RESSALVA

Atendendo solicitação do
autor, o texto completo desta tese
será disponibilizado somente a partir
de 29/07/2020.

UNIVERSIDADE ESTADUAL PAULISTA
"JÚLIO DE MESQUITA FILHO"
Campus de Ilha Solteira

UNIVERSIDADE ESTADUAL PAULISTA "JÚLIO DE MESQUITA FILHO"

CAMPUS DE ILHA SOLTEIRA

DEPARTMENT OF ELECTRICAL ENGINEERING

High gain approach and sliding mode control applied to quadrature interferometer

Abordagem de alto ganho e controle de modos deslizantes aplicados ao interferômetro de quadratura

Luiz Henrique Vitti Felão

Ilha Solteira
2019

Luiz Henrique Vitti Felão

High gain approach and sliding mode control applied to quadrature interferometer

Abordagem de alto ganho e controle de modos deslizantes aplicados ao interferômetro de quadratura

Thesis presented to the post-graduation course of the Engineering Faculty of Ilha Solteira – FEIS – UNESP to obtain the Ph.D grade in Electrical Engineering.

Specialty: Automation.

Advisor: Prof. Dr. Cláudio Kitano

Ilha Solteira

2019

FICHA CATALOGRÁFICA
Desenvolvido pelo Serviço Técnico de Biblioteca e Documentação

F48h

Felão, Luiz Henrique Vitti.
High gain approach and sliding mode control applied to quadrature interferometer / Luiz Henrique Vitti Felão. -- Ilha Solteira: [s.n.], 2019
113 f. : il.

Tese (doutorado) - Universidade Estadual Paulista. Faculdade de Engenharia de Ilha Solteira. Área de conhecimento: Automação, 2019

Orientador: Cláudio Kitano
Inclui bibliografia

1. Interferometria óptica. 2. Interferômetro de quadratura. 3. Controle por modos deslizantes.

João Josué Barbosa
Serviço Técnico de Biblioteca e Documentação
Diretor Técnico
CRB 8-5642

UNIVERSIDADE ESTADUAL PAULISTA

Câmpus de Ilha Solteira

CERTIFICADO DE APROVAÇÃO

TÍTULO DA TESE: HIGH GAIN APPROACH AND SLIDING MODE CONTROL APPLIED TO QUADRATURE INTERFEROMETER

AUTOR: LUIZ HENRIQUE VITTI FELÃO
ORIENTADOR: CLAUDIO KITANO

Aprovado como parte das exigências para obtenção do Título de Doutor em ENGENHARIA ELÉTRICA, área: Automação pela Comissão Examinadora:

Prof. Dr. CLAUDIO KITANO
Departamento de Engenharia Elétrica / Faculdade de Engenharia de Ilha Solteira

Prof. Dr. MARCELO CARVALHO MINHOTO TEIXEIRA
Departamento de Engenharia Elétrica / Faculdade de Engenharia de Ilha Solteira

Prof. Dr. RICARDO TOKIO HIGUTI
Departamento de Engenharia Elétrica / Faculdade de Engenharia de Ilha Solteira

Prof. Dr. JOSEMIR COELHO SANTOS
Departamento de Engenharia de Energia e Automação Elétrica / Universidade de São Paulo

Prof. Dr. GILDER NADER
Centro de Metrologia de Fluidos / Instituto de Pesquisas Tecnológicas do Estado de São Paulo

Ilha Solteira, 29 de julho de 2019

Abstract

Interferometers are extremely sensitive measurement devices, which use the principle of interference between two or more sources of light to generate a pattern of constructive and destructive interference. This pattern contains information about the physical phenomenon under study, and their light intensity can be used to calculate the optical path difference traveled by the two beams. The optical path difference and light intensity relationship is given by a cosine type function. Large disturbances can change the interferometer operation point, reaching nonlinear regions of the interferometric curve and even inducing ambiguities due to the periodicity of the input/output relationship. The present work concerns with the modeling, development and application of a control strategy based on sliding mode control, in a two-beam quadrature interferometer. It was used the high gain approach, which consists in to fully compensate the phase shifts induced on the sensor arm with the control system, in such a way that the voltage control signal becomes proportional to the phase disturbances. Therefore, the demodulation process does not require phase unwrapping algorithms. This implemented system showed capability to improve dynamic range and bandwidth when compared with other control systems in literature that were based on different high gain approach topologies. Also a new method of interferometric phase demodulation is proposed allying this control strategy to a virtual emulated interferometer. This allows keeping the real interferometer in open-loop and retrieving the phase shift information from the control signal of the virtual closed-loop interferometer, thus leading to considerable simplification of the required instrumentation. An ellipse fitting algorithm was applied to the system, allowing the correction of the Lissajous figure formed by both output interferometric signals from an ellipse to a unitary circle. Therefore, the system estimates the phase shift even with quadrature mismatches. Inertial sensors such as accelerometers and gyroscopes can benefit from this system in two major points: first, the sensitivity can be increased without limiting the end of scale of the sensor due to the proportional relation of the voltage control signal and the measured phase shift; and second, the system can be implemented without the need of PZT feedback actuators or modulators and PZT driven circuitry, reducing cost, volume and weight of the sensors.

Key-words: Optical interferometry. Quadrature interferometer. Sliding mode control.

Resumo

Interferômetros são dispositivos de medição extremamente sensíveis, os quais utilizam o princípio de interferência entre duas ou mais fontes de luz para gerar um padrão de interferência construtiva e destrutiva. Este padrão contém informação sobre os fenômenos físicos sob estudo, e sua intensidade luminosa pode ser usada para calcular a diferença de caminho óptico acumulada pelos dois feixes de luz. A diferença de caminho óptico e a intensidade de luz são relacionadas por uma função cossenoidal. Grandes distúrbios podem alterar o ponto de operação do interferômetro, alcançando regiões não lineares da curva característica do interferômetro e até mesmo induzindo ambiguidades, devido à periodicidade da relação entrada/saída. Este trabalho preocupou-se com o modelamento, desenvolvimento e aplicação de uma estratégia de controle baseada em controle com modos deslizantes, em um interferômetro de dois feixes em quadratura. Foi utilizada a abordagem de alto ganho, a qual consiste em utilizar o sistema de controle para compensar completamente os deslocamentos de fase induzidos no braço sensor, de tal forma que o sinal de controle se relaciona com os deslocamentos de fase por uma equação de reta. Portanto o processo de demodulação não necessita de algoritmos de desdobramento de fase. O sistema implementado mostrou capacidade de melhorar a faixa dinâmica e largura de banda quando comparado com outros sistemas de controle na literatura, também baseados na abordagem de alto ganho. Destaca-se que um algoritmo de identificação de elipse foi aplicado no sistema, permitindo a correção da figura de Lissajous formada pelos sinais de saída do interferômetro, de uma elipse para um círculo. Portanto, o sistema estima o deslocamento de fase mesmo com erros na condição de quadratura. Um novo método de demodulação de fase óptica é proposto, aliando esta estratégia de controle com um interferômetro emulado virtualmente. Isto permite manter o interferômetro físico em malha aberta e recuperar a informação de deslocamento de fase a partir do sinal de controle do interferômetro virtual, trazendo considerável simplificação da instrumentação requerida. Sensores inerciais tais como acelerômetros e giroscópios podem se beneficiar deste sistema em dois pontos principais: a sensitividade pode ser aumentada sem limitar o fim de escala do sensor devido à relação proporcional entre o sinal de controle e o deslocamento de fase medido; o sistema pode ser implementado sem a necessidade de moduladores e circuitos de acionamento de PZT, reduzindo o custo, volume e peso.

Palavras-chave: Interferometria óptica. Interferômetro de quadratura. Controle com modos deslizantes.

Dedicated to

Antônia Argentina Vitti Monteiro (*in memoriam*) and Newton Rodrigues Felão (*in memoriam*), whose examples of life have shaped my family by teaching empathy and that with humility one always goes further

Acknowledgements

For those who have shaped my character, my parents Newton and Adélia, sister Isadora, grandmother Jeanette and our entire family. My greatest pride is the love that exists in our family, for being a safe harbor I thank you all.

To Professor Dr. Cláudio Kitano, my advisor, from who I admire the inteligence, competency and professionalism. Thank you very much for accepting me as a doctorate student and for the many lessons. Your dedication is inspiring.

To Professor Dr. Marcelo Carvalho Minhoto Teixeira, without which this work would not have been done, your companionship, suggestions and solidarity influenced me directly. I am grateful for all the learning that I had with you.

To Professor Dr. João Marcos Salvi Sakamoto, for welcoming me into IEAv, believing in me, in our work. For their help and friendship, my heartfelt thanks!

To Professor Dr. Aparecido Augusto de Carvalho, who had a fundamental participation in my formation.

To the friends from our student house, Renan, André, Vander, Marcelo, Joao Carlos, Denis, Joao Gabriel, Manuel, Igor and Dona Jaci, who together formed a second family and a place that I can also call home. Thank you very much.

To laboratory friends Stephany, Joao Paulo, Andryos, Flavio, Galeti, Angel, Guilherme, Gabriel, Renato and Roberta, for the teachings, suggestions, coffees, moments of hard work and also relaxation. You were part of this walk and for that I will be forever grateful. Also to Unesp's servers and employees, in particular to friends, Adilson, Aderson, Hidemassa, Wendel, Chaves and Everaldo, always willing to help! To the great friends Pedro R. Cleto, Bruno J. Silveira and Thiago R. Pentiado, for their strong friendship and companionship.

I would also like to thank FAPESP - São Paulo State Research Support Foundation (Process No. 2017 / 17235-1) for the essential financial support for this research.

“Going in one more round when you don’t think you can, that’s what makes all the difference in your life.” Rocky Balboa

List of Figures

List of Tables

Contents

1 Introduction

The literature about interferometry is a wide and vast subject, since it has been used as a laboratory technique for almost a hundred years. Several developments have increased the accuracy and extended the range of applications of optical interferometry. The most significant of these developments was the advent of the laser in 1960, when, for the first time, an intense source of light, with a remarkably high degree of spatial and temporal coherence became available (HARIHARAN, 2003).

Optical interferometry can be described as a measurement technique, which is based on a phase shift on the electromagnetic field of one beam of light, produced by a physical quantity to be measured. In general, the detection of electromagnetic field phase in optical frequencies (Terahertz) is a nontrivial and prohibitive task, due to the lack of instrumentation capable to operate in such high frequencies. Combining this phase shifted beam with another beam of light (used as a reference of phase), the relative phase can be estimated from the optical intensity, measured with conventional instrumentation, such as quadratic law photodetectors allied to a transimpedance circuit.

The interference phenomenon that occurs with the overlapping of two or more light beams can cause maximum and minimum points of optical intensity as a result of constructive and destructive interference between the different light beams. These intensity distributions are called interference fringes (UDD; SPILLMAN, 2011).

When both light beams of the interferometer have the same wavelength, it is called homodyne interferometer, and when the phase shifted and the reference beams have different wavelengths, it is called heterodyne interferometer.

The main advantage of interferometric sensors comes from their extremely high sensitivity, when compared to other matured sensor technologies. Adversely, this quality is also their main drawback, since they are more susceptible to spurious disturbances which, allied with the nonlinear nature of the interferometer characteristic curve, can cause signal fading (UDD; SPILLMAN, 2011; SHEEM *et al*., 1982), as well as ambiguity of results and direction (CHEN *et al*., 2014). This behavior usually leads to nontrivial procedures to extract the signal of interest, due to the complexity of the signal demodulation process, since it is phase-modulated with a superimposed fading signal.

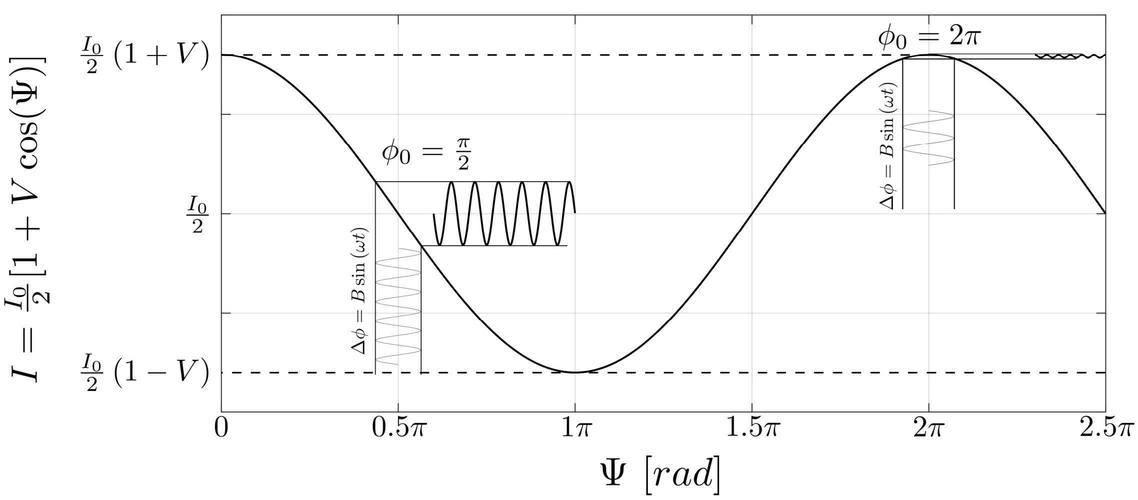
It will be presented in Chapter 2 that the two-beam homodyne interferometric characteristic curve can be expressed as:

$$I(t) = \frac{I_0}{2}\{1 + Vcos[\Delta\phi(t) + \phi_0]\}, \tag{1}$$

where $I(t)$ is the optical intensity output, I_0 is the optical intensity of the laser beam in the input of the interferometric system and $\Delta\phi(t)$ is the phase shift related with the physical quantity to be measured. Factor V is the fringe visibility, a parameter that varies in the range of 0 up to 1 and takes in account the parallelism between the electrical field and polarization of the two combining beams and their optical intensities. The parameter ϕ_0 ideally is a static phase shift related to the difference between the lengths of the interferometer arms.

When the static phase shift ϕ_0 is equal to $\left(\pm\frac{\pi}{2} + 2k\pi\right)$ rad, for $k \in \mathbb{Z}$, the interferometer operates at its maximum sensitivity points. As it can be seem in Figure 1, where $\Psi = \Delta\phi + \phi_0$, these operation points are located at the center of the quasi-linear regions of the cosine characteristic curve and, consequently, for interest signals $\Delta\phi$ with amplitudes much smaller than $\frac{\pi}{2}$ rad, the output optical intensity can be considered proportional to $\Delta\phi$.

Figure 1 - Interferometric characteristic curve.

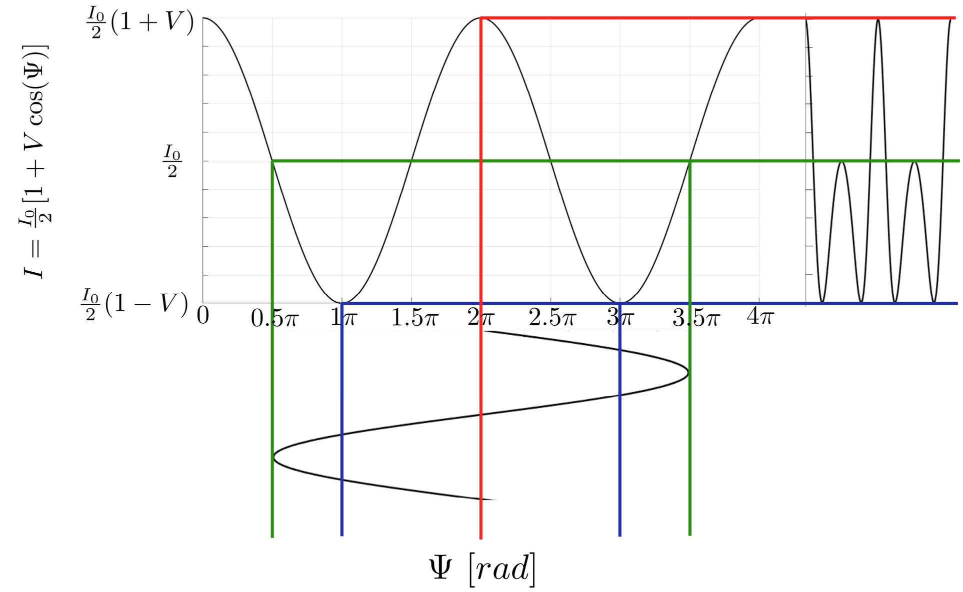


Source: (Modified from MARTIN, 2018)

In an ideal case, ϕ_0 should be constant. However, due to the real-world spurious disturbances over the interferometer, caused by environmental changes, such as, temperature variation (even on the scale of micro kelvin), weak mechanical vibration and air turbulence, it is actually a quasi-static quantity (whose variation usually occurs bellow 20 Hz approximately). Because of this, in practice, it is observed that in a few seconds the amplitude of this drift can easily reach the order of 2π rad or greater (SHEEM *et al.*, 1982). Eventually the drift of ϕ_0 may lead the operation point of the interferometer to $k\pi$ rad, for $k \in \mathbb{Z}$, therefore the operation point may lie in the most nonlinear regions of the characteristic curve. The interferometer input/output relationship in any of these regions distorts and attenuates the output signal, which may vanish (see Figure 1); this phenomenon is known as signal fading.

Another drawback that the nonlinear nature of the interferometric characteristic curve brings is the ambiguity of phase shifts ($\Psi(t)$) direction. As it can be seen in Figure 2, the optical intensity $I(t)$ would be the same, regardless if the phase shift at the input was $\Psi(t)$ or $-\Psi(t)$.

Figure 2 - Interferometric characteristic curve with high modulation depth input signal.



Source: (Modified from MARÇAL, 2008)

Different techniques to overcome the signal fading have been published in literature such as homodyne and heterodyne techniques, with spectral or temporal approaches as well as open-loop or closed-loop methods (UDD; SPILLMAN, 2011).

When using the closed-loop methods, a common and widespread methodology to control nonlinear interferometric systems and avoid the signal fading is to perform the linearization around an operation point by using Taylor series. This approach allows the designer to use the well-developed theory of linear control and, for example, techniques based on root locus, Bode and Nyquist diagrams, and modern control with the description of the system using state space modelling (MELCHIONNI, *et al*., 2015; KARHADE *et al*., 2010; PARK *et al*., 2005). Another interesting approach, sometimes called “feedback interferometry” (SHIRAI et. al, 1999; CHEUNG et. al, 2003), utilizes closed-loop to convert the well-known cosinusoidal input/output curve given by (1) into a saw-tooth profile, where output intensity varies almost linearly within a given interferometer phase range. Works previously reported by some authors (FRITSCH ; ADAMOWSKY, 1981; BASILE *et al*., 1991) presented as main drawbacks of this approach the need for reset circuits and the limitation of operating only in small deviations around the operating point (FLEMMING; ROUTLEY, 2015; CHAO; FA-JIE, 2011), once the control designed for the linearized system can only guarantee local stability.

In the particular case of reset circuits, the reset voltage action will interrupt the measurement function, and this reset glitch can severely compromise the phase detection capability of the sensor temporarily. In many publications, it has been described how to solve this problem by using an optical fiber Michelson interferometer and employing fiber Bragg gratings (FBGs) (XIE *et al*., 2009a; XIE *et al*., 2009b; XIE *et al*., 2009c). However, the reset system is adequate for laboratory conditions but difficult to be used in real-world applications. Moreover, even such an approach still follows the classical concept of a closed-loop interferometer established in the 1980s, by using proportional-integral-derivative (PID) controllers.

In this scenario, one can observe that only few authors exploit the full potential of advanced control theory to solve the interferometry problem, which makes clear that this issue is a very promising field of investigation. Examples of works that use such modern theories include some versions of closed-loop optical voltage sensors (OVS) based on Pockels effect, a kind of polarimetric interferometer whose input-output characteristic curve follows equation (1). Based on the Lyapunov or Lyapunov–Krasovskii functions, control schemes have been designed as robust as possible to solve this problem by LI *et al*. (2015) and LI *et al*. (2014). A control algorithm was developed to guarantee closed-loop OVS mean-square exponential stability with a prescribed H_∞ performance level. Robust control law and Linear Matrix Inequalities (LMIs) were also applied in (HUI *et al*., 2013) to implement a tracking system for the gain drift of the phase modulator based on four-state modulation, which provides a significant improvement in the performance of an optical voltage sensor, and in (DENG *et al*., 2017) for analysing the influence of optical parameters on the performance of closed-loop

OVSs based on Pockels effect, aiming the proposal of a control algorithm that suppresses the nonlinearity caused by the non-ideal parameters of optical devices for optimizing the detection precision of sensor. However, in the context of LMI applied to these systems, the projects still take into account the linearized system. Since the interferometer is a nonlinear system, the linearization can limit the operating range around small deviations from the operation point, and in cases of large disturbances the closed-loop system may reach instability, not ensuring the necessary robustness, accuracy and inserting the need for reset circuits.

The control strategies generally used in closed-loop homodyne interferometers are concerned with the compensation of the spurious low frequency disturbances (ϕ_0). Some authors, however, have used control systems to compensate both the spurious signals and also the signal of interest $\Delta\phi$, by the so called "feedback interferometry", as mentioned before (EOM *et al*., 2001; FRITSCH; ADAMOWSKY, 1981; FISHER; WARDE, 1979). This approach allows obtaining a proportional relationship between the signal of interest and the control signal used to drive the actuator of the system. In this way, the accuracy of the interferometric systems can be combined with an expansion of the measuring range and real-time operation of the system.

The work described by (FISHER; WARDE, 1979) used a single-pole low pass-filter to control a bulk homodyne Mach-Zehnder interferometer, where, by the adjustment of the cutoff frequency and the gain of the filter, the author was capable to compensate $\Delta\phi$ within the limits of 3.5π rad of phase amplitude for low frequencies and amplitudes up to $\frac{\pi}{2}$ rad for 150 Hz of bandwidth. In 1981, Klaus Fritsch and Gregory Adamowsky (FRITSCH; ADAMOWSKY, 1981) proposed an electronic control circuit for a single mode optical fiber Mach-Zehnder interferometer. The control system comprised two cascaded integrators and allowed the detection of phase shifts of the order of 500 μrad rms for frequencies above 500 hertz. After its warmup, the system usually reseted once a minute.

In 2001, (EOM *et al*., 2001) proposed a dynamic compensation of nonlinearity in a homodyne laser interferometer, where a computer collected two phase-quadrature signals, and calculated the DC offsets, the AC amplitudes and the difference from the phase-quadrature by the elliptical fitting with a least-squares method. The authors, however, reached 0.2 Hz for the update rate of the control voltages and concluded that the system cannot be used in real-time applications.

More recently, in the work (XIE *et al*., 2017), the quadrature technique together with a novel iterative algorithm with a digital lock-in phase demodulator was proposed in order to compensate the nonlinear error of a heterodyne interferometer caused by phase demodulating electronics. The algorithm used the quadrature signals, iterative translating and scaling transforms, to correct the phase diagram of the two output signals of the phase demodulator from an ellipse to a circle at the origin. The experimental setup used polarized light in order to obtain the quadrature signals.

Up to the moment, the group at LOE (Laboratory of Optoelectronic - UNESP – Ilha Solteira) has achieved good results in implementing the nonlinear control system based on variable structure in bulk Michelson interferometers and in all-fiber Mach-Zehnder interferometers. This control technique showed robustness, low cost and easy implementation (MARTIN *et al*., 2017a; MARTIN *et al*., 2017b; LYRA *et al*., 2019).

Within this scope, the present work concerns with the application of a novel sliding mode control using the high-gain approach (as designated by Udd and Spillman, 2011) to fully compensate the phase shift of ϕ_0 and $\Delta\phi$ in a Michelson bulk interferometer. The interferometer was modified, as proposed by (LEMES, 2014), in order to generate phase quadrature signals, exploring the spatial phase shift between consecutive interference fringes, therefore without the need of complex polarizing optics. As it will be further discussed in this text, the proposed technique has potential to increase the frequency bandwidth and phase dynamic range of operation when compared to similar systems based on high gain approach described in literature.

Also an innovative concept of demodulation method for quadrature interferometers is presented, having the main advantages of estimating the phase shifts in real-time, without applying phase unwrapping algorithms and without driving a feedback PZT in the reference arm of the interferometer. This proposed method uses the output signals of the open-loop quadrature interferometer and performs a calculation with a dynamic system digitally implemented, in such a way that the overall system becomes equivalent to the closed-loop quadrature interferometer using the high gain approach. In other words, it is an equivalent system, but virtually controlled.

In Chapter 2, a brief theoretical background of two beam interferometers is presented, covering the experiment of Young, which serves as basis for the subsequent deductions of

Michelson bulk interferometer and the modified Michelson interferometer, in order to generate the output signals in quadrature.

The sliding mode control theory is briefly explained in Chapter 3, as well as the modeling of the interferometric system in state space variables and the choice of the sliding surface. Yet in this chapter, the stability analysis, closed-loop simulations and theoretical phase plan are presented. At the end of the chapter we also explained the new concept of demodulation method for quadrature interferometers using the equivalent system virtually controlled.

In Chapter 4, it is described the implementation of the control and logging data system in the chosen embedded plataform, the main difficulties and associated practical issues. The description of the experimental setup and procedures adopted to evaluate the control system are presented. And also, the implemented equivalent system virtually controlled with the ellipse fitting algorithm, in order to guarantee the phase shift estimation, even with mismatches in the quadrature condition between the two interferometers outputs, is discussed.

Finally, in Chapter 5 the main conclusions and proposals for future works are presented.

5 Conclusion and future work

This thesis presented, firstly a theoretical study about two beam interferometry, starting from Young`s experiment and, as it was shown in the previous work of (LEMES, 2014), how spatial displacement on the fringe pattern can be used to obtain a quadrature interferometer without using complex polarizing optics.

Then, a suitable state space modeling for the interferometer was found, in order to apply a control strategy based on sliding mode control and high-gain approach. The objective of this method is to fully compensate the phase shift induced on one of the interferometers arms. The major advantages are that the induced phase shift can be retrieved from the voltage control signal, once they hold a proportional relationship. Consequently there is no need to use phase unwrapping algorithms. This leads to the capability of the system to operate in real-time. The stability of the closed system was studied, and the proposed system showed to be stable in all quadrature points.

Simulations and a theoretical study about the boundary layer were carried out to analyze the behavior of the system when changing its parameters, such as gain and sampling period. It is highlighted that for the smallest value of gain that still is greater than $|\Delta\dot{\phi} + \dot{\phi}_0|$, the sign function operating with the higher sampling frequency showed a smaller boundary layer when compared with the sigmoidal function. By the other hand, for values of gain much greater than $|\Delta\dot{\phi} + \dot{\phi}_0|$, the sigmoidal function showed smaller boundary layer, when compared to the sign function. As a drawback, the sigmoidal function decreases the robustness of the control system, representing a tradeoff between chattering and robustness. Also the behavior of the system trajectory, inside the boundary layer defined by the sigmoidal function, was studied.

In the laboratory stage, the modified Michelson interferometer was assembled, and experimental tests were carried out using the implemented control system. The results showed similarity with the simulations, and comparing with other high gain approach systems described in literature. This work showed an improvement of dynamic range and bandwidth. It is noteworthy that the results of the frequency characterization of the PZT stack actuator PK2 are in agreement with the results obtained with the low modulation depth method.

The current systems discussed in literature, operating in high-gain approach, still use the linearization around the equilibrium point, as example, utilizing PI controllers which presents the reset limitation. It is important to note that high-gain approach interferometry topologies, operating with the physically closed-loop, has as main drawback the need of a precise calibration of the PZT feedback actuator on the reference arm of the interferometer, and therefore the interferometer no more constitutes a primary standard for displacement measurements, as happens with the low gain approach versions.

Attempting to solve this problem, the new concept of the equivalent system virtually controlled showed to be a suitable alternative to measure interferometric phase shifts, presenting the great advantage of not needing a physically feedback PZT actuator and linear voltage amplifier to drive it, reducing cost and hardware requirements. The implemented quadrature correction algorithm showed to be of easy implementation, while also showed to be capable to deal with slow variations of the photodetectors error positioning. The overall system implements the feedback loop by software and therefore, the phase correction signal ϕ_c is obtained in radians. This feature allows the interferometer to be again a primary standard for calibrated displacement measurement and the system can operates in real-time.

The results obtained with the ES for the characterization of the PZT stack actuator PK2 presented an imperfection on the phase frequency response, due to a transport delay between the input and output of the implemented control system. The transport delay was experimentally determined and corrected in the phase frequency response, which does not introduce a distortion to phase correction ϕ_c.

The ES was able to operate in real-time with frequencies up to 500 Hz, however for applications that demands higher frequencies of operation it would not be suitable. In order to attempt such demands, a post processing routine based on the same algorithm used in the ES was designed, tested for higher frequency signals and compared to the algorithm proposed by (LEMES, 2014). The results shown convergence between both methods and also the error between them was presented, that can be minimized through the adjustment of the boundary layer.

The proposed next steps on the development of this work are:

a) To optimize the FPGA code of the implemented equivalent system, decreasing the length of the words of the fixed point data, while taking care to not induce significant quantization errors; change the period of quadrature correction algorithm, in order to decrease the time delay (t_d) and to change the sine and cosine functions implemented in the FPGA by look up tables. These improvements should reduce the transport delay of the system.

b) To assemble an optical fiber quadrature interferometer, in order to also apply the proposed control system.
c) To implement the strategy described by (Su; Drakunov; Özgüner, 2000), where the proposed boundary layer can be made a function of T^2 instead of only a function of T, therefore, reducing the thickness of the boundary layer and by consequence, the chattering of the system.
d) Develop a study using terminal sliding modes and discrete time sliding modes.
e) Implement the analogic version of the ES virtually controlled.
f) Develop an algorithm to adaptively change the gain and the sigmoid parameter ϵ in order to minimize the boundary layer, while obeying the reachability criterion.

It is also important to highlight that the conventional operation of interferometer based sensors working in high modulation depth mode, requires phase unwrapping algorithms in order to estimate the phase shifts unambiguously. Usually those algorithms are post processed, bringing limitations to real-time operation of the sensors. Therefore, most of the applications restrict the end of scale of the sensor to operate at low modulation depth. With the control system proposed in this work, the measurement of phase shift becomes a simple multiplication of the voltage signal applied to the feedback PZT by its frequency response, or using the ES virtually controlled, the phase shift is directly obtained from the voltage control signal. This makes the operation in high modulation depth possible without the need of phase unwrapping algorithms and therefore, increasing the maximum sensibility that could be reached.

References

AMERICAN PHYSICAL SOCIETY. **Michelson and morley**. Available in: http://www.aps.org/programs/outreach/history/historicsites/michelson-morley.cfm. Accessed in: 22 nov. 2017.

ALAOUI, A. ; MOHAMAD, A. Novel digital integrator and differentiator. **Electronics Letters**, Stevenage, v. 29, n. 4, p. 376-378, 1993.

ASTROM, K. J.; RUNDQWIST, L. Integrator windup and how to avoid it. *In*: AMERICAN CONTROL CONFERENCE IEEE, 1989, Pittsburgh. **Conference** […]. Pittisburgh: IEEE, 19898. p. 1693-1698.

BARBASHIN, E. A. **Introduction to the theory of stability**. Nauka: Wolters-Noordhoff, 1967.

BASILE, G.; BERGAMIN, A.; CAVAGNERO, G.; MANA, G. Phase modulation in high-resolution optical interferometry. **Metrologia**, Bristol, v. 28, p. 455-461, 1991.

BERGER, A.; GUTMAN, P. O. A new view of anti-windup design for uncertain linear systems in the frequency domain. **International Journal of Robust and Nonlinear Control**, Oxford, v. 26, p. 2116-2135, 2015.

BIRCH, K. P. Optical fringe subdivision with nanometric accuracy. **Precision Engineering**, Philadelphia, v. 12, n. 4, p. 195 – 198, 1990.

BORN, M.; WOLF, E. **Principles of optics**. Oxford: Pergamon Press, 1986.

BRODTKORB, A. R.; DYKEN, C.; HAGEN, T. R.; HJELMERVIK, J. M. ; STORAASLI, O. O. State-of-the-art in heterogeneous computing. **Scientific Programming**, New York, v. 18, p. 1-33, 2010.

BURTON, J. A. ; ZINOBER, A. S. Continuous approximation of variable structure control. **International Journal of Systems Science**, Abingdon, v. 17, n. 6, p. 875 – 885, 1986.

CHAO, Z.; FA-JIE, D. Closed-loop phase stabilizing and phase stepping methods for fiber-optic projected-fringe digital interferometry. **Review of Scientific Instruments**, Melville, v. 82, 6 p. 113105, 2011. Available: https://aip.scitation.org/doi/pdf/10.1063/1.3658480?class=pdf. Access in: 07 out. 2019.

CHEN, X. H.; ZENG, X. L.; FAN, D.; LIU, Q. C.; BIE, B. X.; ZHOU, X. M.; LUO, S. N. Note: phase retrieval method for analyzing single-phase displacement interferometry data. **Review of Scientific Instruments**, Melville, v. 85, 4 p., 026106, 2014. Available: https://aip.scitation.org/doi/pdf/10.1063/1.4865113?class=pdf. Access in: 07 out. 2019.

CHEUNG, D. C. L.; BARNES, T. H.; HASKEL, T. G. Feedback interferometry with membrane mirror for adaptive optics. **Optics Communications**, Amsterdam, v. 218, p. 33-41, 2003.

DAVIS, J. P. ;RABINOWITZ, P. **Methods of numerical integration**. Chelmsford: Courier Corporation, 2007. 612 p.

DENG, W.; LI, H.; ZHANG, C.; WANG, P. Optimization of detection accuracy of closed-loop optical voltage sensors based on pockels effect. **Sensors**, Basel, v. 17, n. 1723,13 p., 2017. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5579804/. Access in: 07 out. 2019.

DHAR, V. K.; TICKOO, A. K.; KAUL, S. K.; KOUL, R. ; DUBEY, B. P. Artificial neural network-based error compensation procedure for low-cost encoders. **Measurement Science and Technology**, Bristol, v. 21, p. 1 – 9, 2010.

EOM, T.; KIM, J. Y.; JEONG, K. The dynamic compensation of nonlinearity in a homodyne laser interferometer. **Measurement Science and Technology**, Bristol, v. 12, 4 p., 1734-1738, 2001. Available: https://iopscience.iop.org/article/10.1088/0957-0233/12/10/318/pdf. Access in: 07 out. 2019.

ERTUGRUL, M.; KAYNAK, O.; SABANOVIC, A. ;OHNISHI, K. A generalized approach for Lyapunov design of sliding mode controllers for motion control applications. **Advanced Motion Control, Proceedings of IEEE**, Piscataway, v. 96, n. 1, 407-412, 1996.

FISHER, A. D.; WARDE, C. Simple closed-loop system for real-time optical phase measurement. **Optics Letters**, Washington, v. 4, 131-133, 1979.

FLEMING, A. J. ; ROUTLEY, B. S. A closed-loop phase-locked interferometer for wide bandwidth position sensing. **Review of Scientific Instruments**, Melville, v. 86, 7 p., 115001, 2015. Available: https://aip.scitation.org/doi/10.1063/1.4935469. Access in: 07 out. 2019.

FRITSCH, K. ;ADAMOWSKY, G. Simple circuit for feedback stabilization of a single-mode optical fiber interferometer. **Review of Scientific Instruments**, Melville, v. 52, p. 996-1000, 1981.

GAO, Z.; ZHOU, B.; HOU, B.; LI, C.; WEI, Q. ; ZHANG, R. Self-calibration of angular position sensors by signal flow networks. **Sensors**, Basel, v. 18, p. 1-18, 2018. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6111312/. Access in: 07 out. 2019.

GIALLORENZI, T. G.; BUCARO, J. A.; DANDRIDGE, A.; SIEGEL, G. H.; COLE Jr., J. H.; RASHLEIGH, S. C.; PRIEST, R. G. Optical fiber sensor technology. **IEEE Transactions on Microwave Theory and Technology**, Piscataway, v. 30, n. 4, 472 – 511, 1982.

GREGORCIC, P.; POZAR, T.; MOZINA, J. Quadrature phase-shift error analysis using a homodyne laser interferometer. **Optics Express**, Washington, v. 17, n. 18, p. 16322 – 16331, 2009.

HARIHARAN, P. **Basics of interferometry**. San Diego: Academic Press, 2007.

HARIHARAN, P. **Optical interferometry**. San Diego: Academic Press, 2003.

HECHT, E. **Optics**. 4. ed. San Francisco: Addison Wesley, 2002.

HEYDEMANN, P. L. M. Determination and correction of quadrature fringe measurement errors in interferometers. **Applied Optics**, Washington, v. 20, n. 19, p. 3382-3384, 1981.

HUI, L.; LAN, B.; LIJING, L.; SHULING, H.; XIUJUAN, F.; CHUNXI, Z. Tracking algorithm for the gain of the phase modulator in closed-loop optical voltage sensors. **Optics & Laser Technology**, London, v. 47, p. 214–220, 2013.

JOHNSON, M. L. ; FAUNT, L. M. Parameter estimation by least-squares methods. **Methods in Enzymology**, Maryland Heights, v. 20, p. 1 – 37, 1992.

KAPOOR, N.; TEEL, A. R.; DAOUTIDIS, P. An anti-windup design for linear systems with input saturation. **Automatica**, Oxford, v. 34, n. 5, p. 559-574, 1998.

KARHADE, O. G.; DEGERTEKIN, F. L.; KURFESS, T. R. Active control of microinterferometers for low-noise parallel operation. **IEEE/ASME Transactions on Mechatronics**, Piscataway, v. 15, p. 1-8, 2010.

LEMES, A. S. **Novas configurações de interferômetros de quadratura e de técnicas de detecção de fase óptica baseadas em *Phase Unwrapping***. 2014. 143 f. Dissertação (Mestrado em Engenharia Elétrica) – Faculdade de Engenharia, Universidade Estadual Paulista, Ilha Solteira, 2014. Available: https://repositorio.unesp.br/handle/11449/111112. Access in: 07 out. 2019.

LI, H.; CUI, L.; WNAG, X.; LIN, Z.; ZHANG, C. “Analysis and design of loop gains to optimize the dynamic performance of optical voltage sensor based on pockels effect. **Journal of Lightwave Technology**, Piscataway, v. 33, p. 3108-3115, 2015.

LI, H.; CUI, L.; LIN, Z.; LI, L.; ZHANG, C. An analysis on the optimization of closed-loop detection method for optical voltage sensor based on pockels effect. **Journal of Lightwave Technology**, Piscataway, v. 32, p. 1006-1013, 2014.

LOZIER, J. A steady state approach to the theory of saturable servo systems. **IRE Transactions on Automatic Control**, Piscataway, v. 1, n. 1, p. 19 – 39, 1956.

LYRA, S.; MARTIN, R. I.; PEREIRA, F. C.; SILVA, E. C. N.; TEIXEIRA, M. C. M.; KITANO, C. Digital control system for two-beam optical interferometry using variable structure and sliding modes method. **Proceedings of SPIE**, v. 10917, 109171N, 2019. Available: https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10917/109171N/Digital-control-system-for-two-beam-optical-interferometry-using-variable/10.1117/12.2510385.full?SSO=1. Access in: 07 out. 2019.

MARTINEZ, G. A. **Análise interferométrica da influência dos suportes de fixação de piezoatuadores ao bredboard**: alteração da resposta em frequência para nanodeslocamentos. 2018. 106 f. Dissertação (Mestrado em Engenharia Elétrica) – Faculdade de Engenharia, Universidade Estadual Paulista, Ilha Solteira, 2018. Available: https://repositorio.unesp.br/handle/11449/181661. Access in: 07 out. 2019.

MARTIN, R. I.; SAKAMOTO, J. M. S.; TEIXEIRA, M. C. M.; MARTINEZ, G. A.; PEREIRA, F. C.; KITANO, C. Nonlinear control system for optical interferometry based on variable structure control and sliding modes. **Optics Express**, Washington, v. 25, p. 6335-6348, 2017a.

MARTIN, R. I.; SAKAMOTO, J. M. S.; TEIXEIRA, M. C. M.; KITANO, C. Variable structure and sliding modes nonlinear control system applied to a fiber optic interferometer. **Proceedings SPIE**, v. 10453, 5 p., 10453W, 2017b. Available: https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10453/2272548/Variable-structure-and-sliding-modes-nonlinear-control-system-applied-to/10.1117/12.2272548.full. Access in: 07 out. 2019.

MARTIN, R. I. **Nonlinear control system based on variable structure and sliding modes for two beam optical interferometry**. 2018. 127 f. Thesis (Doctorate Degree in Electrical Engineering) – Faculty of Engineering, Sao Paulo State University, Ilha Solteira, 2018. Available: https://repositorio.unesp.br/handle/11449/153459?locale-attribute=en. Access in: 07 out. 2019.

MELCHIONNI, D.; MAGNANI, A.; PESATORI, A.; NORGIA, M. Development of a design tool for closed-loop digital vibrometer. **Applied Optics**, Washington, v. 54, n. 32, p. 9637-9643, 2015.

MENEZES, J. P. C. **Análise teórica e experimental de um método interferométrico de detecção de fase óptica auto-consistente e com elevada faixa dinâmica, aplicado à caracterização de atuadores piezoelétricos flextensionais**. 2009. 146 f. Dissertação (Mestrado em Engenharia Elétrica) – Faculdade de Engenharia, Universidade Estadual Paulista, Ilha Solteira, 2009. Available: https://repositorio.unesp.br/handle/11449/87033. Access in: 07 out. 2019.

NADER, G. **Desenvolvimento de técnicas de caracterização de transdutores piezoelétricos**. 2002. 182 f. Tese (Doutorado em Engenharia Elétrica) – Escola Politécnica, Universidade de São Paulo, São Paulo, 2002. Available: https://www.teses.usp.br/teses/disponiveis/3/3132/tde-20052003-185121/pt-br.php. Access in: 07 out. 2019.

NATIONAL INSTRUMENTS. **myRIO-1900 user guide and specifications**. Available in: www.ni.com/pdf/manuals/376047a.pdf. Access in: 07 ago. 2018.

PARK, T. J.; CHOI, H. S.; HAN, C. S.; LEE, Y. W. Real-time precision displacement measurement interferometer using the robust discrete time Kalman filter. **Optics & Laser Technology**, London, v. 37, p. 229-234, 2005.

PENG, Y.; VRANCIC, D.; HANUS, R. Anti-windup, bumpless, and conditioned transfer techniques for PID controllers. **IEEE Control Systems**, Piscataway, v. 16, n. 4, 48-57, 1996.

POZAR, T.; MOZINA, J. Enhanced ellipse fitting in a two-detector homodyne quadrature laser interferometer. **Measurement Science and Technology**, Bristol, v. 22, p. 1 – 8, 2011.

RAN, M.; WANG, Q.; DONG, C. Anti-windup design for uncertain nonlinear systems subjected to actuator saturation and external disturbance. **International Journal of Robust and Nonlinear Control**, Oxford, v. 26, n. 15, p. 3421-3438, 2016.

RIBEIRO, J. M. S. **Controle discreto com modos deslizantes em sistemas incertos com atraso no sinal de controle**. 2006. 126 f. Tese (Doutorado em Engenharia Elétrica) – Faculdade de Engenharia, Universidade Estadual Paulista, Ilha Solteira, 2006. Available: https://repositorio.unesp.br/handle/11449/100364. Access in: 07 out. 2019.

RUBINOWICZ, A. Thomas young and the theory of diffraction. **Nature**, Washington, v. 180, n.4578, 160-162, 1957.

SAKAMOTO, J. M. S. **Sensor em fibra óptica aplicado à caracterização de atuadores piezoelétricos flextensionais**. 2006. 154 f. Dissertação (Mestrado em Engenharia Elétrica) – Faculdade de Engenharia, Universidade Estadual Paulista, Ilha Solteira, 2006. Available: https://repositorio.unesp.br/handle/11449/87227. Access in: 07 out. 2019.

SALEH, B. E. A.; TEICH, M. C. **Fundamentals of photonics**. New Jersey: John Wiley & Sons, 2007.

SHEEM, S. K.; GIALLORENZI, T. G.; KOO, K. Optical techniques to solve the signal fading problem in fiber interferometers. **Applied Optics**, Washington, v. 21, n. 4, p. 689-693, 1982.

SHIRAI, T.; BARNES, T. H.; HASKEL, T. G. Surface-profile measurement by means of a polarization Sagnac interferometer with parallel optical feedback. **Optics Letters**, Washington, v. 24, p. 297-299, 1999.

SLOTINE, J. J.; SASTRY, S. S. Tracking control of non-linear systems using sliding surfaces, with application to robot manipulators. **International Journal of Control**, Abingdon, v. 38, n. 2, p. 465-492, 1983.

SLOTINE, J. J. ; LI, W. **Applied nonlinear control**. New Jersey: Prentice Hall, 1991.

SU, W.; DRAKUNOV, S. V. ; ÖZGÜNER, Ü., “An $O(T^2)$ boundary layer in sliding mode for sampled-data systems. **IEEE Transactions on Automatic Control**, Piscataway, v. 45, n. 3, 482 – 485, 2000.

TAKIY, A. E. **Análise teórica e experimental de uma nova técnica de processamento de sinais interferométricos baseada na modulação triangular da fase óptica**. 2010. 148 f. Dissertação (Mestrado em Engenharia Elétrica) – Faculdade de Engenharia, Universidade Estadual Paulista, Ilha Solteira, 2010. Available: https://repositorio.unesp.br/handle/11449/87038. Access in: 07 out. 2019.

TARBOURIECH, S.; TURNER, M. Anti-windup design: an overview of some recent advances and open problems. **IET Control Theory and Applications**, Stevenage, v. 3, n. 1, p. 1 – 9, 2009.

TURNER, M. C.; SOFRONY, J.; HERRMANN, G. An alternative approach to anti-windup in anticipation of actuator saturation. **International Journal of Robust and Nonlinear Control**, Oxford, v. 27, n. 6, p. 963-980, 2016.

UDD, E. ; SPILLMAN, W. B. J. **Fiber optic sensors**: an introduction for engineers and scientists. New York: Wiley, 2011.

UTKIN, V. I. Sliding mode control design principles and applications to electric drives. **IEEE Transactions on Industrial Electronics**, Piscataway, v. 40, n. 1, p. 23-36, 1993.

UTKIN, V. I. **Sliding modes on control and optimization**. Heidelberg: Springer-Verlag, 1992.

UTKIN, V. I. Variable structure systems with sliding modes. **IEEE Transactions on Automatic Control**, Piscataway, v. 22, n. 2, p. 212 – 222, 1977.

WU, C.; SU, C.; PENG, G. Correction of nonlinearity in one-frequency optical interferometry. **Measurement Science and Technology**, Bristol, v. 7, p. 520 – 524, 1996.

XIE, F.; CHEN, X.; ZHANG, L. High stability interleaved fiber Michelson interferometer for on-line precision displacement measurements. **Optics and Lasers in Engineering**, London, v. 47, p. 1301-1306, 2009c.

XIE, F.; CHEN, Z.; REN, J. Design and analysis of a highly stabilized optical fiber Michelson interferometer measurement system. **Sensors and Actuators A: Physical**, Washington, v. 152, p. 176-181, 2009b.

XIE, F.; CHEN, Z.; REN, J. Stabilisation of an optical fiber Michelson interferometer measurement system using a simple feedback circuit. **Measurement**, Amsterdam, v. 42, p. 1335-1340, 2009a.

XIE, J.; YAN, L.; CHEN, B.; ZHANG, S. Iterative compensation of nonlinear error of heterodyne interferometer. **Optics Express**, Washington, v. 25, n. 4470, 13 p., 2017.

XU, J.; XU, Q.; CHAI, L.; LI, Y. ; WANG, H. Direct phase extraction from interferograms with random phase shifts. **Optics Express**, Washington, v. 14, n. 2, p. 20620—20627, 2010.

YOUNG, K. D.; UTKIN, V. I. ; OZGUNER, U. A control engineer's guide to sliding mode control. **IEEE Transactions Control System Technology**, Piscataway, v. 7, n. 3, p. 328-342, 1999.

ZHENG, A.; KOTHARE, M. V.; MORARI, M. Anti-windup, design for internal model control. **International Journal of Control**, Abingdon, v. 60, n. 5, p. 1015-1024, 1994.