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CAMPUS DE ILHA SOLTEIRA

DEPARTMENT OF ELECTRICAL ENGINEERING

STEPHANY DE SOUZA LYRA

CLOSED LOOP INTERFEROMETRY: INNOVATIVE PROPOSALS FOR OPTICAL PHASE DETECTION BY USING MODERN CONTROL APPROACHES

Ilha Solteira
2022

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

Specialty: Automation.

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Ilha Solteira

2022

FICHA CATALOGRÁFICA
Desenvolvido pelo Serviço Técnico de Biblioteca e Documentação

L992c

Lyra, Stephany de Souza.
Closed loop interferometry: innovative proposals for optical phase detection by using modern control approaches / Stephany de Souza Lyra. -- Ilha Solteira: [s.n.], 2022
85 f.

Tese (doutorado) - Universidade Estadual Paulista. Faculdade de Engenharia de Ilha Solteira. Área de conhecimento: Automação, 2022

Orientador: Cláudio Kitano
Coorientador: Marcelo Carvalho Minhoto Teixeira
Inclui bibliografia

1. Interferometria óptica. 2. Controle moderno. 3. Filtro ressonante. 4. Estrutura variável e modos deslizantes.

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CRB/8 - 9999

UNIVERSIDADE ESTADUAL PAULISTA

Câmpus de Ilha Solteira

CERTIFICADO DE APROVAÇÃO

TÍTULO DA TESE: Closed loop interferometry: innovative proposals for optical phase detection by using modern control approaches

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Ilha Solteira, 04 de fevereiro de 2022

Dedico

Aos meus avós pelas raízes de nossa natureza. A meus pais, Del e Mônica, pelo fundamento que me manteve. À minha irmã pelas inúmeras distrações. Ao meu companheiro, Alexsson, por sempre me lembrar de ter um pouco mais de fé. Sem vocês, eu não teria conseguido.

AGRADECIMENTOS

Agradeço a Deus todos os dias pela força e coragem para encarar os desafios desta vida, fé para não desistir e alegria por todas as bênçãos.

Aos meus pais, Mônica e Del, a minha irmã, Sabrina, e ao amor da minha vida, Alexsson, por todo apoio e suporte, que me fizeram chegar até aqui.

Ao meu orientador, Prof. Dr. Cláudio Kitano, pelo exemplo e dedicação, como professor e incentivador.

Ao Prof. Dr. Marcelo Carvalho Minhoto Teixeira pelas ideias mirabolantes, que inspiraram este trabalho.

Ao técnico Everaldo L. de Moraes por todo suporte nos experimentos malucos do LOE.

A meus colegas do laboratório, Guilherme, Perdido e João Paulo, que me ajudaram de toda a forma, e que trabalhando em conjunto fizeram chegar mais longe. Obrigada pela amizade e pelos ‘cafésis’!

E ao CNPq (Processo 140058/2019-2), pelo apoio financeiro que foi essencial para este trabalho.

“Once we accept our limits, we go beyond them.”
– Albert Einstein.

ABSTRACT

In this work we present a nonlinear control system applied to the two beam optical interferometer, operating with high gain approach (full compensation of interferometric phase), in order to convert the interferometric characteristic curve to a linear characteristic and eliminate complex algorithms for optical phase demodulation (which can involve phase unwrapping methods). The highlight of this work is the use of resonant filter within the controller, is a new proposal that brings together two powerful tools of the nonlinear control: the resonant filter and variable structure. The variable structure has been proved to be an important tool as well as efficient and robust enough to stabilize the interferometer. Also, the structure of the filter allows working with a considerable smaller gain when working in resonance, when compared to previous works. The controlling system was tested on the quadrature interferometer in open loop using a virtual feedback interferometer controlled, which gives equivalence of the physical feedback. This method of implementation was chosen due the need of higher sampling rate and to avoid a greater delay. The system proposed was also studied by changing the controller input (with and without switching, the variable structure, and changing the switching from a sign function to a sigmoidal one). After the experimental test, a piezoelectric flextensional actuator was evaluated under all the variations of the system proposed, and then compared under the same measurement to the arc tangent classical method and the discrepancy between methods in a range of 1,000 Hz was less than 5%, thereby the system developed is validated for measurements of optical phase.

K**ey-words:** optical interferometry; high gain approach; resonant filter; nonlinear control.

RESUMO

Neste trabalho apresentamos um sistema de controle não linear aplicado ao interferômetro óptico de dois feixes, operando com abordagem de alto ganho (compensação total de fase interferométrica), a fim de converter a curva característica interferométrica para uma característica linear e eliminar algoritmos complexos para demodulação óptica de fase (que pode envolver métodos de desdobramento de fase). O destaque deste trabalho é o uso do filtro ressonante dentro do controlador, é uma nova proposta que reúne duas poderosas ferramentas do controle não linear: o filtro ressonante e a estrutura variável. A estrutura variável provou ser uma ferramenta importante, eficiente e robusta o suficiente para estabilizar o interferômetro. Além disso, a estrutura do filtro permite trabalhar com um ganho consideravelmente menor ao trabalhar em ressonância, quando comparado a trabalhos anteriores. O sistema de controle foi testado no interferômetro de quadratura em malha aberta utilizando um interferômetro de realimentação virtual controlado, que dá equivalência da realimentação física. Este método de implementação foi escolhido devido à necessidade de maior taxa de amostragem e para evitar um maior atraso. O sistema proposto também foi estudado alterando a entrada do controlador (com e sem chaveamento, a estrutura da variável, e mudando a função de chaveamento de uma função de sinal para uma função sigmoide). Após o teste experimental, um atuador flextensional piezoelétrico foi avaliado sob todas as variações do sistema proposto, e então comparado sob a mesma medida ao método arco tangente clássico e a discrepância entre os métodos na faixa de 1.000 Hz foi menor que 5%, assim o sistema desenvolvido é validado para medições de fase óptica.

Palavras-chave: interferometria ótica; alto ganho; filtro ressonante; controle não linear.

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LIST OF SYMBOLS

A	Factor of proportion [V]
A_1	Coefficient matrix of the state variables regarding the input dynamics
B_1	Coefficient matrix of the inputs regarding the input dynamics
C_1	Coefficient matrix of the state variables regarding the output of the system
C_2	Coefficient matrix of optical phase regarding the output of the system
D_1	Coefficient matrix of the inputs regarding the output of the system
E_0	Electric field of the laser source
E_{01}	Amplitude of the electric field of the reference arm
E_{02}	Amplitude of the electric field of the sensor arm
E_R	Electric field of the reference arm
E_S	Electric field of the sensor arm
E_T	Electric field of the sensor arm
$G_{PZT_{fb}}$	Feedback actuator gain [rad/V]
G_{AMP}	Linear amplifier gain [V/V]
G_{DC}	Gain of the filter in zero Hertz of frequency
I_0	Optical intensity of the laser
I_R	Optical intensity of the reference arm
I_S	Optical intensity of the sensor arm
K_0	Proportional gain (controller input without switching)
K_1	Set of the stable equilibrium points
K_2	Set of the instable equilibrium points
T_s	Sampling period
f_n	Resonant frequency [Hz]
f_s	Sampling frequency [Hz]
l_s	Total difference between the length of the arms in the absence of stimulus [m]
n_s	Refraction index of the ambient
v_{PD}	Voltage generated by the photodetector [V]
v_{fb}	Feedback voltage [V]
x_1	State variable
x_2	State variable
ω_S	Modulation frequency [rad/s]
ϕ_0	Quasi-static phase between the arms [rad]

ϕ_{c}	Correction phase or controlling signal
ϕ_{t}	Total phase
ΔL	Displacement measured with the optical phase [m]
$\Delta\phi$	Interest signal [rad]
$\in$	Is an element of
$\mathcal{L}\{\cdot\}$	Laplace transform
$\mathcal{L}^{-1}$	Inverse Laplace transform
Q	Interferometer point of operation
$\mathbb{Z}$	Set of integers
Γ	Gain of the switching function (signal or sigmoidal function) of the controller
A	Parameter of the gain filter ratio
B	Parameter of the resonant filter transfer function for the discrete system
C	Parameter of the resonant filter transfer function for the discrete system
D	Parameter of the resonant filter transfer function for the discrete system
G	Gain of the filter
$G(s)$	Transfer function of the filter
I	Irradiance, the optical intensity
$U(s)$	Laplace transform of the input
V	Visibility of the interference pattern
a	Parameter of the resonant filter
k	Constant of multiplicity
s	Variable in frequency of the Laplace transform
t	Time [s]
u	Controller input
v	Voltage generated by the photodetector normalized in AV factor [V]
x	Phase modulation index [rad]
y	Output of the system
z	Variable of the z-plane
$\mathcal{Z}\{\cdot\}$	Z-transform
λ	wavelength of optical source radiation [nm]
π	Number pi
ω	Optical frequency [rad/s]
ω	Optical frequency [rad/s]

ϵ Sigmoid parameter of approximation

ϕ Total difference of phase between the arms or phase shift [rad]

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1 INTRODUCTION

The interferometric principle is based on the interference of two light beams, usually laser beams, due the coherence that laser source offers, among others advantages. Using the interference phenomenon, the system works with the diffe405rence between the reference beam and the sensor one being able to measure whichever factor is disturbing the sensor, purposely. Its main purpose is to convert an optical phase variation between its arms in a variation of optical intensity, which can be measured electronically. This optical phase variation can be inserted in the system through many modes that it is possible to. In the case of this work it is inserted through an excited piezoelectric actuator that produces small displacements. The interferometric system has a high sensitivity, being able to measure mechanical displacements in the order of 10^{-14} m (YIMNIRUN *et al*, 2003). For this and others benefits, this system can be applied in many areas and for measurement of different physical quantities: nanotechnology (DEVASIA *et al*., 2007), samples' positioning in microelectronics (VERMA *et al*., 2005), masks' alignments and others sectors of fine mechanics, where there is need for microscopic positioning.

However, being so sensitive it has its disadvantages: the system can also capture environmental disturbances (such as vibrations, temperature variations, air turbulences, etc.). In other words, mitigate these effects it is one of the main challenges presented to interferometry. Thereby, due to the systems' nonlinear nature, problems as fading signal (SHEEM *et al*., 1982), as well as ambiguity of results and sense direction (CHEN *et al*.,2014) can appear and for that matter, making necessary the use of phase unwrapping algorithms (DEBNATH *et al*., 2009) which makes the measurement process complex, or else, the use of active compensations methods.

Over fifteen years now, the members of LOE - Laboratory of Optoelectronics (Faculty of Engineering of Ilha Solteira - FEIS, Universidade Estadual Paulista - UNESP), have been developing interferometry applications (MARTIN, 2018; MARTIN *et al*., 2017; GALETI *et al*., 2015a; GALETI *et al*., 2013; MARÇAL *et al*., 2012a; MARÇAL *et al*., 2012b; BARBOSA *et al*., 2010; MARÇAL *et al*., 2007), with special interest in the development of new techniques of detection of optical phase using low cost interferometers and simple electronic, and utilizing the advantages offered by the current digital signal acquisition and processing systems.

Due the challenges the interferometric system presents and in order to characterize new models of piezoelectric actuators, the members of LOE have been developing unprecedented interferometric methods in the measurement of microscopic and submicroscopic displacements, processing the photodetected signals in the frequency (GALETI *et al*., 2015a; GALETI *et al*., 2013) or time domain (CONNELY, 2015; GALETI, *et al*., 2015b).

The temporal methods may require elements of active compensation (the interferometric system in closed loop) in order to operate around the quadrature condition (optimal point of operation) steadily in low gain mode (UDD; SPILLMAN, 2011), or, to linearize the interferometry characteristic curve, in high gain approach (CHEUNG *et al*., 2003), as proposed in this study.

This work comes to present a nonlinear control system with high gain approach for the two beam optical interferometer. The innovation brought here is to use the nonlinear control with a resonant filter. The goal is to explore the high gain approach without the need of interferometer in quadrature (FELÃO, 2019), which reduces the coast of extra optical elements. Once more the closed loop system operates with high gain approach, i.e. on full compensation, in order to linearize the interferometer transfer curve (not through the traditional Taylor series, but by closed loop control techniques) and eliminate a complex process of demodulation (which can involve phase unwrapping methods). Also, by using the resonant filter it is possible reduce the error of the system by using the resonant filter in resonance. This system ends up uniting two powerful tools of the nonlinear control: the resonant filter and a variable structure. The variable structure has been proved to be an important tool as well efficient and robust enough to stabilize the interferometer. Also, it is one of the main techniques of nonlinear control due to its simplicity of implementation and robustness characteristic (UTKIN, 1978; ITKIS, 1976; DECARLO *et al*., 1988).

Furthermore, its application to nonlinear systems, as in the case of the interferometric system, it strongly justified and allows satisfying the requirements of efficient operation of laser interferometers, guaranteeing high performance and robustness (MARTIN *et al*., 2017).

Chapter 2 presents a theoretical background regarding the two beam interferometer. It is described the Bulk Michelson interferometer (used in the experimental setups), the interferometer signal and its peculiarities. Also, the configuration of this interferometer in quadrature due an application proposed in Chapter 4.

The control theory is presented in Chapter 3: the controller proposed and its variations are described with the stability analysis along with its behavior. Also, they are tested preliminary via simulations in order to prove the theory described. Besides, a discrete analysis of the system had to be done due some issues regarding the sampling rate of the system.

Chapter 4 comes to present the experimental setup and the procedures used in tests presented in this research, as well as a brief description of the platforms used in the setups (hardware) and its connections. In the end of the chapter, a method of implementation is presented to solve some problems with the physical closing of the feedback control with the interferometric system.

All the results obtained are disclosed in Chapter 4 as well. The resonant control, those same problems of the modified control where predicted in Chapter 3. It was tested using the method of the virtual controller presented in Experimental Setup section of Chapter 4. The resonant control was tested for four different strategies in order to improve the gain relation far from the filter resonance and the chattering effect.

Finally, Chapter 5 brings the conclusions and discussion for future work.

5 CONCLUSION AND FUTURE WORK

The variable structure is an elegant solution for the control and stabilization of the two beam optical interferometer. Along with it, the sliding mode brings simplicity of implementation, lowering costs and robustness. It is noteworthy that none of the methods studied, need the interferometer to be in quadrature, unless when using the virtual interferometer on the implementation of the method.

The resonant control, this new approach, looks promising due its high accuracy and robustness (for the systems with switching). One can conclude that all the resonant systems tested do work and assure the simulations and theory developed in this work. All the system variations seem to work with little discrepancy when compared to the arc tangent method. Whereas the system with sigmoidal function is smoother than the other and has the smallest error (as foreseen already being said in such applications (MARTIN, 2018; FELÃO, 2019)).

Also, we can notice that the resonant filter has characteristic of filtering a specific frequency with very high gain, there goes an advantage of working in resonance, which could be a powerful substitution on procedures to measure really small displacements. Also, since in resonance the gain of the filter goes to infinite and during the switching, the signal function also has an infinite gain, this brings a capability of full compensation (high gain approach) with a lower range of controller gain than studied before.

On the developing of this research we could evaluate the advantages and issues that the high gain approach brings. It is an approach with easy results, once the correction phase is always proportional to the interest signal. But, the fact that it needs to compensate a composed signal come with some issues: it can be a problem for processing (when working with a real-time implementation), since it ends up needing a higher sampling rate or can be limiting in gain by an analogic circuit. Also, closing a physical feedback loop is a bit challenging due the hardware available. And the risk of vibrating the feedback PZT to physical damage, reducing the frequency range that the control systems can compensated safely and out of instability (to operate in higher frequencies, it needs a higher gain generating chattering and amplifying vibrations in the PZT of feedback).

For future works, a solution for the issues presented is to implement the systems using analog circuits, or a platform with a close sampling rate (such as FPGA), allowing the system to have a physical feedback, or even using the virtual method proposed by Felão (2019). Each case comes with advantages of increasing the sampling rate and disadvantages due the peculiarities of the methods. Also, the resonant system with both inputs could be test using the sigmoidal function instead.

In conclusion the resonant control system comes with the advantages of the high gain approach, without the need of the interferometer quadrature (when implemented using a physical feedback), as the high gain proposed by Felão (2019), and relies on small errors and smaller gains specially when operating in resonance.

BIBLIOGRAPHY

BARBOSA. F. A. A.; NADER, G.; HIGUTI, R. T.; KITANO, C.; SILVA, E. C. N. A simple interferometric method to measure the calibration factor and displacement amplification in piezoelectric flextensional actuators. **Controle & Automação**, Heidelberg, v. 21, n. 6, p. 577-587, 2010.

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, n. 026106, p. 4 , 2014.

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

DEBNATH, S. K.; KOTHIYAL, M. P.; KIM, S. W., Evaluation of spectral phase in spectrally resolved white-light interferometry: Comparative study of single-frame techniques. **Optics and Lasers in Engineering**, London, v. 47, p. 1125–1130, 2009.

DECARLO, R. A.; ZAK, S. H.; MATTHEWS, G. P. Variable structure control of nonlinear multivariable systems: a tutorial. **Proceedings of the IEEE**, New York, v. 76, p.212–232, 1988.

DEVASIA, S.; ELEFTHERIOU, E.; MOHEIMANI, S. O. R. A survey of control issues in nanopositioning. **IEEE Trans. Control Syst. Technol.,** Piscataway, v. 15, n. 5, p. 799– 823, 2007.

FELÃO, L. H. V. Thesis: High gain approach and sliding mode control applied to quadrature interferometer. UNESP, Ilha Solteira, 2019.

GALETI, J. H. **Medição interferométrica de fase óptica através do método de segmentação do sinal amostrado**. 2011. 115 f. Masters dissertation (Ph.D grade in Electrical Engineering) – Faculdade de Engenharia, Universidade Estadual Paulista - UNESP, Ilha Solteira, 2011.

GALETI, J. H.; BERTON,P. L.; KITANO, C.; HIGUTI, R. T.; CARBONARI, R. C.; SILVA, E. C. N. Wide dynamic range homodyne interferometry method and its application for piezoactuators displacement measurements. **Applied Optics**, Washington, v. 52, n. 28, p. 6919-6930, 2013.

GALETI, J. H.; HIGUTI, R. T.; SILVA, E. C. N.; KITANO, C. Nanodisplacement measurements of piezoelectric flextensional actuators using a new interferometry homodyne method. **IEEE Transactions on Instrumentation and Measurement**, Piscataway, v. 64, n. 5, p. 1256-1265, 2015a.

GALETI, J. H.; KITANO, C.; CONNELLY, M. J. Improved synthetic-heterodyne Michelson interferometer vibrometer using phase and gain control feedback. **Applied Optics**, Washington, v. 54, n. 35, p. 10418-10424, 2015b.

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

ITKIS, U. **Control systems of variable structure**. Jerusalem: Israel Universities, 1976.

LEÃO, J. V. F. **Interferometria óptica aplicada à medição de amplitudes de vibração nanométricas em piezoatuadores flextensionais**. 2004. Dissertação (Mestrado em engenharia elétrica) – Faculdade de Engenharia de Ilha Solteira, Universidade Estadual Paulista, Ilha Solteira, 2004.

LE LETTY, R.; CLAEYSSEN, F.; BARILLOT, F.; LHERMET, N. Amplified piezoelectric actuators for aerospace applications. *In*: PROCEEDINGS OF THE AMAS WORKSHOP ON SMART MATERIALS AND STRUCTURES–SMART. **Proceedings** [...] [*S. l.: s.n.*], 2003. v. 3, p. 51–62.

LEMES, A. S. **Novas configurações de interferômetros de quadratura e de técnicas de detecção de fase óptica baseadas em phase unwrapping**. 2014. 146 f. Dissertação (Mestrado em Automação) - Faculdade de Engenharia, Universidade Estadual Paulista - UNESP, Ilha Solteira, 2014.

MARÇAL, L. A. P.; LEÃO, J. V. F.; NADER, G.; HIGUTI, R. T.; KITANO, C.; SILVA, E. C. N. Analysis of Linearity and Frequency Response of a Novel Piezoelectric Actuator Using a Homodyne Interferometer and the J1- J4 Method. **IEEE Transactions on Instrumentation and Measurement**, Piscataway, v. 56, p. 954-961, 2007.

MARÇAL, L. A. P. **Novas técnicas de detecção de fase óptica em interferômetros homódinos aplicadas à caracterização de atuadores piezoelétricos flextensionais**. 2008. Tese (Doutorado em engenharia elétrica) – Faculdade de Engenharia de Ilha Solteira, Universidade Estadual Paulista, Ilha Solteira, 2008.

MARÇAL, L. A. P.; HIGUTI, R. T.; KITANO, C. A simplified and higher dynamic range version of the J1 J4 method for optical phase measurements, **Microwave and Optical Technology Letters**, Hoboken, v. 54, p. 387-392, 2012a.

MARÇAL, L. A. P.; KITANO, C.; HIGUTI, R. T.; NADER, G.; SILVA, E. C. N. A high dynamic range method for direct readout of dynamic phase change in homodyne interferometers. **Measurement Science & Technology**, Bristol, v. 23, p. 1-12, 2012b.

MARTIN, R. I. **Nonlinear control system based on variable structure and sliding modes for two beam optical interferometry**. 2018. 127 f. (PhD Thesis) - Faculdade de Engenharia, Universidade Estadual Paulista - UNESP, Ilha Solteira, 2018.

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. **Optic Express**, [*s. l.*], v. 25, p. 6335-6348, 2017.

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 flextencionais**. 2009. 147 f. Tese (Mestrado em Engenharia Elétrica) – Faculdade de Engenharia, Universidade Estadual Paulista - UNESP, Ilha Solteira, 2009.

NIEZRECKI, C.; BREI, D.; BALAKRISHNAN, S.; MOSKALIK, A. Piezoelectric actuation: state of the art. **The shock and vibration digest**, Sage, v. 33, n. 4, p. 269–280, 2001.

NATIONAL INSTRUMENTS. **Programação gráfica**. [*S. l.: s. n.*], 2015. Disponível no endereço: http://www.ni.com/getting-started/labview-basics/pt/dataflow. Acesso em: 10 fev. 2020.

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.

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

UTKIN, V. I. **Sliding modes and their application in variable structure systems.** Moscow: MIR, 1978.

YIMNIRUN, R.; MOSES, P. J.; MEYER JR., R. J.; NEWNHAM, R. E. A single-beam interferometer with sub-ångstrom displacement resolution for electrostriction measurements, **Measurement Science and Technology**, Bristol, v. 14, p. 766-772, 2003.