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NLFXLMS AND THF-NLFXLMS ALGORITHMS FOR WIENERHAMMERSTEIN NONLINEAR ACTIVE NOISE CONTROL

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By

RADIK SRAZHIDINOV

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Master of Science

October 2016

DEDICATION

I dedicate this thesis to all Kyzylkia "Sebat" high school teachers.

Education is not a business; it is one of the human's wings.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Master of Science

NLFXLMS AND THF-NLFXLMS ALGORITHMS FOR WIENER-HAMMERSTEIN NONLINEAR ACTIVE NOISE CONTROL

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RADIK SRAZHIDINOV

October 2016

Chairman : Associate Professor Raja Mohd Kamil b. Raja Ahmad, PhD
Faculty : Engineering

Filtered-X least mean square (FXLMS) control algorithm is a conventional algorithm employed to cancel the noise in linear environment. However, in practical applications nonlinearities may present. These nonlinearities are usually associated with the secondary path components, such as amplifiers and loudspeakers. Block oriented method is used to represent the linear and nonlinear components in the secondary path. Usually, linear components are represented by finite impulse response (FIR) filters and nonlinear component with saturation nonlinearity scaled error function (SEF). Nonlinear FXLMS (NLFXLMS) control algorithm based on SEF has been previously developed to cancel the noise in environment with external factors that can cause nonlinearity. The major drawback of using SEF based NLFXLMS (SEF-NLFXLMS) is that the degree of nonlinearity must be known in advance for good control performance. In recent works, it was shown that the SEF can be approximated using tangential hyperbolic function (THF) for Hammerstein and Wiener NLFXLMS algorithms, such that the degree of nonlinearity can be estimated using modelling approach. The THF-NLFXLMS method is extended here for Wiener-Hammerstein model. Using this method, the need for the knowledge of the degree of nonlinearity in advance can be avoided. The proposed algorithm models the Wiener-Hammerstein linear and nonlinear components in the secondary path and applies the estimated degree of nonlinearity of the nonlinear secondary path in the control algorithm design.

In previous works, SEF-NLFXLMS and THF-NLFXLMS algorithms for Hammerstein and Wiener structures were developed where the acoustic path is assumed to be a unit gain. However, this assumption may lead to inaccurate secondary path model. In this work, the modelling of acoustic path using FIR filters is incorporated for both algorithms for Wiener-Hammerstein structure. The development of these algorithms becomes the first and second objectives of this research. It is hypothesised that incorporating the acoustic path model would improve the modelling of the secondary path and subsequently improves the level of noise cancellation.
The proposed SEF-NLFXLMS and THF-NLFXLMS algorithms are compared with the conventional FXLMS and 2nd order Volterra FXLMS algorithms (which is

determined to be of comparable computational complexity with the THF-NLFXLMS). The simulation results show that the Wiener-Hammerstein THF-NLFXLMS has close performance with the SEF-NLFXLMS. It outperforms the FXLMS by 2.5dB and 4dB and 2nd order Volterra FXLMS by 3.5dB and 4.5dB for low and medium degrees of nonlinearity, respectively. In addition, Wiener-Hammerstein THF-NLFXLMS shows better performance compared to Wiener THF-NLFXLMS algorithm.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Master Sains

ALGORITMA NLFXLMS DAN ALGORITMA THF-NLFXLMS UNTUK KAWALAN AKTIF BUNYI TAK LELURUS WIENER-HAMMERSTEIN

Oleh

RADIK SRAZHIDINOV

Oktober 2016

Pengerusi : Profesor Madya Raja Mohd Kamil b. Raja Ahmad, PhD
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Algoritma kawalan tapisan-X min kuasa dua terkecil (*FXLMS*) adalah algoritma konvensional yang digunakan untuk memansuhkan bunyi dalam persekitaran lelurus. Walau bagaimanapun, dalam aplikasi yang praktikal, faktor ketaklelurusan barangkali wujud. Faktor ketaklelurusan selalunya dikaitkan dengan komponen-komponen dalam laluan sekunder, seperti amplifier dan pembesar suara. Kaedah blok terhala digunakan untuk mewakili komponen lelurus dan tak lelurus dalam laluan sekunder. Biasanya, komponen lelurus diwakili oleh penapis sambutan dedenyut terhingga (*FIR*) manakala komponen tak lelurus yang mempunyai ketepuan ketaklelurusan diwakili oleh fungsi ralat berskala (*SEF*). Algoritma kawalan *FXLMS* tak lelurus (*NLFXLMS*) berdasarkan *SEF* telah dibangunkan sebelum ini untuk memansuhkan bunyi dalam persekitaran tak lelurus. Kelemahan utama menggunakan *SEF* dalam *NLFXLMS* adalah tahap ketaklelurusan yang perlu diketahui terlebih dahulu bagi mendapatkan kawalan prestasi yang baik. Kajian terkini telah menunjukkan bahawa SEF boleh dianggarkan menggunakan fungsi tangen hiperbolik *(THF)* untuk algoritma *NLFXLMS* Hammerstein dan Wiener, yang mana tahap ketaklelurusan boleh dianggarkan menggunakan pendekatan pemodelan. Kaedah *THF-NLFXLMS* dilanjutkan di sini untuk model Wiener-Hammerstein. Dengan menggunakan kaedah ini, tahap ketaklelurusan tidak perlu diketahui terlebih dahulu. Algoritma yang dicadangkan untuk memodelkan komponen lelurus dan taklelurus *Wiener-Hammerstein* dalam laluan sekunder dan mengaplikasikan penganggaran dalam mengenal pasti tahapan ketaklelurusan laluan sekunder dalam rekabentuk algoritma kawalan.

Dalam kajian yang lalu, algoritma *SEF-NFXLMS* dan *THF-NLFXLMS* untuk struktur Hammerstein dan Weiner telah dibangunkan yang mana gandaan laluan akustik dianggap sebagai satu. Tetapi anggapan berkenaan boleh menyebabkan model laluan sekunder tidak tepat. Dalam kajian ini, kaedah permodelan laluan akustik menggunakan FIR telah menggabungkan struktur algoritma Wiener-Hammerstein. Usaha membangunkan algoritma ini merupakan objektif pertama dan kedua kajian ini. Secara hipotesis, menggabungkan model laluan akustik akan mengelokkan model untuk laluan sekunder seterusnya memperbaiki tahap pemansuhan bunyi.

Algoritma *THF-NLFXLMS* yang dicadangkan telah dibandingkan dengan beberapa penanda aras iaitu algoritma *SEF-NLFXLMS*, algoritma *FXLMS* konvensional, dan algoritma tahap kedua Volterra *FXLMS* (yang mempunyai tahap kerumitan pengiraan yang standing dengan *THF-NLFXLMS*). Keputusan simulasi menunjukkan bahawa Wiener-Hammerstein *THF-NLFXLMS* mempunyai prestasi yang hampir sama dengan algoritma *SEF-NLFXLMS*. *THF-NLFXLMS* melebihi prestasi algoritma *FXLMS* dengan 2.5dB dan 4dB manakala melebihi prestasi algoritma Volterra *FXLMS* tahap kedua dengan 3.5dB dan 4.5dB bagi tahap ketaklelurusan rendah dan sederhana masing-masing. Selain itu, Wiener-Hammerstein *THF-NLFXLMS* telah menunjukkan prestasi yang lebih baik berbanding algoritma Wiener *THF-NLFXLMS*.

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I certify that a Thesis Examination Committee has met on 6 October 2016 to conduct the final examination of Radik Srazhidinov on his thesis entitled "NLFXLMS and THF-NLFXLMS Algorithms for Wiener-Hammerstein Nonlinear Active Noise Control" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

ADC	Analog to Digital Converter
ANC	Active Noise Control
BFXLMS	Bilinear Filtered-X Least Mean Square
DAC	Digital to Analog Converter
FIR	Finite Impulse Response
FXLMS	Filtered-X Least Mean Square
IIR	Infinite Impulse Response
LFXLMS	Leaky Filtered-X Least Mean Square
LMS	Least Mean Square
LNL	Linear Nonlinear Linear
LTI	Linear Time Invariant
MOVFXLMS	Minimum Output Variance Filtered-x Least Mean Square
MSE	Mean Square Error
NANC	Nonlinear Active Noise Control
NARMAX	Nonlinear Autoregressive moving models with exogenous inputs
NLFXLMS	Nonlinear Filtered-X Least Mean Square
SEF	Scaled Error Function
SEF-NLFXLMS	Scaled Error Function based Nonlinear Filtered-X Least Mean Square
SISO	Single Input Single Output
THF	Tangential Hyperbolic Function
THF-NLFXLMS	Tangential Hyperbolic Function based Nonlinear Filtered-X Least Mean Square
VFXLMS	Volterra Filtered-X Least Mean Square

VLFXLMS	Variable Leaky Filtered-X Least Mean Square
VMOVFXLMS	Variable Minimum Output Variance Filtered-X Least Mean Square

LIST OF SYMBOLS

$\%e$	Percentage of the approximation error
$f_{THF}[\cdot]$	Tangential hyperbolic function
$\hat{f}_{THF}[\cdot]$	Estimated tangential hyperbolic function
$\hat{\alpha}_0$	Initial value of $\hat{\alpha}$
$\hat{\beta}_0$	Initial value of $\hat{\beta}$
h_i	Coefficient of the Volterra filter
$A_i(n)$	Coefficients of the Bilinear filter delayed input
B_{2n}	Even index Bernoulli number
$B_i(n)$	Coefficients of the delayed output
$C_i(n)$	Coefficients of the Bilinear filter delayed input-output cross multiplied sample
P_v	Order of the Volterra filter
$\hat{S}(n)$	First estimated secondary path
$\hat{K}(n)$	Second estimated secondary path
$d\hat{f}_{THF}[\cdot]$	Derivative of the estimated tangential hyperbolic function
$\hat{d}(n)$	Estimated primary noise signal at the observer
$e_{nl}(n)$	Nonlinear error
$f'[\cdot]$	Derivative of the nonlinear function
$f_{SEF}[\cdot]$	Scaled error function
$x_f(n)$	Filtered reference signal
γ_0	Optimum leakage factor
η^2	Degree of nonlinearity in SEF function
$*$	Convolution operator
$\nabla J(n)$	Derivative of the cost function

$H(n)$	The matrix of the Volterra coefficient
$J(n)$	Cost function
L	Length of FIR filter (1^{st} secondary path)
M	Length of FIR filter (2^{nd} secondary path)
N	Number of samples
$P(n)$	Primary path
$S(n)$	First secondary path
$K(n)$	Second secondary path
$W(n)$	Controller
$d(n)$	Primary noise signal at the observer
$e(n)$	Linear error
$f[\cdot]$	Nonlinear function
$sgn(x)$	Sign function
$v(n)$	Modelling signal
$x(n)$	Reference signal
$z(n)$	Gaussian measurement noise
α	Scaling parameters in THF function
β	Degree of nonlinearity in THF function
γ	Leakage factor
μ	Step size of the adaptive algorithm
ξ	First scaling parameter of the sigmoid function
ϑ	Second scaling parameter of the sigmoid function
ϱ	Scaling parameter of the soft clipping function

CHAPTER 1

INTRODUCTION

1.1 Background

Noise pollution has many negative effects on human health, such as: hearing loss, cardiovascular disease, mental illness and negative social behaviour [1] and [2]. Figure 1.1 shows that in most states of Malaysia the noise level exceed both day and night time limits. High frequency noise can be controlled using passive methods, for example barriers and silencers. However, this method is not effective for low frequency noise below 500Hz, because this low frequency noise has longer wavelength that allows the noise to penetrate through the barriers and silencers [3]. An active noise control (ANC) method is on effective method that can be used to cancel low frequency noise using the principle of superposition.

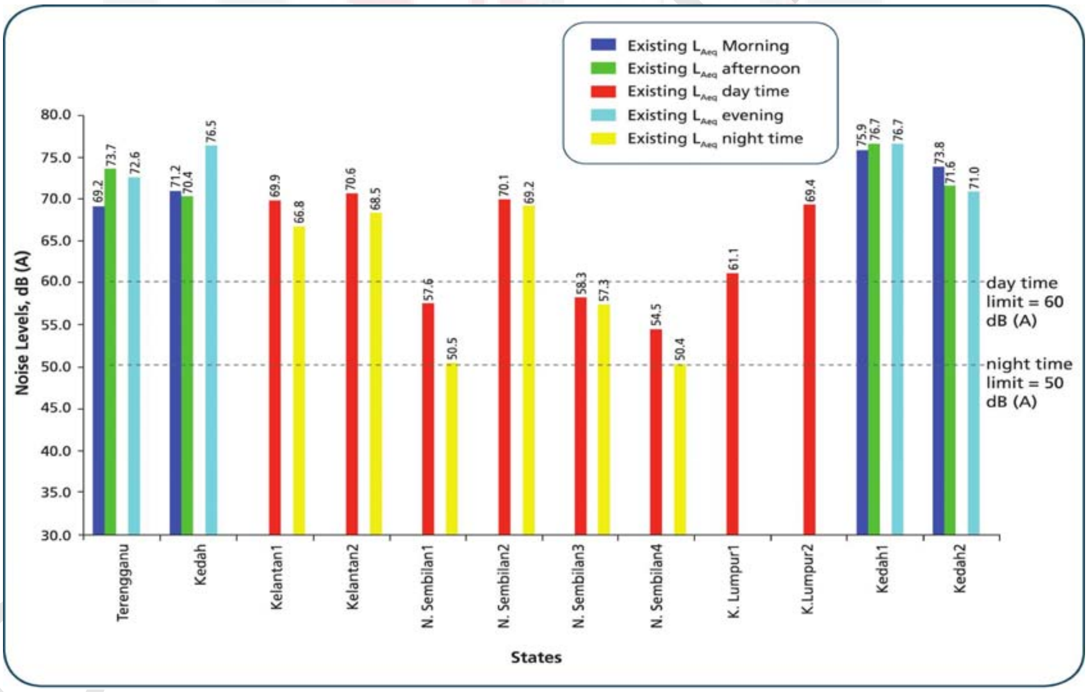

Figure 1.1 : Noise level for selected urban residential areas in various states of Malaysia

Nonlinear active noise control (NANC) is a method to cancel an unwanted noise by generating an antinoise through secondary source (loudspeaker) in the system that contains secondary path nonlinearity [1]. Adaptive control technique is widely applied to design the controller in order to overcome the nonlinearity in the NANC. The two methodologies used in designing an adaptive NANC are direct and indirect methods. For the direct method, adaptation of the controller is achieved without utilizing the nonlinear model of the secondary path. An example of direct method algorithms such as filtered-X least mean square (FXLMS), bilinear FXLMS (BFXLMS), Volterra FXLMS (VFXLMS), leaky FXLMS (LFXLMS) and minimum output variance (MOVFXLMS). In the indirect method, the controller is designed by utilizing the secondary path's nonlinear saturation model. Nonlinear FXLMS (NLFXLMS) is the only algorithm that fall under this method, where the scaled error function (SEF) is used to represent the nonlinear saturation model [2]. Block oriented structure is usually used to represent secondary path by separating it into linear and nonlinear blocks [3]. Three block oriented structures are used in NANC: Wiener (linear-nonlinear), Hammerstein (nonlinear-linear) and Wiener-Hammerstein (linear-nonlinear-linear). In [2] and [4], the Wiener and Hammerstein NLFXLMS algorithms were proposed. These algorithms have the best performance in NANC system and low computational complexity. The application of NLFXLMS algorithm for Wiener-Hammerstein block oriented structure is yet to be developed and becomes the subject of this research.

The secondary path in ANC consists of D/A and A/D converters, amplifier, actuators, sensors and acoustic path [5]. In practice, one of these components may be nonlinear. Wiener-Hammerstein block oriented structure can be used when the nonlinear component exists between two linear filters. For instance, a nonlinear loudspeaker is sandwiched between linear amplifier and linear acoustic path [5].

Nonlinearity in secondary path is commonly represented by saturation nonlinearity and the clipping effect is represented using SEF [6]. The major drawback of using SEF based NLFXLMS (SEF-NLFXLMS) is the requirement of prior knowledge about the system's nonlinearity degree. In the work [4] and [7], the SEF was approximated by using tangential hyperbolic function (THF) for Wiener and Hammerstein NLFXLMS algorithms. It was shown that THF can model SEF with certain level of accuracy. Least mean square (LMS) algorithm is used to model the nonlinearity block represented by THF and this information can be used in THF based NLFXLMS (THF-NLFXLMS) algorithm control design.

1.2 Problem Statement

SEF-NLFXLMS gives the highest results of noise cancellation. It is used as a benchmark in performance comparison since SEF-NLFXLMS utilizes the true value of the nonlinearity degree which is represented by saturation model [4]. This saturation nonlinearity in NLFXLMS algorithm is usually modelled by SEF [2]. The algorithm is limited in practical application due to the requirement of prior information about the nonlinearity degree that is usually assumed to be known [4] and [7]. This limitation leads to the development of the THF-NLFXLMS algorithm where the nonlinearity degree is estimated by modelling the secondary path. The most general and complete representation of block oriented NANC structure is the Wiener-Hammerstein model. Wiener-Hammerstein structure has advantage over Hammerstein and Wiener structure because it includes acoustic path into modelling rather than assuming that it is a unit gain. It is hypothesized that modelling the acoustic secondary path would improve the level of noise cancellation. However, SEF-NLFXLMS and the improved THF-NLFXLMS algorithms have not yet been developed for this structure and are addressed in this research.

1.3 Aims and Objectives

The aim of this research is to develop a methodology for modelling the nonlinearity in Wiener-Hammerstein secondary path structure and use this model to design an active noise controller based on THF-NLFXLMS algorithm. The proposed algorithm must have comparable performance with the benchmark SEF-NLFXLMS in terms of level of noise cancellation. The following objectives have been outlined in order to achieve the aims of the research:

1. To develop benchmark SEF-NLFXLMS algorithm for Wiener-Hammerstein structure.
2. To develop a methodology for modelling the nonlinearity in Wiener-Hammerstein secondary path structure and use this model to design THF-NLFXLMS algorithm.
3. To compare the performance of SEF-NLFXLMS and THF-NLFXLMS with FXLMS and 2^{nd} order VFXLMS algorithms.

1.4 Research Scope

The work is restricted to single-input single-output (SISO) feedforward ANC system. The feedforward strategy is used to control the noise at the observer. All the transfer function and filters, including reference signal and primary path, are assumed to be linear except the nonlinear block in secondary path which is represented by a memoryless saturation nonlinearity. This work involves designing and simulating the proposed modelling and control techniques. At the control stage, an alternative THF-NLFXLMS algorithm is proposed and compared with NLFXLMS, FXLMS and 2^{nd} order Volterra algorithms with similar complexity. Figure1.2 illustrates the research scope which is covered in this simulation.

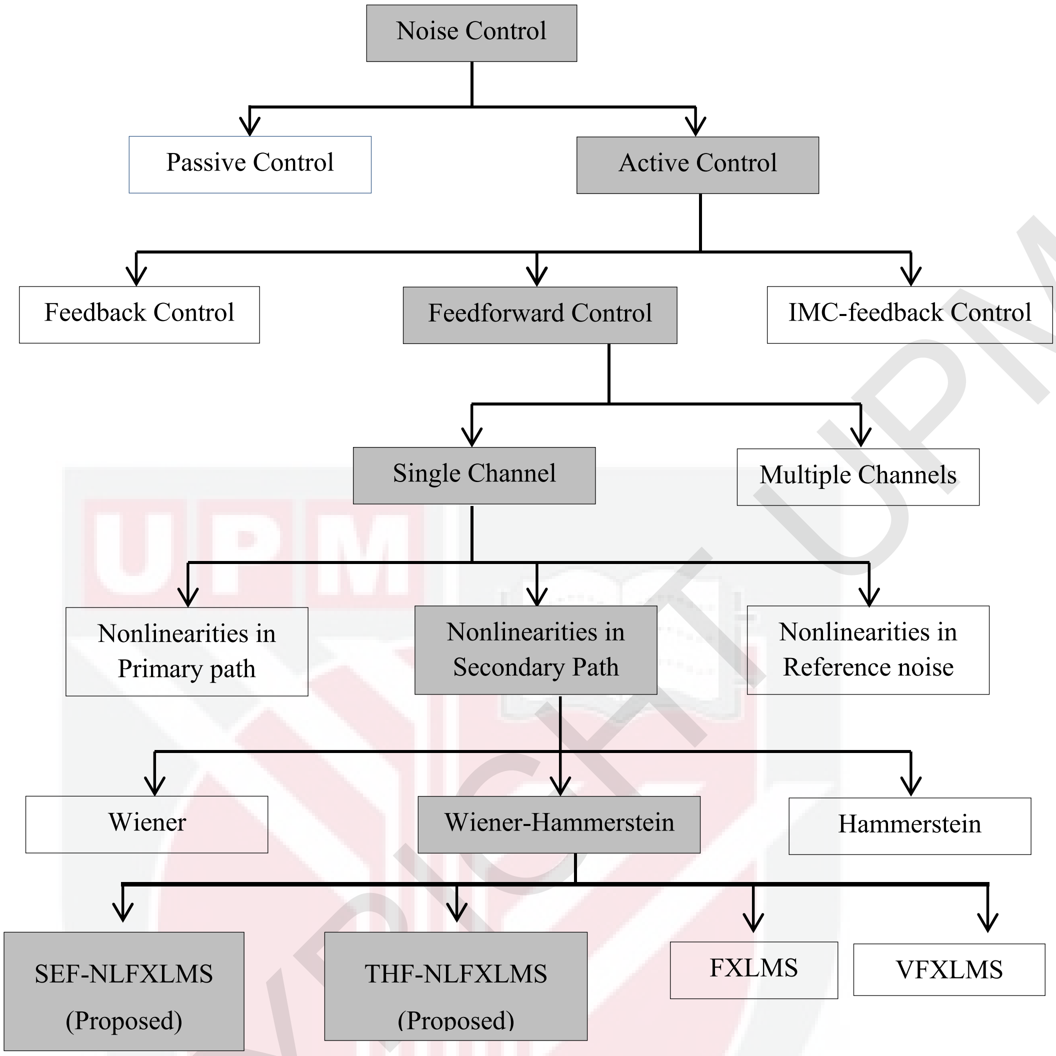

Figure 1.2 : Research scope

1.5 Methodology

The methodology of this research has three substantial parts: development of SEF-NLFXLMS control algorithm, secondary path modelling, and THF-NLFXLMS control algorithm. Firstly, the SEF-NLFXLMS algorithm is developed for Wiener-Hammerstein block oriented structure. Then, the secondary path is modelled with saturation nonlinearity that is estimated using THF.

To overcome the drawback of SEF-NLFXLMS where the nonlinearity degree must be known in advance, the proposed secondary path model was used to design THF-NLFXLMS algorithm. This proposed control algorithm is compared with SEF-NLFXLMS, FXLMS and 2nd order Volterra FXLMS (with similar computational complexity as THF-NLFXLMS) using Mean Square Error (MSE) criterion.

1.6 Thesis Organization

This thesis is organized into five chapters. Chapter 1 presents the introduction, research problems, research objectives, research aim and methodology of the study. Chapter 2 presents the literature review related to the algorithms of NANC systems. Nonlinearities in the secondary path and their mathematical representations are discussed. Block oriented structure of nonlinear secondary path are provided in this section. In Chapter 3, the SEF-NLFXLMS and THF-NLFXLMS algorithms are developed and derived for NANC with nonlinearities in secondary path with Wiener-Hammerstein structure. The secondary path modelling is proposed to estimate the secondary path linear and nonlinear values. In chapter 4, the numerical simulation is performed for the proposed secondary path modelling and control, the THF-NLFXLM algorithm is compared with SEF-NLFXLM, FXLMS and 2^{nd} order VFXLMS algorithms. Finally, in Chapter 5 the conclusion is provided with possible future perspectives of the work.

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