The 3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure
Vancouver, British Columbia, Canada
November 13-16, 2007

USE OF LOCK-IN AMPLIFIER AND PID CONTROL IN DISTRIBUTED BRILLOUIN SENSOR SYSTEM FOR STABILIZATION OF EOM BIAS VOLTAGE DRIFT

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Abstract

It is possible to monitor the strain along the entire length of structures such as bridges or pipelines with the use of an optical fiber based distributed Brillouin sensor. The system measures the amount of light scattered from a cw pump beam into a pulsed probe beam at all locations throughout the fiber. In such a system, it is crucial to keep the probe pulse energies uniform for constant signal to noise ratio. This means that the pulse base level (DC leakage from the electro-optic modulator) must be locked. In this paper we will examine two different methods of locking the electro-optic modulator (EOM) bias voltage and look at the advantages and disadvantages of each locking method. It is found that the two locking methods, one based on a lock-in amplifier and the other using proportional-integral-derivative (PID) control, both have applications in which they excel at locking the pulse base.

INTRODUCTION

Distributed Brillouin fiber optic sensors are capable of measuring the strain and temperature of structures along the entire length of the sensing fiber.[1-4] The sensor monitors the interaction between two counter-propagating laser beams in an optical fiber, the cw pump and the pulsed probe.[1] In order to produce the pulsed probe beam, an electro-optic modulator (EOM) is used to turn the probe beam on and off to produce the spatial resolution for distributed sensors. Since the EOM can never block 100% of the light from the laser, the probe beam will always have a dc component in addition to the pulse. In the strain sensing system, the dc component is sometimes beneficial and sometimes harmful to the sensor performance depending on the application[2, 3]. The critical problem with the EOM pulsing system is that, over time, the dc component does not stay constant, but slowly drifts resulting in reduced sensor performance – even when a stabilized voltage is applied. This means pulse energy fluctuates with time, causing SNR variation and higher measurement error. We will look at two different methods of reducing the drift of the pulse base. The first method is to lock the pulse base using a lock-in amplifier; the second method is to lock the pulse base to a set value using a proportional-integral-derivative (PID) control algorithm implemented in software. Clearly there is a need for control of the dc level on the probe pulses. In this paper we will describe and compare the two locking methods. It is found that each of the locking methods has strengths and weaknesses that make them ideal in particular applications. In applications using short pulse lengths and larger dc component, the

PID locking method is superior. In applications that require large extinction ratio and long fiber length, the lock-in amplifier method is the better performer.

BRILLOUIN SENSOR SYSTEM

The Brillouin sensor system detects the temperature and strain of a structure by measuring the Brillouin frequency shift of the attached sensing fiber at each point along its entire length. The Brillouin frequency is a material property of the fiber which varies linearly with temperature and strain.[5] The interaction of the counter-propagating pump and probe laser beams results in the transfer of power to the pulsed Stokes beam at the expense of loss of power from the cw pump beam. The interaction of the two beams is at a maximum when their beat frequency is equal to the frequency of the acoustic wave generated (the Brillouin frequency). That is, the depletion of the pump beam is a maximum when $\nu_p - \nu_s = \nu_B$, where ν_p is the pump frequency, ν_s is the Stokes frequency, and ν_B is the Brillouin frequency. A Brillouin loss profile is measured by scanning the beat frequency over a range of frequencies and detecting the intensity lost from the pump beam. A diagram of the sensor is shown in figure 1. Spatial resolution is achieved by relating the location along the fiber to the time interval between the launch of the pulse and the detection time: $z = tc/(2n)$. From the loss profiles collected, the Brillouin spectrum can be constructed at each point along the fiber and the Brillouin frequency, ν_B, measured to determine the temperature and strain at all locations along the fiber.[2]

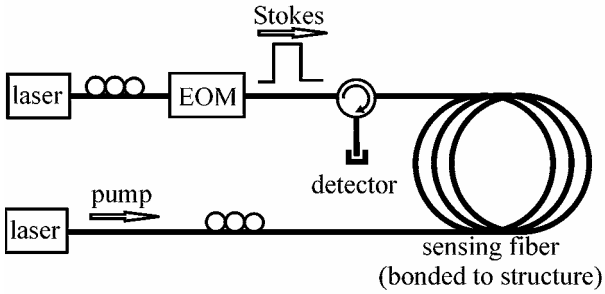

Figure 1. Distributed Brillouin strain sensor

ELECTRO-OPTIC MODULATOR

In the sensor system, a Mach-Zehnder electro-optic modulator is used to convert a cw laser beam into a pulsed beam with controllable pulse width and extinction ratio. The EOM currently being used has a maximum extinction ratio on the order of 30 dB, which means that the pulsed beam will always contain a cw component, known as leakage or pulse base. Although the presence of a cw component is usually detrimental to the system performance, at short pulse width (< 10 ns), some dc component is beneficial in reducing the bandwidth of the Brillouin spectrum for better measurement accuracy[6]. The Lithium Niobate ($LiNbO_3$) Mach-Zehnder EOM operates by splitting the power from the input into two "arms", at least one of which is a $LiNbO_3$ waveguide as in figure 2. Applying a voltage across the $LiNbO_3$ waveguide changes its index of refraction and thus alters the speed of propagation in arm 1. When the two arms are combined back together, the optical fields will have a phase relationship determined by the voltage applied. If the fields are in-phase the optical output will be a maximum, while out-of-phase fields will result in minimal optical output[7]. This dependence of a

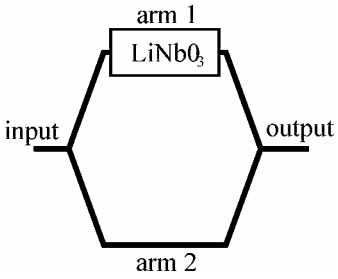

Figure 2. Mach-Zehnder EOM

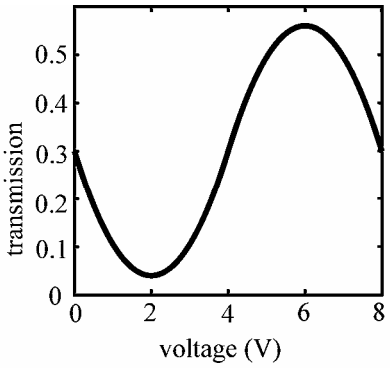

Figure 3. EOM transfer curve

transmittance on applied voltage is best visualized as a modulation transfer curve as in figure 3. The transfer curve can slowly change over time due to charging effects, or variations in temperature, wavelength, optical power, or polarization[7, 8]. The drift of the transfer function results in a drift of the optimal bias point and the stabilization of this drift is the topic of the rest for this paper.

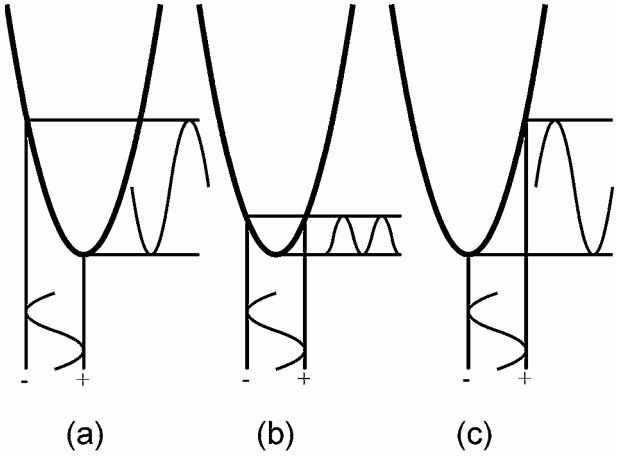

Figure 4 . Effect of bias voltage on EOM optical output

LOCK-IN AMPLIFIER

A lock-in amplifier outputs a dc voltage that is proportional to the amplitude of the input signal at the reference frequency, and also depends on the phase difference between the input and reference.[9] The lock-in amplifier can be used to lock the bias voltage to a minimum in the EOM transfer curve in the following way. The reference signal from the lock-in amplifier is fed into the bias port of the EOM – this provides a small modulation of f_{ref} on top of the optical pulses and ensures that the input frequency is equal to f_{ref} for optimal detection. In the case that the bias voltage is set at the transfer function minimum, as in figure 4b, the amplitude of the modulation on the optical output will be very small and at a frequency of $2f_{ref}$ so that there will be zero output from the lock-in amplifier. In the case that the bias voltage has drifted away from the minimum of the transfer function, the modulation amplitude will grow larger and the phase will depend on the drift direction as shown in figure 4a and 4c. When the bias voltage is too low, a minimum in the electrical modulation results in a maximum in optical output – the opposite is true when the bias voltage has drifted too high, a minimum in the electrical modulation results in a minimum optical output. The phase of the reference signal must be set so that a positive drift of the bias voltage will provide a negative output from the lock-in amplifier and vice-versa. The drift is corrected by applying the output directly to the EOM bias port. The layout of the stabilization scheme is shown in figure 5. It should be noted that although the lock-in

amplifier method is only capable of locking the pulse base to the minimum of the EOM transfer curve, the minimum pulse base level can be effectively increased by increasing the reference modulation amplitude. However, the increase of the pulse base level is accompanied by a significant increase in the measurement noise.

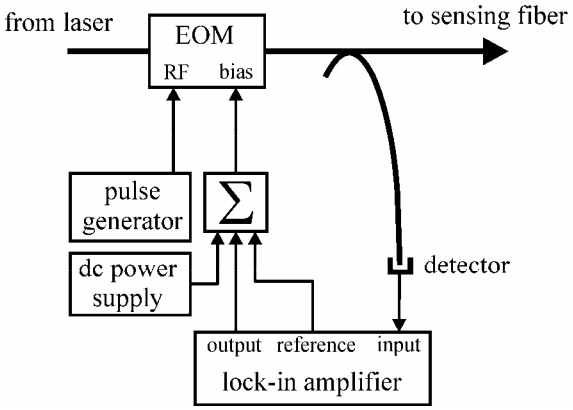

Figure 5. Bias locking setup with lock-in amplifier

In an experiment, it was found that the detected pulse base drifted by 1.04 μW over 11 minutes when no locking was present and drifted by only 0.47 μW over 30 minutes when locked with the lock-in amplifier using a reference modulation amplitude of 100 mV (figure 6). Repeating the experiment with modulation amplitude of 268 mV yielded a pulse base drifted of 0.69 μW over 18 minutes (figure 7). In addition to a decrease in stability at 268 mV modulation, the rms noise in the measurement also increased from 0.14 μW to 0.49 μW.

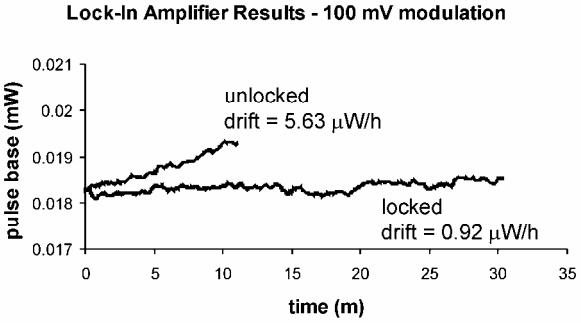

Figure 6. Results of locking with lock-in amplifier

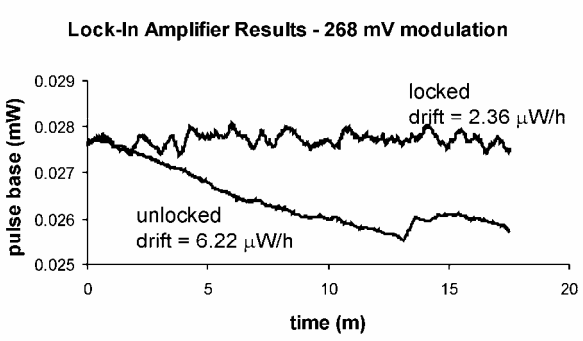

Figure 7. Results of locking with lock-in amplifier

PID CONTROL

PID control can be used to lock a process variable to a desired setpoint.[10] In many cases, it is not necessary to include the derivative control, this was found to be the case in the pulse base locking scheme since the drift was a slow, gradual process. PI control was used for this paper. To stabilize the bias drift in the sensor system using PI control, a fraction of the Stokes beam is split off after the EOM and the pulse base is measured with a dc-coupled photodetector. The setpoint of the PI controller can be chosen so that the pulse has a desired extinction ratio. The measured pulse base is compared to the setpoint to find the error signal, which is sent to the PI controller. The output from the PI controller is used to adjust the bias voltage to the EOM via a GPIB

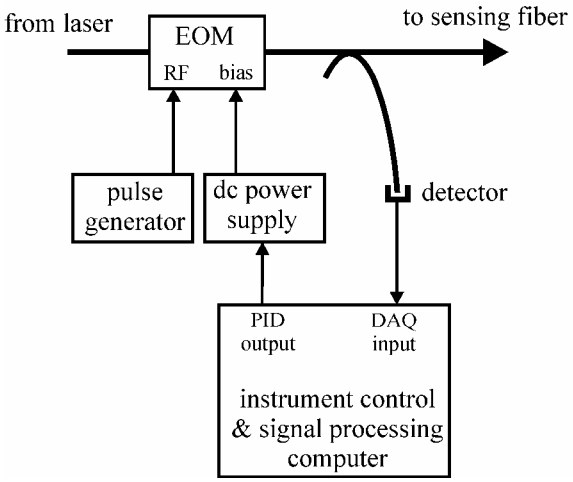

Figure 8. Bias locking setup with PID control

controlled power supply. The PID locking system is shown in figure 8. The experimental results shown in figure 9 reveal that this method is successful in reducing the bias drift significantly, from 3.31 μW down to 0.36 μW over 30 minutes. So far, the limitation of this method has been found to be the voltage adjustment resolution of the GPIB power supply.

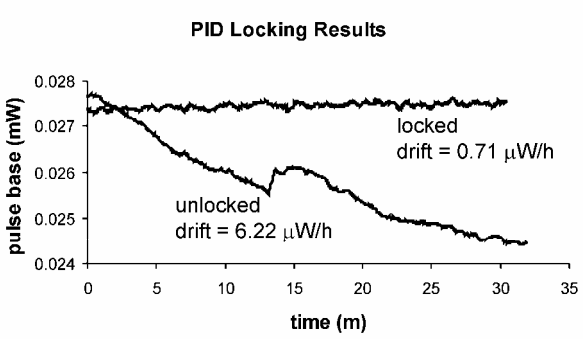

Figure 9. Results of locking with PID control

COMPARISON OF LOCKING METHODS

The two locking methods that have been discussed have been shown experimentally to work very well in the Brillouin sensor system. However, each method has its own benefits and drawbacks and also there are applications in which only one or the other will work. In most cases, when large pulses and long fiber lengths are used, it is desirable to provide Stokes pulses with the largest possible extinction ratio[2,11] – in this case, the lock-in amplifier method of bias locking is clearly superior. The lock-in amplifier method locks the bias voltage to the minimum of the EOM transfer curve; this is impossible to do with the PID method because it must operate on a region of the transfer curve that is monotonically increasing. There are also cases where accuracy and spatial resolution of the sensor can be increased by providing very short (1 - 10 ns) pulses with a lower extinction ratio (10 – 20 dB).[3,11] The PID method excels in this application since the extinction ratio can be chosen arbitrarily – the lock-in method can only operate at the minimum of the transfer curve (at a set extinction ratio) and thus would not be suitable.

CONCLUSIONS

Both methods of locking the bias voltage of the EOM in the Brillouin sensor performed well and both have applications that they excel in. The lock-in amplifier method allows the bias voltage to be locked to the minimum of the EOM transfer curve, but does not provide the option of setting the extinction ratio to any other value. The PID method allows for the bias to be locked at any level (except the transfer curve minimum), and is simple to implement into the sensor system.

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