoretically, there are infinite numbers of modes in any continuous system/structure, but we however in practice translate the modal sum to a convenient finite number by the criterion of convergence.

Combining equations 2.1 to 2.3, the equation governing  $w_n$  is given in a matrix form by

$$M\ddot{w}_n + Kw_n = F_n \tag{2.4}$$

M and K are the mass and stiffness matrices respectively while  $F_n$  is a generalized modal force vector.

The (n, m) element of M and K are following

$$M_{nm} = \int_0^v \rho(x) \,\sigma_n^T(x) \sigma_m(x) \,dx \qquad 2.5$$

and

$$K_{nm} = \int_0^v \sigma_n^T(x) L[\sigma_m(x)] dx \qquad 2.6$$

M and K are always diagonal matrices.

## III. MATERIALS AND METHODS

Materials

- Single mode fiber optic cable
- Optical Time Domain Reflectometer(OTDR): Anritsu MT9083A-063
- Patch Panel
- Media Converter/Transmission Equipment
- Flash Drive

**Test Procedure** 

Power laser from the OTDR was fed into the single mode optical fiber under test to test for continuity before measurements were taken. The fiber under test(FUT) was connected to the OTDR via the patch panel port. The FUT were hence laid in the grooves of the bridge in preparation for taking measurements. The FUT has a total length of 5km, refractive index of 1.4682, the optical pulse width was set to 5ns with a wavelength of 1300ns. Measurements were taken and the appropriate traces were logged on the OTDR built-in memory space while the dynamic interaction time between the optical fiber and the traversing vehicle as captured on a time series video clip. The logged data were later copied to a flash drive and appropriately analyzed using trace view 5.0 software.

#### IV. MEASUREMENTS AND TABLES

The measurement were taken in two trips characterized by different level of

- traffic and pedestrian activities and the losses for each trip were separately analyzed and
- presented. Traffic and pedestrian activities was severe on the first trip while the second

trip witnessed a lesser activity on the bridge. The analyzed losses in the FUT were

categorized under two categories following: Losses associated with the vibration of the

FUT due to vehicular and pedestrian motions and those associated with optical

reflection/backscatter. The scope of this research was limited to extraction and

interpretation of the losses associated the vibration of the FUT from the OTDR logged

- data while the other categories of losses was neglected because they were characterized
- as noise events arising from backscattered signals coming from the optical end of the FUT

after travelling an optical distance of approximately 60meters.

	Trace No	Loss 1(dB)	Loss 2 (dB)	Trace No	Loss 1(dB)	Loss 2 (dB)	Trace No	Loss 1(dB)	Loss 2 (dB)
	1	0.323	0.314	14	0.285	0.283	32		0.016
						0.033			0.029
	2	0.344	0.311	15		0.329	33	0.015	0.048
									0.03
									0.032
	3	0.184	0.321	16		0.32	in the second		
1		0.065					34		0.038
11		0.012		17		0.278			0.038
11 -		0.022			-		_		-0.011
				18		0.29			0.058
				1100		-0.016			
	4	0.274	0.275	-			35		0,101
				19		0.32		100	0.096
									/
	5	0.172	0.301				36		0.097
		0.098		20		0.293			
							37	0.011	0.095
				21	0.014	0.108			
	6	0.201	-0.015			0.018	38		0.296
		0.092	0.311						
				22			39	0.013	0.293
	7	0.172	0.297				40		-0.014
		0.09		23		0.015			0.291
				24					
	8	0.253	-0.015						
	-		0.315	25	-0.03				
	9	0.02	0.298						
	-			26	0.046				
	10	-0.013	0.306						
				27		0 147			
	11		0 243						
			0.210	28					
	12	0 244	0 244						
		0.2.11	0.211	29		0 293			
				20		0.385			
	13	0.252	0.238	30		0.000			
	10	0.202	0.031	00					
			0.001	31		0.061			
		1		51	I	0.001			

# TABLE I: ANALYSED VIBRATION LOSSES FOR THE TWO TRIPS

#### VI. RESULTS

A detailed comparison of the graphed values of the vibration figure (a)-figure (f) reveals that significant losses were associated with vibration values accrued for trip 2. I will be quick to bring to remembrance that the trip 2 data acquisition were done amidst absence of traffic delay such that the transverse impact time between the FUT and the vehicles was transient. The loss variation in figure (a)figure (b) above is owned to the fact that there exist a variation in the types and weight of the vehicle that transverse the FUT. Larger peak value of attenuation suggests that the vehicle are either fast moving, high momenta vehicles at the instant of impact or heavy duty vehicles such that there exist a linear relationship between the momentum of the vehicle (vibration source) and the degree of loss. The viability of the results is establish from as a stepwise comparison of the observations earlier concluded from the graphs with the visual observation as recorded on a time series video clips. Also the mean attenuation comparison for both trips confirms a larger mean loss value and a lesser standard deviation for trip 1 to trip 2. We conclude that on a day characterized by lesser traffic, the vehicular momenta are higher, the impact time between the vehicle and the FUT is transient hence, vibration severity is much thus producing a higher optical loss in the FUT.





Fig (a): Variation of Location loss for the 40 trace samples of trip1, Fig (b): Variation of Location loss for the 40 trace samples of trip2, Fig (c): Loss variation for the two trips compared side to side, Fig (d): Loss comparison for the two trips, Fig (e): Loss comparison for the two trips in Line graph, Fig (f): Mean loss variation for the two trips

#### VII. CONCLUSION

Sequel to the above observed and experimental result, it may be reasonable to conclude that optical fibers can be used as vibration sensor for which degree of vibration could be modeled as a linear variation of optical loss (attenuation) in the FUT since the result of our graph data predicts a successful linear interaction between such properties i.e. the empirical loss values agrees to produce a linear variation with the severity of optical vibration. This idea to the best of my knowledge opens up a fresh page in weight and speed sensing technology on high ways and in theory raises a question on mathematical models and equations on the variation of momentum with respect to optical loss.

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