SIGNAL ENHANCEMENT OF RADIO FREQUENCY POWER MEASUREMENT IN 1/f NOISE

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Specially dedicated to my late father, Zali bin Ibrahim, late grandmother Jaharah bt Othman, my family and friends and all those who have contributed in this research.

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ABSTRACT

One of the prevalence challenges in the radio frequency (RF) power sensor development is to reduce noise in the acquired signal. The noise in the signal subsequently contributes to the error in the measurement of signal parameters. Sources of noise could come from the chain of signal conditioning and acquisition in the sensor circuitry. The assumption of additive white Gaussian noise (AWGN) to model a measurement is not valid since many applications such as in RF power measurement has the noise coloured with 1/f spectrum characteristics. With this characteristics, the assumption of independent and identically distributed (IID) used in signal detection and estimation becomes not valid. By whitening process, the 1/f noise characteristics can be converted to be similar to white noise. The analysis results of decimation, linear prediction, Burg algorithm and chopper with averaging shows that the proposed methods can be used effectively. Both Burg algorithm and linear prediction are more complex due to the need to perform matrix inversion. The decimation and chopper with averaging are the least complex but it could only meet the requirements if the sample size is more than 300 samples. After performing the whitening, the wavelet transform and de-noising are implemented to remove noise as much as possible while preserving the signal characteristics. As results, it can be seen that the noise is removed while the characteristics of the pulse signal is preserved by the Haar wavelet. However, the recovered signal is distorted when using Daubechies 5 wavelet with significant reduction in noise. Based on the result for RF power measurement for different whitening methods in Monte Carlo simulation, Burg algorithm yields the highest total variance reduction which is 97.13%, followed by the linear prediction which is 90.3%, decimation 64.11% and lastly, chopper with averaging, 3.10% for SNR of 8 dB. Although Burg algorithm is more complex compared to decimation, it preserves all the signal samples which is more suitable for pulse signals and it is the best whitening method used in this research.

ABSTRAK

Salah satu halangan yang terdapat di dalam frekuensi radio (RF) adalah untuk mengurangkan hingar yang terdapat di dalam isyarat. Hingar didalam sesuatu isyarat menyebabkan berlakunya kesilapan dalam mengukur isyarat parameter. Hingar terhasil daripada rangkaian dan juga penerimaan isyarat di dalam litar sensor. Andaian yang digunakan di dalam *additive white Gaussian noise* (AWGN) untuk membentuk satu ukuran tidak boleh digunakan kerana masalah hingar di dalam kuasa RF hadir dengan ciri-ciri spektrum 1/f. Berdasarkan ciri-ciri ini, andaian taburan tak bersandar dan serupa (IID) yang digunakan dalam mengesan dan menganggar isyarat menjadi tidak sahih. Melalui proses pemutihan, hingar 1/f boleh ditukarkan kepada hingar putih. Keputusan daripada analisis desimasi, ramalan linear, algoritma Burg dan pemenggal dengan purata menunjukkan kaedah yang dicadangkan ini dapat digunakan dengan berkesan. Kaedah algoritma Burg dan ramalan linear adalah lebih kompleks berbanding analisa desimasi kerana memerlukan proses sonsangan matriks. Desimasi dan pemenggal dengan purata adalah kaedah yang kurang kompleks tetapi ia hanya dapat memenuhi semua kriteria yang ditetapkan jika saiz sampel melebihi 300 sampel. Setelah melalui proses pemutihan, jelmaan *wavelet* dan menyah hingar dilaksanakan untuk menyingkirkan hingar sebanyak yang boleh di samping mengekalkan ciri-ciri isyarat. Sebagai hasilnya, dapat dilihat bahawa hingar berjaya disingkirkan sementara ciri-ciri isyarat nadi dapat dikekalkan oleh *wavelet* Haar. Walau bagaimanapun, isyarat yang dipulihkan itu berubah apabila menggunakan *wavelet* Daubechies 5. Berdasarkan keputusan simulasi Monte Carlo pengukuran kuasa RF untuk kaedah pemutihan yang berbeza, didapati bahawa algoritma Burg menghasilkan jumlah penurunan varians yang paling tinggi iaitu 97.13%, diikuti dengan ramalan linear iaitu 90.3%, desimasi 64.11% dan akhir sekali pemenggal dengan purata, 3.10% untuk SNR 8 dB. Walaupun algorithma Burg lebih kompleks berbanding desimasi, ia mampu mengekalkan semua sampel isyarat dan lebih sesuai untuk isyarat nadi dan merupakan kaedah pemutihan yang paling bagus untuk digunakan dalam kajian ini.

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LIST OF ABBREVIATIONS

ADC	-	Analog-to-digital converter
ADF	-	Adaptive-correlation filtering
AUC	-	Area under curve
AWGN	-	Additive white Gaussian noise
CMOS	-	Complementary metal-oxide semiconductor
CW	-	Continuous wave
CWT	-	Continuous wavelet transform
DC	-	Direct current
DSP	-	Digital signal processor
DWT	-	Discrete wavelet transform
ECG	-	Electrocardiogram
EMG	-	Electromyography
FDR	-	False discovery rate
FIR	-	Finite impulse response
GHz	-	GigaHertz
GPP	-	Graphics performance primitive
HFO	-	High frequency oscillation
IID	-	Independently identically distribution
IIR	-	Infinite impulse response
ISI	-	Inter-symbol interference
kHz	-	KiloHertz
LAN	-	Local area network
LPF	-	Low pass filter
LTE	-	Long term Evolution
MAD	-	Median absolute value
MIMO	-	Multiple input multiple output

MOSFET	-	Metal-oxide semiconductor field effect transistor
MRA	-	Multi-resolution analysis
MSE	-	Mean square error
OFDM	-	Orthogonal frequency division multiplexing
OFDMA	-	Orthogonal frequency division multiple access
PC	-	Personal computer
PDF	-	Probability density function
PEF	-	Prediction error filter
PR	-	Precision and recall
PSD	-	Power spectral density
RAM	-	Random access memory
RF	-	Radio frequency
RIA	-	Random interpolation average
RROMP	-	Random refined orthogonal matching pursuit
s	-	second
SGWT	-	Second generation wavelet transform
SNR	-	Signal-to-Noise ratio
SPICE	-	Simulation program with integrated circuit emphasis
SQRD	-	Sorted QR decomposition
STFT	-	Short time Fourier transform
SURE	-	Stein's unbiased risk estimation
TM	-	Time frequency
UE	-	User equipment
USB	-	Universal serial bus
WPT	-	Wavelet packet transform
WSS	-	Wide sense stationary

LIST OF SYMBOLS

γ	-	Fitting parameter
λ_H	-	High corner frequency
λ_L	-	Low corner frequency
E_{m-1}^{f}	-	Forward prediction error
E_{m-1}^{b}	-	Backward prediction error
$t = a_0^m$	-	Discretized parameters of scaling
$a = ka_0^m$	-	Discretized parameters of shifting
γ	-	Threshold value
$\overline{S}_{xx}$	-	Mean spectrum
$\sigma_{xx}{}^2$	-	Variance spectrum
*	-	Complex conjugate
$A_k[n]$,	-	Highpass filters
$1/\tau_{zc}$	-	Inverse zero crossing
A	-	Channel area
a	-	Dilation factor
$a_m[k]$	-	Reflection coefficient of the predictor
$a_p(n)$.	-	FIR coefficient
$a_p[m]$	-	Filter coefficients of the forward prediction filter
c_k	-	Fourier series coefficients
C_{ox}	-	Gate oxide capacitance
D_k [n]	-	Lowpass filter
f	-	Frequency
$f(x)$	-	Periodic function
f_0	-	Fundamental frequency

f_c	-	Chopper frequency
$H(f)$	-	Frequency response
$h(t)$	-	System impulse response
$h(\tau)$	-	Mother wavelet
$h[n]$	-	Impulse response
I_d	-	Total current
$iN(\tau)$	-	Noise source
K	-	Number of segment
k_l	-	Decomposition level
k_m	-	Modified factor
k_F	-	1/f parameter
kT	-	Thermal energy
M	-	Segment length
N_0	-	Noise power
N_t	-	Trap density
P	-	Filter length
$R\_xx\ (\tau)$	-	Autocorrelation function
$R_{xx}[m]$	-	Autocorrelation function of forward prediction filter
$S\_xx\ (f)$	-	Power spectrum
S_0	-	Fitting parameter
$S_n(f)$	-	Power spectral density
$S_{vv}(f)$	-	Power spectrum of the white noise
T	-	Period
T_0	-	Time period
t_{0x}	-	Effective gate-oxide thickness
T_s	-	Sampling period
$v(t)$	-	White noise source
$w(t)$	-	Basis function
$x[n]$	-	Discrete-time signal
$x_k(t)$	-	Averaging segment
$y[n]$	-	Decimated signal
τ	-	Time delay
γ	-	Rate of change in magnitude

CHAPTER 1

INTRODUCTION

1.1 Background

Since the late 1800s, there has been a need to measure the output of radio frequency (RF) circuits when Nikola Tesla first demonstrated the wireless transmission [1]. The modern realization of the peak power meter came into being in the early 1990s while the development of radar and navigation systems led to the application of RF and microwave power in the late 1930s. Thus it was necessary to determine the level of power output.

RF power sensors are designed to measure the power of various types of signals either in continuous wave (CW) or in pulse. The output level of a transmitter is the most critical factor in the design of communication and radar system and it is important to have reliable and accurate measurements [2]. With today's complex modulation schemes, the need to accurately and efficiently measure RF power has become crucial in obtaining performance from communication systems and components.

One of the prevalence challenges in the RF power sensor development is to reduce noise in the acquired signal. The presence of noise in the signal will subsequently contribute to the error in the measurement of signal parameters. Sources of noise could come from the chain of signal conditioning and acquisition in the sensor circuitry [3]. The main contribution comes from the 1/f noise that originates from the semiconductor components used in the sensor design.

1.2.1 Problem Statement

The power spectrum of 1/f noise decays proportionately over frequency which results in an autocorrelation function that spreads over the lag axis. This property of the autocorrelation function shows strong dependencies between signals observed over adjacent time instants. Thus, the assumption of independently identically distribution (IID) and stationary which forms the basis for classical signal detection and estimation techniques are not valid in the context of 1/f noise [4]. Therefore, there is a need to convert the coloured noise into white noise in order to make sure that the IID can be used.

In this research, the signal will undergo several processing stages: whitening, wavelet transform, de-noising and reconstruction. The choice of whitening methods is important to ensure the process maintains the original signal characteristics [22]. As for the wavelet transform, it could cause distortion in the signal, so it was necessary to ensure that the choices of basis wavelet function are determined correctly [29]. De-noising is important to recover information in a signal that is corrupted by noise [35] while reconstruction is used to recover back the original signal after performing de-noising [79]. Previously, the method used by the industry does not convert the characteristics of 1/f noise, into white noise. Thus, another method need to be defined to certify that the characteristics of noise can be converted efficiently.

The computational complexity of an algorithm is a measure of how many steps the algorithm will require in the worst case for an instance or input of a given size. Large computational complexity means larger amount of resources to solve them, such as time and storage. It is necessary to reduce the computational complexity for the implementation purpose to make it simpler and less complex [8]. Less number of coefficients and less number of samples means less number of processing and less number of computational complexity. It is important to make sure that the computational complexity is reduce in order to guarantee the implementation process.

1.3 Research Objectives

Followings are the objectives proposed for this research: -

i. To carry out specific investigations on the 1/f noise characteristics aiming at solving the assumption of IID.

ii. To design an algorithm that can transform the characteristics of 1/f noise into white noise, suitable signal transformation and de-noising method while preserving the original signal.

iii. To verify the effectivenes of the proposed method based on the computational complexity and viability of the implementation in the proposed application.

1.4 Research Scope

The scopes of this research are:

i. The signal of interest in this research is continuous signal such as communication signal and also pulse signal which is radar.

ii. The work focuses on the signal processing algorithms and its implementation in firmware design will be done by the industrial collaborator.

iii. The actual noise data are collected from the industry collaborator for validation purposes. The data are obtained from diode and thermocouple. Each data set has 32 bits resolution with 51,200 sample points at sampling rate of 195323.5 Hz.

iv. The 1/f noise model is developed to test whether the noise used in this research is similar with the actual noise samples. This is also to ensure that all the algorithms are tested under the same conditions as at the industry.

v. The input signal used in this research is a random signal.

vi. The sampling frequency for developing the algorithm is based on normalized frequency of 1 Hz. To use with the data provided by the industry, the sampling frequency will be adjusted as required.

vii. All development and simulations are conducted using the MATLAB mathematical software.

1.5 Research Procedure

The research procedure is shown is Figure 1.1.

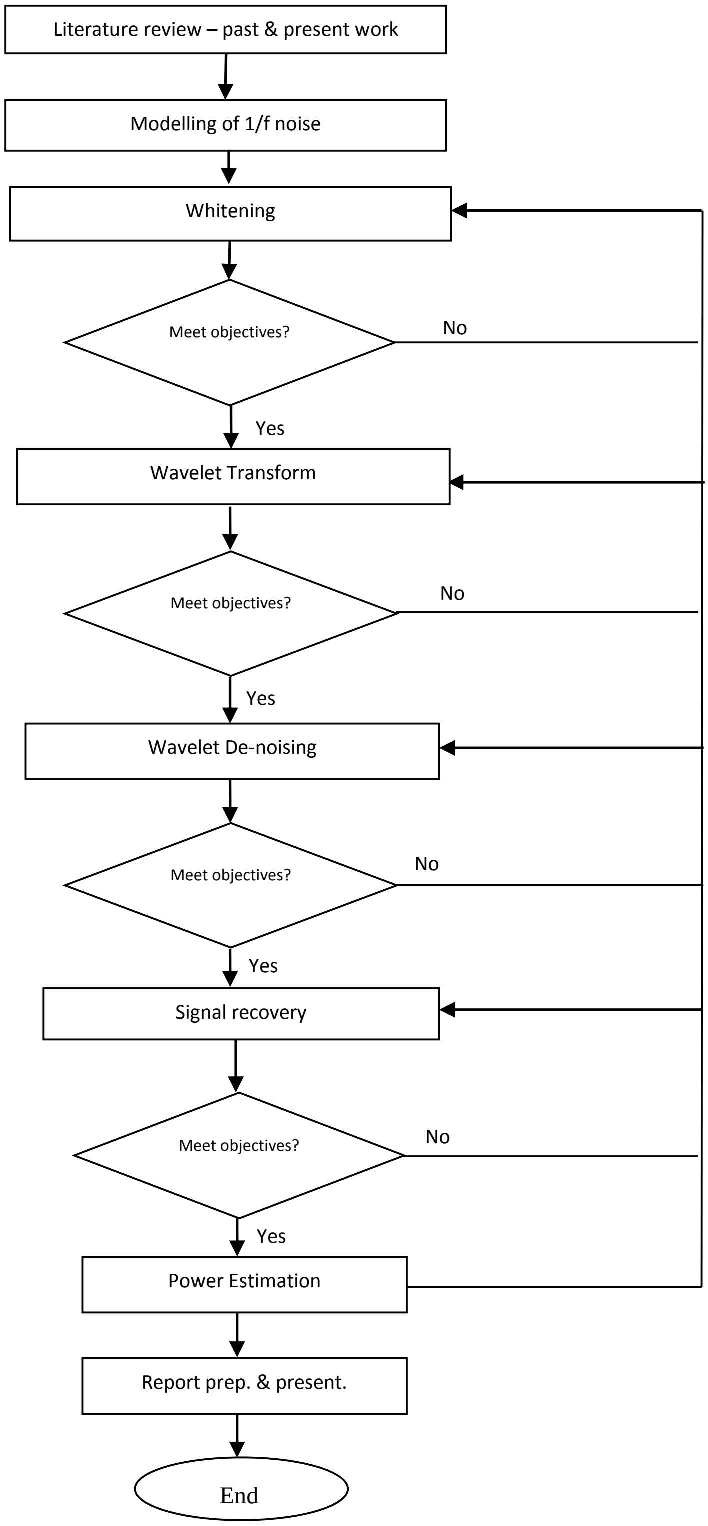

Figure 1.1 Research procedure.

1. **Literature review**: The focuses are on past as well as recent work related to 1/f noise. The knowledge gaps are also highlighted along with the reviews.

2. **Modelling of 1/f noise**: The 1/f noise is modeled for the simulation purposes.

3. **Whitening**: The whitening process converts the 1/f noise to additive white Gaussian noise (AWGN). The choices for whitening process are decimation, linear prediction, Burg algorithm, chopper with averaging and averaging. The best method will be decided by considering the balance between the complexity and accuracy in the power measurement.

4. **Wavelet transform**: The wavelet transform is used either with the Haar or Daubechies basis function that isolate the signal from noise.

5. **De-noising**: Hard or soft thresholding is used for the de-noising with the wavelet transform.

6. **Signal reconstruction**: Signal reconstruction is performed to reverse the effect of the whitening process.

7. **Power estimation**: The power estimation process is implemented on the signal to measure its power.

8. **Discussion and result**.

1.6 Thesis Organization

This thesis is structured into five chapters. Chapter 1 introduces the background of the research and highlights the problem statement, objectives, and the scope of this research. The research methodology is also outlined in this chapter.

Chapter 2 covers the literature review and the theoretical background of the research. The review focuses on the communication signal, RF power sensor, architecture of RF power sensor, 1/f noise model, whitening method, wavelet transform, and de-noising.

Chapter 3 describes the research methodology that was used to analyze the simulation and also the actual data. In this chapter, all the method proposed will be tested and the performance will be validated. All research activities in whitening and de-noising the signal are described in details.

Chapter 4 presents the analysis and the discussing of the result. The performances of the whitening methods, wavelet transforms, de-noising, signal reconstruction and power estimations are discussed comprehensively. The comparisons of the outcome are presented as well.

Chapter 5 concludes the outcome and the findings of the research. In order to improve the performance of the proposed method, this chapter provides some suggestions and recommendations for potential future study.

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