

Tracking of Real and Complex Sinusoids using Piloted Adaptive Notch Filter

Abstract

In digital signal processing, frequency estimation and tracking of sinusoids in noise using adaptive notch filter is an important area of research to solve problems in radar, communications, biomedical and other related areas. This filter is popularly implemented using the least mean squares (LMS) algorithm in which the notch frequency is updated iteratively using either a fixed or an adaptive step-size to eventually converge to the frequency of the input signal. A large step-size will increase the rate of convergence but will result in larger misadjustment, while a small step-size will decrease the rate of convergence but will yield smaller misadjustment. So, in view of this trade-off, a variable step-size LMS algorithm is preferred over a fixed step-size LMS algorithm. Conventional variable step-size algorithms determine the step-size based on time-domain averaging of the gradient estimate at each sampling instance. The piloted adaptive notch filter (PANF) is a new concept in adaptive filtering which determines the step-size value based on the estimated distance between the main notch frequency and the input frequency with the help of pilot notches. This thesis aims at investigating the concept of PANF, originally proposed to estimate and track real sinusoid, to further enhance its performance and to extend the concept of pilot notches for signals in complex domain.

A performance comparison of the PANF with the second-order adaptive infinite impulse response (IIR) lattice notch filter and the adaptive IIR notch filter with constrained poles and zeroes is undertaken. This steady-state analysis of the frequency estimate, using simulations, with variables such as notch bandwidth and signal to noise ratio (SNR) is conducted to verify the excellent performance exhibited by the PANF over other algorithms. However, the probability of correct steering direction can be further improved under low SNR conditions.

A new steering direction determination mechanism, using a time-domain averaging based gradient analysis of the piloted notch cost function at several frequency points at the same sampling instant, is proposed to determine the direction of the main notch with respect to the input sinusoid frequency. This frequency domain information is then combined with time domain information to develop an algorithm for the determination of variable step-sizes for improved speed of convergence with significant reduction in steady-state mean square error (MSE).

A generalized mathematical formulation and filter structure with more number of pilots added to the original PANF is proposed. This will help to have an option for a range of step-size values. Thus, the transition from a very large step-size value to a very small step-size value is achieved in one or more intermediate step-size values. This reduces the probability that the main notch overshoots the optimum with large step-size producing large output error when it is close to the input frequency. Simulation results are presented to show the improvement in performance over PANF. Our study also revealed that the pole-radius of the notches plays an important role which needs a more detailed investigation.

A detailed analysis of pole position approximation for pilot notches is then undertaken, to understand its overall effect on steering direction determination and convergence of the notch filter. An improved PANF with a variable pole-radius mechanism is introduced. This scheme significantly reduces the transient effect and improves the steering direction determination mechanism of the notch filter. Computer simulations demonstrate the excellent performance of the variable-pole radius PANF to significantly outperform the traditional PANF with respect to the speed of convergence and steady-state MSE.

Aforementioned work leads to the development of a generalized formulation for multiple pilot-pairs adaptive notch filter (MPPANF) filter structure with the introduction of more number of pilots, variable pole-radius mechanism, and improved steering direction determination. Simulation results are presented to verify the excellent performance exhibited by the MPPANF and variable pole-radius multiple pilot-pairs adaptive notch filter (VP-MPPANF) over PANF with respect to the speed of convergence and steady-state MSE. A detailed theoretical analysis of the proposed adaptive notch filter is presented with the mechanisms put together for an enhanced performance. Mathematical formulation for the determination of probability of correct steering direction along with the effect of input SNR, notch bandwidth and notch frequency on probability of correct steering direction is presented.

We formulate a complex piloted adaptive notch filter (CPANF) to estimate and track the frequency of complex sinusoidal signal. A novel complex coefficient filter structure with a main notch and pilot notches to track the frequency of the input complex sinusoid with a variable step-size least mean squares (LMS) based algorithm is presented. The adaptive step-size is chosen based on the steering direction information from the notches. The notch frequency is updated iteratively using an adaptive step-size to eventually converge to the frequency of the input complex sinusoid. Simulation results verify the excellent performance exhibited by the CPANF over conventional complex adaptive notch filter (CANF) with respect to the speed of convergence and steady-state MSE. Theoretical analysis is also presented which closely follows the simulation results. Finally, the filter is implemented to suppress complex sinusoidal interference in a QPSK spread spectrum communication systems which shows improvement over conventional CANF in overall bit error rate (BER).

This research leads to a detailed understanding and development of piloted adaptive notch filter to estimate and track both real and complex sinusoids.