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ABSTRACT

In this work, we present the application of a nonlinear control system, based on variable structure control and sliding modes, to a fiber optic Mach-Zehnder interferometer. We showed that this control system is able to keep the interferometer in quadrature, suppress the signal fading, lead to high accuracy control, featuring ease of implementation and high robustness. Thus, the controlled interferometer was employed for the measurement of frequency response and mechanical resonances of a cylindrical piezoelectric actuator. The advantages of an all-fiber interferometric sensor combined with the proposed nonlinear control system features compactness, light weight, alignment free, electromagnetic immunity, high sensitivity, geometric versatility, robustness, real-time high precision measurement, and possibility of operation in harsh environments.

Keywords: Optical Interferometry, All-fiber Mach-Zehnder Interferometer, Nonlinear Control, Variable Structure Control and Sliding Modes

1. INTRODUCTION

The authors have been developing a nonlinear control system, based on variable structure control and sliding modes,[1] which was able to keep optical interferometers in quadrature and suppress fading. This nonlinear controller presented high robustness, ease of implementation and low cost, thus showing a superior performance when compared with a linear controller. This system was applied in a former work to a bulk Michelson interferometer, showing that the fading was suppressed and the interferometer was kept in phase quadrature point.[1] In this work, we present the application of this nonlinear control system to an all-fiber optic Mach-Zehnder interferometer. We showed that this control system also work for fiber interferometers, since it was kept in quadrature, even under strong external disturbances. Thus, the controlled interferometer was employed for the measurement of frequency response and mechanical resonances of a cylindrical piezoelectric actuator, showing its capability to properly detect mechanical vibrations. The nonlinear control system proposed can then be applied in several types of interferometers, provided that the characteristic equation be similar.

2. THEORY

The all-fiber Mach-Zehnder interferometer used in this work is shown schematically in Fig. 1(a). The light from the laser is split in two by the optical fiber coupler, with part of the light being guided by the reference fiber and the other part being guided by the sensor fiber. These two parts, after passing through the sensor and reference fiber coils, are recombined by a second optical fiber coupler and detected by two photodetectors. At this point, a suitable demodulator is used to detect the signal of interest.

The characteristic equation for the Mach-Zehnder interferometer in photodetector 1 and 2 (PD1 and PD2 in Fig. 1(a)), in terms of optical intensity, is given by:

$$I_1(t) = \frac{I_o}{2}\{1 - \cos[\phi(t)]\}, \tag{1}$$

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$$I_2(t) = \frac{I_o}{2}\{1 + \cos[\phi(t)]\}, \tag{2}$$

where I_o is the laser intensity and $\phi(t)$ is the total phase difference between the interferometer arms. This type of equation presents a nonlinear behavior due to the sinusoidal nature of the interferometer fringe profile. The total phase $\phi(t)$ can be divided in two terms, one being the signal of interest, $\Delta\phi(t)$, and the other, the static phase shift between the two interferometer arms, ϕ_o, as:

$$\phi(t) = \Delta\phi(t) + \phi_o(t). \tag{3}$$

In an ideal case, ϕ_o should be constant, however, due to the actual spurious disturbances over the interferometer, it is actually a quasi-static quantity (variation usually occurs bellow 20 Hz), and in a few seconds the amplitude of this drift can easily be on the order of 2π rad or greater.[2] This variation on ϕ_o makes the interferometer operation point to vary with time and can cause signal fading.

The photodetector convert the optical intensity outputs in electrical voltage, with a proportionality constant A. A difference operation between of Eq. 1 and Eq. 2 produces the following output:

$$v(t) = AV\cos[\phi(t)], \tag{4}$$

where the constant A accounts for the laser power, photodiode responsivity, amplifier gain, and V is the fringe visibility.

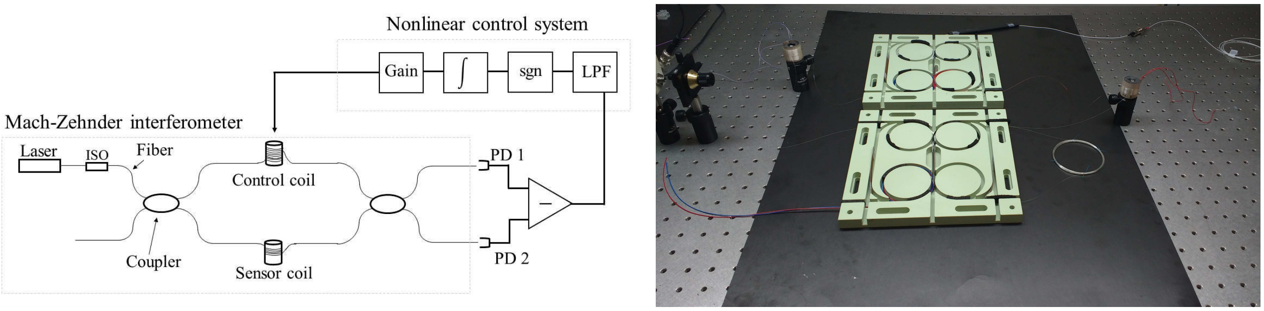
The nonlinear control system is then used to keep ϕ_o as constant and in the condition of phase quadrature,[1] i.e., $\phi_o = \pi/2$, we obtain:

$$v(t) = AV\cos\left[\Delta\phi(t) + \frac{\pi}{2}\right] = -AV\sin[\Delta\phi(t)]. \tag{5}$$

For low modulation depth, $\Delta\phi(t) << 1$ rad, $\sin[\Delta\phi(t)] \approx \Delta\phi(t)$ and $\Delta\phi(t)$ can be measured directly from $v(t)$. For the cases where $\Delta\phi(t) >> 1$ rad, a suitable phase-unwrapping demodulation technique should be used for $\Delta\phi(t)$ measurement.[1,2]

3. RESULTS

The photograph of the experimental setup developed in this work is shown in Fig. 1(b). This Mach-Zehnder configuration comprises a CW diode laser (wavelength at 1550 nm), an isolator (center wavelength at 1550 nm ISO), single mode fibers (operating wavelength at 1550 nm), two single mode optical fiber couplers (operating wavelength at 1550 nm C1 and C2), two phase modulators (comprising a cylindrical piezoelectric transducer wounded by an optical fiber coil - PZT1 and PZT2) and two photodetectors (PD1 and PD2). Therefore, two different phase modulators were incorporated into the Mach-Zehnder: one was in the sensor arm with 21 m of fiber length, and the other in the reference arm (where the control feedback actuates) with 3 m of fiber length, as shown in Fig. 1(b).



(a) (b)

Figure 1. Experimental setup (a) Schematic of losses and fiber lengths in the all-fiber Mach-Zehnder interferometer. (b) Photograph of Mach-Zehnder interferometer.

The feedback loop presented in Fig. 1(a) comprises the Mach-Zehnder interferometer, a low-pass filter (LPF), the sgn function (sign function with gain 15 V); the integrator followed by an amplifier with gain 21 V/V and the feedback piezoelectric actuator.

To eliminate the disturbances, the control system makes the output of LPF equal to zero, that is the setpoint of the system, taking the error signal to zero. Since the setpoint is zero, the cosine argument should be an odd multiple of $\pi/2$ rad, leading to a phase quadrature operation point.[1] To exemplify how the control system acts, if an initial condition makes the signal error positive when the control starts, the signal function will switch to a positive value, leading the integrator output to increase at a positive rate. Consequently, the output will decrease, leading the error to zero and output signal came to be stabilized. The system will operate in an analogous way for a negative initial condition.

It should be noted that before applying the nonlinear control in the interferometer it is necessary to suppress the DC signal of its output. Unlike the Michelson interferometer, the all-fiber Mach-Zehnder interferometer provides two output signals that are 180° out of phase, as can be seen in Eqs. 1 and 2. This feature allows us to obtain an output without a DC component, by adding a simple difference electronic circuit.

Once the interferometer with the nonlinear control system was setup, we applied a sinusoidal signal to the piezoelectric cylinder (in the sensor arm) and verify if the interferometer with the nonlinear control system was able to measure the corresponding phase variation, suppressing the spurious signals. So, to generate the $\Delta\phi(t)$, we applied a sinusoidal input signal to the PZT1 with peak voltage of 600 mV and frequency of 2 KHz. In Fig. 2, the input signal is represented as the top solid line, while the two interferometer output signals as the bottom, solid and dashed lines.

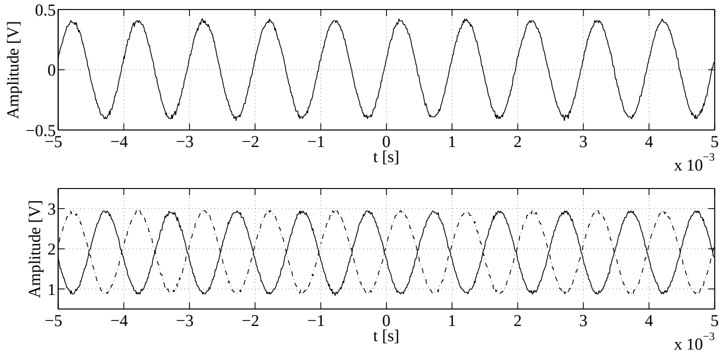


Figure 2. Interferometric input signal (top solid line) and the two outputs signals (bottom solid and dashed line).

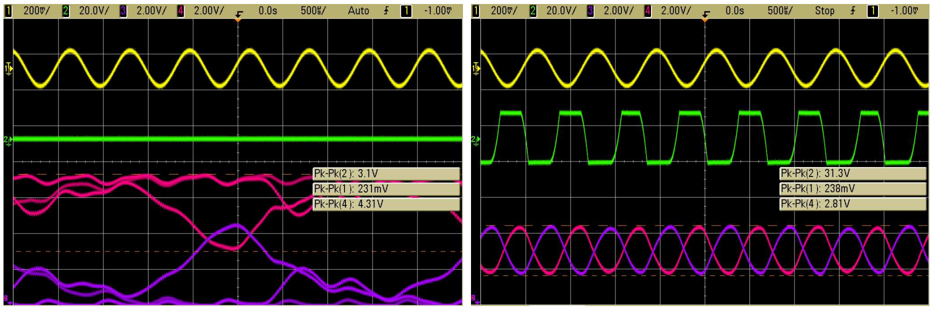
As we can observe, in closed-loop operation, the interferometer output signal did not present fading and the sinusoidal signal was properly recovered. It is noteworthy that the two closed-loop output signals are 180° shifted, as predicted in Eq. 1 and Eq. 2.

In a second test, a soldering iron was drawn near the sensor coil to vary the temperature and to verify the robustness of the nonlinear control system. Thus, in open-loop operation (nonlinear controller turned off), the interferometer output presented signal fading and the amplitude drifted over 90 rad in a few seconds, which compromise the interferometer operation. On the other hand, in close-loop operation (nonlinear controller turned on), even with severe external disturbance (the soldering iron imposing a temperature variation of 430 K), the system presented a suitable behavior, i.e., the nonlinear control system satisfied the interferometer quadrature condition and eliminated signal fading.

During the experiments, we observed that all-fiber interferometers are less sensitive to mechanical disturbances than bulk interferometers. However, all-fiber interferometers are more sensitive to temperature variation, which may be due to polarization variation on the fiber.[3]

Also, we noted that the nonlinear control system can deal with noise in the control arm. For instance, if we expose the whole system to an electronic noise caused by inductive reactors from fluorescent lamps (approximately

8 V_{RMS}) and observed that in open loop operation shown in Fig. 3(a), this strong noise was present in the interferometric output signal. On other hand, in closed loop operation shown in Fig. 3(b), the surrounding noise was eliminated in the output signal.



(a) (b)

Figure 3. Interferometric input signal (yellow), two output signals (red and purple) and signal function (green) in (a) open loop operation and (b) closed loop operation with the system expose to an electronic noise.

Finally, the frequency response of the phase modulator PZT2 curve was obtained from 1 Hz to 25 kHz, by applying sinusoidal signals on sensor arm (PZT2) and measuring the phase variantion. The results are shown in Fig. 4. The resonance is centered on approximately on 10 Hz. In Fig. 4, it can be observed that the gain for low frequency (less than 20 Hz) is 7.17 rad/V.

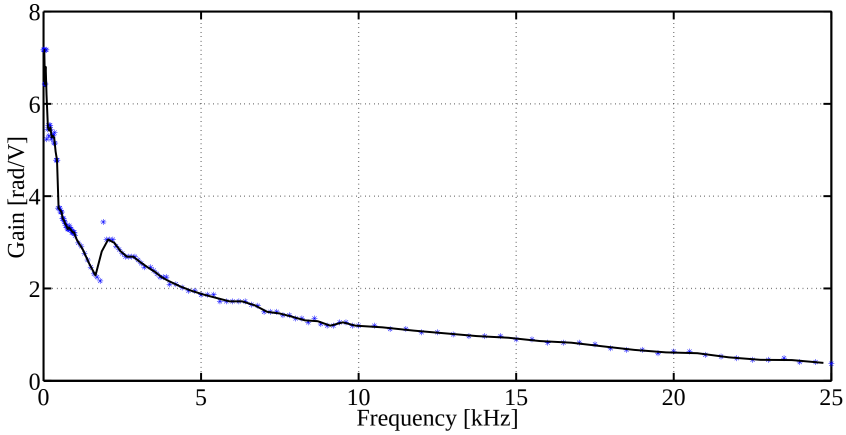


Figure 4. Frequency response of the piezoelectric transducer in study.

4. CONCLUSION

In this work, we presented the application of the nonlinear control with variable structure and sliding modes in an all-fiber Mach-Zehnder interferometer. Using a nonlinear control technique to suppress the signal fading,[1] it was possible to acquire the frequency response, and mechanical resonances of the PZT2 phase modulator. The nonlinear control system makes the interferometer suitable for real-time precise measurement. The advantages of an all-fiber interferometric sensor combined with the proposed nonlinear control features compactness, light weight, alignment free, high sensitivity, geometric versatility, robustness, real-time high precision measurement, possibility of operation in harsh environments, as well as several different applications and the possibility of being embedded in the device. Besides that, for the proposed system, the fading problem was avoided using regular single-mode fibers with a low-cost nonlinear control,[1] which reduces the overall costs.

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REFERENCES

[1] Martin, R. I., Sakamoto, J. M. S., Teixeira, M. C. M., Martinez, G. A., Pereira, F. C., and Kitano, C., "Nonlinear control system for optical interferometry based on variable structure control and sliding modes," *Opt. Express* **25**(6), 6335–6348 (2017).

[2] Udd, E. and Spillman, W. B. J., [*Fiber Optic Sensors: An Introduction for Engineers and Scientists*], John Wiley & Sons, New York (2011).

[3] Stowe, D. W., Moore, D. R., and Priest, R. G., "Polarization fading in fiber interferometric sensors," *IEEE Transactions on Microwave Theory and Techniques* **30**(10), 1632–1635 (1982).