Experimental Study of Vibration Sensitivity in Unidirectional Polarimetric Current Sensors

P. Tantaswadi, S. Maheshwari, and C. Tangtrongbenchasil
Sirindhorn International Institute of Technology, Thammasat University,
School of Electrical Engineering and Information Technology,
PO Box 22,Thammasat Rangsit Post Office, Pathumthani 12121

Abstract

Accuracy of current measurement in optical fiber current sensor is affected by the environment perturbations to the sensing fiber such as mechanical vibrations, acoustic perturbations, and temperature changes. This paper presents the experimental study of the effect of mechanical vibrations on the current measurement error. Results show that current measurement error varies linearly with the amplitude of vibration. We also develop a novel mathematical model for vibration sensitivity in unidirectional polarimetric current sensors. In this paper, we believe that it is the first time that the effect of vibration to the single-mode-sensing fiber on the current measurement error in fiber optic polarimetric current sensor is formulated. Simulation results agree well with the experimental results.

Keywords: current sensor, polarimetry

1. INTRODUCTION

Fiber-optic current sensors have received considerable attention for possible application in electric power industry as magneto-optic current transformers (MOCTs) [1]-[5]. These MOCTs inherently have several potential advantages over conventional ferromagnetic current transformers (CTs) like flat bandwidth response (DC to several MHz), wide linear dynamic range (more than five orders of magnitude), no hysteresis, insensitive to EMI and RFI owing to their all-dielectric structure. smaller size, lighter weight, easy installation, immune to catastrophic explosive failures [1].

In practice the current sensors are invariably exposed to acoustic vibrations [2]-[4]. Vibration change the linear birefringence (δ) in the sensing coil of fiber which in turn changes the evolution of the state of polarization of the light through the sensing coil.

In this paper a general mathematical model of vibration sensitivity due to birefringence effect in sensing part in unidirectional polarimetric is presented. Corroborating experimental results are also presented.

2. PRINCIPLES

When plane polarized light propagates in an optical fiber wound around a current carrying wire, the induced magnetic field causes a rotation of the linear polarization plane of lightwave by the magneto-optic Faraday effect. This angle of Faraday rotation, F, is given by $F = VNI$, (1)
where V is the Verdet constant of the optical fiber, N is the integral number of turns of fiber, I is the current through the wire. The Verdet constant depends on source wavelength and temperature. For example, the operating wavelength λ is 633 nm and the Verdet constant V is 4.68 $\mu rad/A_{rms}$.

In Eq (1) to measure current I, with constants N and V, we need to measure Faraday rotation, F, for which we can use a unidirectional polarimeter sensor shown in Figure 1. It consists of input linear polarized electric field (E_{in}) entering the sensing fiber loop, an analyzer aligned θ degrees with respect to the birefringence fast axis of the fiber loop, and a detector.

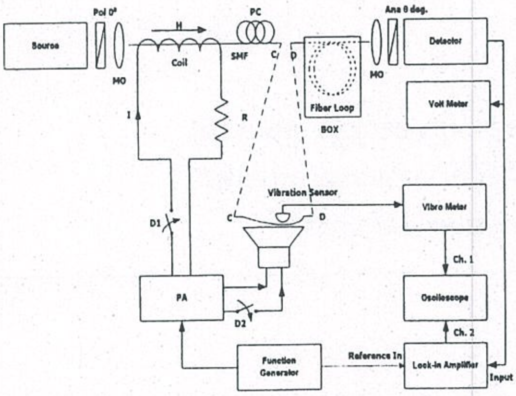

Figure 1 Unidirectional polarimetric current sensor and its experimental set-up, MO: microscope objective lens, SMF: single-mode fiber, PC: polarization controller, Ana: analyzer, PA: power amplifier

In our experiment, we align the analyzer with θ of 60°, where the output signal-to-noise ratio (SNR) is better than that at θ of 45°, where the sensitivity of the sensor is maximum. A normalized intensity at output ($Intensity \propto |E_{out}|^2$) of the detector is given by [2]

$$\frac{I_{60^\circ}}{I_0} = \frac{1}{4} + \frac{\sqrt{3}}{2}\frac{\sin(\sqrt{4(F+T)^2+\delta^2})}{\sqrt{4(F+T)^2+\delta^2}}\cdot(F+T) + \left[1-\cos(\sqrt{4(F+T)^2+\delta^2})\right]\cdot\frac{(F+T)^2}{4(F+T)^2+\delta^2} \quad (2)$$

where E_{out} is the output electric field and I_0 is the maximum intensity at the detector. δ, F, T, and α are the linear birefringence, Faraday rotation, twist-induced (circular) birefringence, and total birefringence in radians.

2.1 Current measurement

For an ideal fiber (δ, T=0) Eq (2) becomes

$$\frac{I_{60^\circ}}{I_0} = \frac{1}{2}\left[1+\sin(2F-30^\circ)\right] \quad (3)$$

In Eq (3) when no current is applied (F=0) the output is constant. When AC current ($I(t) = A\sin\omega t$) is applied (where A is zero-to-peak amplitude in Ampere), F can be described by

$$F(t) = V\,N\,I(t) = (VNA)\sin\omega t = F_0 \sin\omega t \quad (4)$$

$F_0 = VNA$ is a constant. Substituting Eq (4) into (3), we obtain the phase modulation signal at detector's output.

$$v_D = \frac{K}{2}\left[1+\sin(2F_0\sin\omega t - 30^\circ)\right], \quad (5)$$

where K is the maximum output voltage at the detector. For very small value of F_0 Eq (3) can be approximated by [2]

$$v_D(t) = v_{DC} + v_{AC}(t) \approx v_{DC} + v_{(0-p)}\sin(\omega t) \approx \frac{K}{2}\left[1+2\sqrt{3}F_0\sin(\omega t)\right] \quad (6)$$

When F_0 is small and less than 0.04 radian, detector voltage $v_{(0-p)}$ is linear proportional to the applied current amplitude (A) as given by $V_{(0-p)} \propto 2\sqrt{3}F_0$.

2.2 Signal Modulation

Current measurement can be found by a ratio of $v_{(0-p)}$ to v_{DC}, which is known as "signal modulation." Thus signal modulation using Eq (6) is given by

$$\frac{v_{(0-p)}}{v_{DC}} = 2\sqrt{3}F_0 = 2\sqrt{3}VNA \quad (7)$$

The sensor output is linear up to 0.04 *rad* ($\sin(x) \approx x$, when $x < 0.04\,rad$) or about 8,500A_{rms} ($.04rad/\ V = 4.68\times10^{-6}\,rad$ for wavelength of 633 nm). If the applied current is 1000 A_{rms} the signal modulation using Eq (7) will be 1.62x10^{-2}. In practice, δ is not negligible but T is *e.g.* δ = 0.660 and T = 0.05 radians. When the applied current is 1,000 A_{rms}, the signal modulation using Eq (2) and (6) is 1.378x10^{-2}. Scale factor of the sensor is defined by $SF = \frac{\text{signal modulation (in experiment)}}{\text{signal modulation of the ideal case}}$.

In this case, the scale factor SF is 0.85.

3. MATHEMATICAL MODELING OF LINEAR BIREFRINGENCE CHANGE Vs VIBRATION (11)

We consider the linear birefringence in the sensing fiber being composed of bending-induced linear birefringence (δ_{DC}) and vibration-induced linear birefringence(δ_v). Vibration induced linear birefringence is caused by transverse strain or vibration [3]

$$\delta_v = {}^{2\pi}\!/_{\lambda}\,\Delta n\, l, \quad (8)$$

where Δn is the refractive index change induced by stress in the medium (silica in this case), l is the effective length (under perturbation) of fiber, and λ is the center wavelength of the source. The refractive index change is given by $\Delta n = -\frac{n^3}{2} p\sigma = 0.311\sigma$, where n is the (unperturbed) refractive index of medium, σ is the strain and p is the photoelastic constant of fiber (p = 0.2 in silica). The (static) bending-induced birefringence (δ_{DC}) per turn of a fiber loop with radius R under no tension can be described by [3]

$$\delta_{DC} \approx \frac{0.6\pi}{R} \ ^{\circ}/\text{turn}. \tag{10}$$

In our case, R of 0.3 m results in δ_{DC} of 6.3 °/turn. Six turns of fiber loop result in δ_{DC} of 37.8°.In our case, R of 0.3 m results in δ_{DC} of 6.3 °/turn. Six turns of fiber loop result in δ_{DC} of 37.8°.

We assume that (total) linear birefringence (δ) in single-mode sensing part is the algebraic sum of the (static) bending-induced linear birefringence and vibration-induced linear birefringence.

$$\delta = \delta_{DC} + \delta_v \sin(\omega_v t), \tag{11}$$

where $\omega_v = 2\pi f_v$ and f_v is the frequency of the vibration δ_v and T is much smaller than δ_{DC} in our configuration.

3.1 Current measurement error due to vibrations

In this section we formulate a mathematical model of the vibration sensitivity. In Eq (2), if no current (F = 0) and no vibration are applied (and assume that the δ_{DC} and T are constant), the output should be constant. However when the vibration is present it perturbs the linear birefringence and modulates the angular rotation, which is not distinguishable from that of the Faraday rotation (F). Substituting Eq (11) into (2), we obtain a phase modulation signal even at no applied current. It is named apparent current or false current and is given by

$$\frac{I_{60^\circ}}{I_0} = \frac{1}{4} + \frac{\sqrt{3}}{2}\frac{\sin(\sqrt{4T^2 + (\delta_{DC} + \delta_v \sin\omega_v t)^2})}{\sqrt{4T^2 + (\delta_{DC} + \delta_v \sin\omega_v t)^2}} \cdot T + \left[1 - \cos(\sqrt{4T^2 + (\delta_{DC} + \delta_v \sin\omega_v t)^2}\right] \cdot \frac{T^2}{4T^2 + (\delta_{DC} + \delta_v \sin\omega_v t)^2} \tag{12}$$

The value of δ_V is assumed to vary linearly with the mechanical vibration and thus signal modulation varies with the same frequency When $2T, \delta_v \ll \delta_{DC}$, Eq (12) becomes

$$\frac{I_{60^\circ}}{I_0} = \frac{1}{4} + \frac{\sqrt{3}}{2}\frac{\sin(\delta_{DC} + \delta_v \sin\omega_v t)}{\delta_{DC} + \delta_v \sin\omega_v t} \cdot T + [1 - \cos(\delta_{DC} + \delta_v \sin\omega_v t)] \cdot \frac{T^2}{(\delta_{DC} + \delta_v \sin\dot{\omega}_v t)^2} \tag{13}$$

3.2 Simulated false current due to vibrations

Using Eq (13), it is shown in Figure 2 that for small vibration of single-frequency, the signal modulation varies linearly with δ_v and has the same frequency as that of the vibration.

4. EXPERIMENTAL SETUP AND RESULTS

The sensor depicted in Figure 1 was built. A wire coil with 1000 turns to simulate large value of current was used as the current carrying conductor. It was wrapped around one turn of sensing fiber The optical source was a HeNe laser with 20 mW of output optical power at operating wavelength of 633 nm. A single-mode fiber manufactured by 3M was employed. Fiber polarization controller (PC) was used prior to the single-mode fiber loop (with a radius of 30 cm to simulate the sensing part) in order to launch the linearly polarization into the linear birefringence (fast) axis of the sensing fiber. The analyzer was aligned 60° to the angle with maximum output intensity (fast axis of the fiber end).

4.1 Actual current measurement

We can find characteristics of the fiber sensor by applying current to the coil and then measuring signal modulation. The coil generates magnetic field and induces Faraday rotation in the sensor. Applied current of 1 A_{rms} to the coil of 1,000 turns is equivalent to the current of 1,000 A_{rms}. The power amplifier supplies the current to the sensing coil in Figure 1 (switch D1 is closed and D2 is opened). The sensor's output voltage consists of two parts: a DC part (v_{DC}) corresponding to the average output intensity at analyzer angle θ of 60°and an AC part (v_{AC}) corresponding to actual current measurement. Its rms value can be measured by a lock-in amplifier. In an ideal case (δ_{DC} is about 1 to 2 degrees/ turns), we get signal modulation of 1.62×10^{-2}. From our experiment, signal modulation is 1.29×10^{-2}. This agrees well with our analysis that δ_{DC} and T are 0.660 and 0.05 radians, respectively.

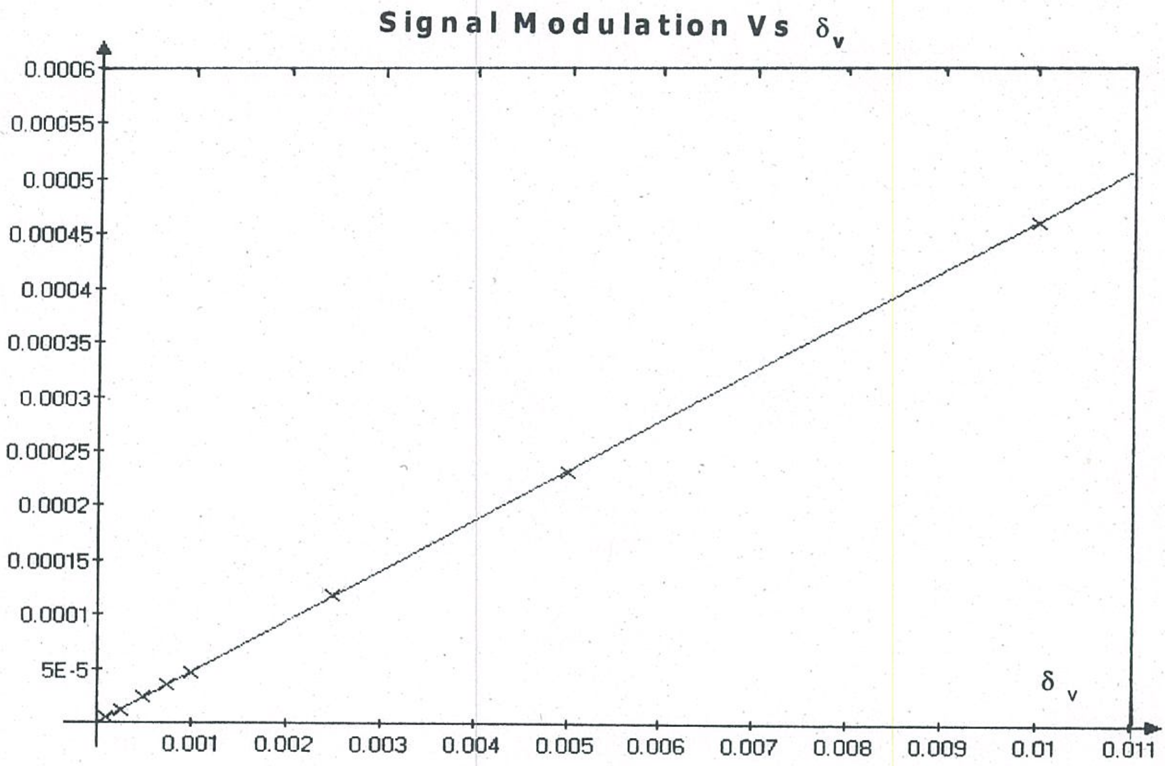

Figure 2 Signal modulation Vs vibration-induced linear birefringence δ_v.

4.2 Relationship between vibration and false current

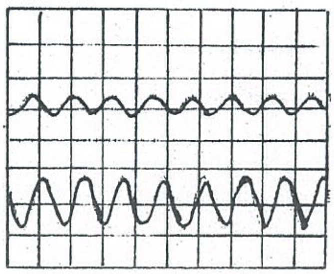

Figure 3 Vibration of 6.63 m/s^2 at the frequency of 400 Hz (top trace) and corresponding sensor's output (bottom trace).

In Figure 1, mechanical vibration was applied just in front of the single-mode fiber loop. A speaker was kept in a closed box and about 7 cm of fiber was attached to the top of the box. This box was made from acoustic absorbing material in order to isolate acoustic perturbations from disturbing alignment of the photodetector and the other optic components in the system. A power amplifier supplies signal of 400 Hz to the speaker (switch D2 is closed and D1 is opened). This produces vibration of 400 Hz. A piezo-electric accelerometer was attached to the top of the box closed to the fiber to quantify the magnitude and frequency contents of mechanical vibration. The vibration sensor is

NP-3110s manufactured by Ono Sokki and its signal conditioner is IMV TrendVibro Z model VM 4105. The output voltage of the detector was given to a Stanford Research lock-in amplifier model SR 530 to read the rms value of the AC part ($v_{(0-p)}$). DC value (v_{DC}) is measured by a DC voltmeter.

Figure 3 shows the effect of vibration on the sensor when no applied current to the sensing coil. The vibration amplitude is 6.63 (0-p) m/s^2 at the frequency of 400 Hz. Figure 4 shows signal modulation Vs amplitude of vibration from the accelerometer in m$_{(0\text{-}p)}$ /s^2. The output of the IMV vibrometer and the lock-in amplifier were given to an oscilloscope (see Figure 3).

5. DISCUSSIONS

In actual current measurement, under no vibration ($\delta_V = 0$), δ_{DC} and T are constant, the applied current is 1,000 A_{rms}.turn, the signal modulation is 1.378x10^{-2} using Eq (2). In our experiment it was 1.29x10^{-2} this is due to the efficiency of magnetic producing coil being only 93.6%. The signal modulation (or false current) varies linearly with vibration amplitude (see Figure 5). Also, simulation of our model shows that signal modulation varies linearly with δ_V. Thus, δ_V varies linearly with vibration amplitude (see Figure 5).

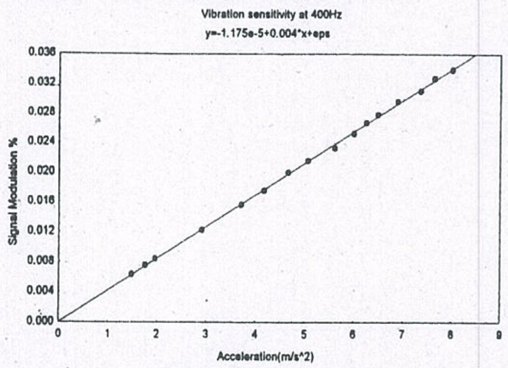

Figure 4 Vibration amplitude (0-p) m/s^2 Vs Signal modulation. The Vibration frequency is 400 Hz.

As a result, 1 g (9.8 m/s^2) of vibration produces around 46 A_{rms}.turns of the false current. With good packaging and the annealed sensing fiber (δ_{DC} is about 1 to 2 degrees/ turns) , the effect will be smaller by a few orders of magnitude. In our system vibration lower than 0.6 m/s^2 (due to noise floor limit) does not result into false current. Also, we can protect the fiber leads to the sensing fiber by using PM fiber leads which may be strewn virtually anywhere throughout the power systems with no concern of false signal detection due to vibrations. The noise equivalent current is about $0.33A_{rms.turn}/\sqrt{Hz}$.

6. CONCLUSION

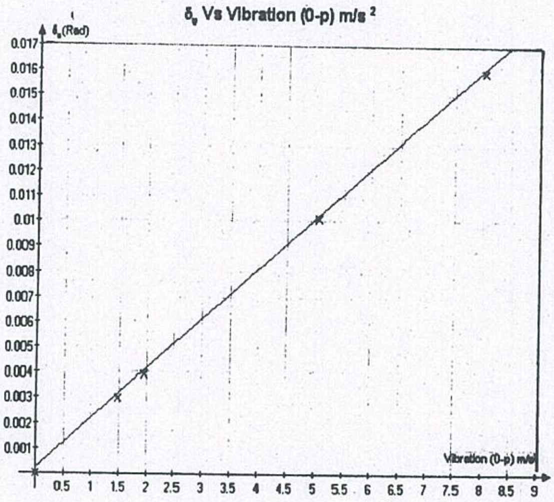

Figure 5 Linear birefringence change Vs Vibration amplitude (0-p) in m/s^2.

We have demonstrated a novel mathematical model for vibration sensitivity in the unidirectional polarimetric current sensor (UDPS). Experimental study shows that the linear birefringence δ_V due to mechanical vibration (to our understanding, no experimental studies were reported for vibration sensitivity with a single frequency of vibration and no effect of acoustic perturbations to the other optic components) changes linearly with vibration amplitude. This sensor's residual sensitivities to environmental disturbances can be further reduced by a damped packing such as putting sensing fiber part in a gel-filled tube together with employing two polarization scheme, where the two sensor's output at the +45^o and –

45° to the output fiber axes. Also, 'spun' low birefringence or annealed fiber can be used to reduce the value of (static) linear birefringence δ_{DC}. Further investigation of the magnitude of linear birefringence change under the influence of vibration should be done experimentally with the help of optical modulator.

7. ACKNOWLEDGEMENT

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