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Denoising of measured lightning electric field signals using adaptive filters in the fractional Fourier domain

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ABSTRACT

In this paper, adaptive filters are applied (in the fractional Fourier transform domain – FRFd) for denoising lightning electric-field signals, both in high and low signal-to-noise-ratio (SNR) environments. These filters are based on the concentration energy property of the fractional Fourier transform (FRFT). The proposed method integrates the advantages of leakage least mean square (LLMS) and normalized least mean square (NLMS) algorithms, including a leakage factor γ and a normalized step-size μ, in order to reduce the memory effect when tracking a non-stationary signal and also to reduce the effect of the input signal power on the algorithm performance, respectively. Parameter estimation of adaptive filters is analyzed in several case studies for various lightning-generated electric field signals. The adaptive algorithm is shown to provide better performance in low SNR environments. Finally, some analyses (in terms of temporal parameters of lightning electric-field signals) are included to demonstrate the validity of the method.

1. Introduction

Cloud-to-ground (C–G) lightning is a natural phenomenon that occurs when electrical charges travel between a charged cloud and the ground. C–G lightning is known to cause damage in equipment and structures as well as failure and malfunctioning in electrical, electronic and communication systems; and occasionally, it causes serious injuries (sometimes leading to death) in humans and animals. These reasons make the study of lightning an essential research area.

In engineering applications, the most important lightning parameters are the return stroke current and its associated electromagnetic fields [1]. These parameters can be identified and analyzed using direct and indirect measuring methods. Measurements of lightning-generated electric fields (LEF) have been carried out in the past four decades and, consequently, many features have been revealed so as to understand the lightning phenomena [1]. However, the measured signals are the result of the interaction between LEF, noise components (mainly produced by the measuring system) and other disturbances that appear in the electromagnetic environment. In such scenario, it is extremely useful for the study of lightning to separate the original signal from the undesired components, including the noise that obscures measurements. On the other hand, denoising techniques are an essential area in engineering applications for enhancing signal-to-noise ratio of corrupted signals. These techniques include many parameters which are based on time domain, frequency domain and time–frequency analysis that allow an adequate interpretation of the original signal features [2,3]. For these reasons, the EMC-UNC and GCEM-UD research groups have been working on a program to study and classify lightning using filtering techniques in order to process and analyze the radiated electric field produced during the discharge.

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Several methods to analyze the frequency spectra of LEF measurements have been used in the past [1,4,5]. However, these methods have not been widely used to remove the undesired components from original LEF signals, except for a few techniques based on the classic Fourier transform as well as on the wavelet transform (WT) [6]. Adaptive filters have been used in many signal processing applications such as signal modeling, data analysis, control, spectral analysis and equalization [3,7,8]. Various adaptive algorithms, including least mean square (LMS) and recursive least square (RLS), have been developed on various domains, e.g., Fourier [9] and Wavelet [10] to remove the noise components from original signal. The convergence rate of adaptive filtering in a specific transform domain may be much faster than those filters in the time domain. Moreover, compared to time domain, adaptive filters usually need fewer parameters [11].

The fractional Fourier transform (FRFT) is a generalization of the conventional Fourier transform (FT) and has been popular in applications such as optics, time–frequency analysis, filter design and denoising, signal compression, parameter estimation, music and biomedical signal processing, mechanical vibrations and pattern recognition [12–14]. Compared with the FT, the FRFT is more flexible and suitable for processing non-stationary signals such as chirps and transients. Recently, FRFT was used in a first approach to an alternative technique for denoising LEF measurements using band-pass filters in the fractional Fourier domain (FRFd) [15].

The implementation of adaptive filtering in the FRFd has shown satisfactory results in recent years, especially in the analysis of linear frequency modulated (LFM) signals [16,17]. This type of filters avoids the difficulties of adaptation in a time-varying signal environment by transforming such signals to FRFd, where signals vary slowly. This paper presents the application and parameter estimation of an adaptive filter using FRFT in order to reduce the noise components as well as other undesired signals in LEF measurements. The application combines features of conventional least mean square (LMS) algorithms with the properties of normalized LMS (NLMS) and leakage LMS (LLMS) algorithms.

The remaining of the paper continues as follows: Section 2 describes the lightning-generated electric field measuring system. Section 3 introduces FRFT by illustrating some of its properties and also by presenting its discrete version (DFRFT). In Section 4, LMS, LLMS and NLMS algorithms in the FRFd are explained. Section 5 describes the NL-LMS algorithm in FRFd and presents its convergence condition. In Section 6, simulation results of adaptive filtering in LEF signals are presented and the effects of different algorithm parameters are analyzed. Results of the denoising process in FRFd and further temporal-parameter analysis of LEF signals are shown in Section 7. Finally, some conclusions are drawn in Section 8.

2. Lightning-generated electric field (LEF) measuring system

The LEF measurements used in this paper were extracted from the records obtained by the EMC-UNC research group during two thunderstorm seasons. Measurements were made in Bogotá-Colombia localized at 4° 36′ N, 74° 5′ W and 2600 m above sea level. The measuring system employed in the LEF measurements is shown in Fig. 1. In a general form, it is composed by the following parts [18]:

- *Parallel plate antenna*: Two circular 0.45 m diameter metallic parallel plates were used. There was a 0.03 m air gap between them, supported by insulating elements.
- *Electronic circuit*: The main element was a buffer amplifier LH0033, with 100 MHz bandwidth and 1.5 kV/μs slew rate. In addition, an attenuator with a value of −20 dB was used at the circuit input to avoid inconveniences when measuring near lightning signals.
- *Oscilloscope*: A LeCroy LC574 digital store oscilloscope (DSO) was used to record the signals. The data information was stored with a time resolution (sampling time) of 400 ns.
- *Coaxial cables*: Two RG58/U coaxial cables were used to connect the devices. First, a 0.6 m length cable was used to transmit the signal from the antenna to the electronic circuit. Second, a 20 m length coaxial cable was used between the electronic circuit and the oscilloscope.

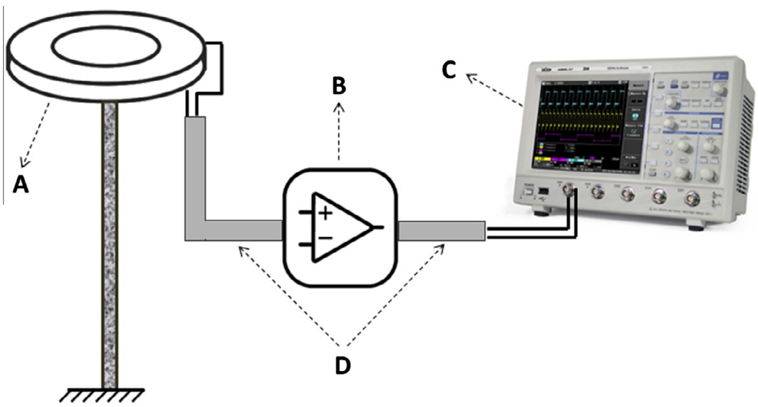

Fig. 1. LEF measuring system. (A) Parallel plate antenna. (B) Electronic circuit. (C) Oscilloscope. (D) Coaxial cable.