Journal of Sound and Vibration 401 (2017) 311–325

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

A novel cost-effective parallel narrowband ANC system with local secondary-path estimation

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ARTICLE INFO

Article history:
Received 23 September 2016
Received in revised form
27 February 2017
Accepted 24 April 2017
Available online 17 May 2017

Keywords:
Active noise control
Adaptive digital filters
Adaptive algorithms
Narrowband noise
Adaptive notch filters
Model identification

ABSTRACT

Many noise reduction applications are targeted at multi-tonal disturbances. Active noise control (ANC) solutions for such problems are generally based on the combination of multiple adaptive notch filters. Both the performance and the computational cost are negatively affected by an increase in the number of controlled frequencies. In this work we study a different modeling approach for the secondary path, based on the estimation of various small local models in adjacent frequency subbands, that greatly reduces the impact of reference-filtering operations in the ANC algorithm. Furthermore, in combination with a frequency-specific step size tuning method it provides a balanced attenuation performance over the whole controlled frequency range (and particularly in the high end of the range). Finally, the use of small local models is greatly beneficial for the reactivity of the online secondary path modeling algorithm when the characteristics of the acoustic channels are time-varying. Several simulations are provided to illustrate the positive features of the proposed method compared to other well-known techniques.

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1. Introduction

Rotating components in industrial machinery emit high-level low-frequency periodic noise, that may cause severe physiological and psychological distress on human beings in case of long periods of exposure. Traditional passive noise-control techniques such as enclosures, barriers and silencers are not particularly suited for low-frequency noise control, because the noise wavelengths are large with respect to the thickness of the acoustic absorbers typically allowed in these applications. A viable alternative is provided by active noise control (ANC) techniques. ANC exploits the superposition principle, whereby the undesired noise is cancelled (or attenuated) by injecting an anti-noise signal of equal amplitude and opposite phase (destructive interference) using a secondary source, such as a loudspeaker [1,2]. The anti-noise signal is generated by an adaptive filter fed with a reference signal, that has to be well correlated with the noise, and tuned using algorithms of the Least Mean Squares (LMS) family. In particular, the basic algorithm is a variation of the LMS algorithm, denoted FxLMS, which suitably takes into account the secondary path (*i.e.*, the measurement and control chain).

Since most of the spectral power in the applications mentioned above is concentrated in tonal components, specific ANC techniques have been developed to address periodic noise. Adaptive notch filters employ synthesized sine waves as reference signals, tuned to the noise frequencies (either known in advance or estimated), and suitably modulate them in amplitude and phase to track the disturbance [3,1]. The multi-tonal case is typically addressed by combining in parallel

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http://dx.doi.org/10.1016/j.jsv.2017.04.034
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several single-tone adaptive notch filters, each fed by a sinusoid at a given frequency. The parameters of each adaptive notch filter are tuned with the FxLMS algorithm, which implies that each sinusoidal reference signal be convolved with an estimate of the secondary path in order to obtain the filtered-reference signals used in the algorithm [4]. Since the acoustic environment in practical applications is often time varying, narrowband ANC systems typically include a subsystem that updates the secondary path estimate during system operation to avoid performance degradation and instability issues.

The basic parallel-form narrowband ANC system described above suffers from four problems: (i) A single error signal containing the contribution of all tonal components is used to update each adaptive notch filter unit. (ii) The filtering operations on the reference signals have an increasing impact in terms of computational load as the number of controlled frequencies increases, since the FIR filters used to model the secondary path need a large number of coefficients to achieve sufficient modeling accuracy; (iii) The online modeling subsystem is slow to react to changes in the secondary path, mainly because of the large number of parameters of the employed models; (iv) The choice of a suitable step size for each adaptive notch filter unit is a crucial – and not trivial – task in practice.

The first issue is a known source of degradation of the performance of the multi-tonal parallel system with respect to the single-tone case, both in terms of convergence speed and noise reduction [5]. The main reason for this is the mutual interference between the different tonal components originated by the error signal. To tackle this issue a parallel narrowband ANC system was proposed in [5] that employed a bank of bandpass filters to separate the frequency components of the error and drive each adaptive notch filter with the appropriate error component. Though such filters were designed to be delayless (at least at the center of the pass-band), it is argued in [6] that they exhibit a peak in the group delay which increases as their bandwidth is decreased. Simulations showed that this overlooked issue limits the convergence speed to the extent that the conventional narrowband controller still converges faster. For this reason, this method is not further considered in the comparison analysis provided in this work.

Regarding issue (ii), several solutions have been proposed in the literature with the aim of reducing the computational burden of the parallel-form narrowband ANC system, while at the same time yielding the same performance in terms of noise canceling and speed of convergence. One first idea to account for the secondary path without incurring in high computational costs dates back to 1989, when Ziegler developed a narrowband ANC system that compensates the phase shift introduced by the secondary path at the controlled frequencies with a suitable number of unit delay blocks, so that the reference-filtering operations only consist in delaying the reference signal by a given number of samples [7]. While computationally very efficient, this solution suffers from convergence speed and noise canceling performance issues, due to the estimation errors on the secondary path. More recently [8] Xiao proposed a system where the reference-filtering operations are reduced to one, by summing the reference signals first, convolving their sum with the secondary-path estimate, and finally retrieving the individual filtered reference signals by filtering the convolved signal through a bank of bandpass filters. Xiao's system only performs one reference-filtering operation regardless of the number of controlled frequencies and often achieves the same convergence-speed and noise canceling properties of the basic parallel-form narrowband ANC system. However, the correct design of the bandwidth of the bandpass filters is critical for an appropriate separation of the filtered reference signals, and becomes increasingly difficult as the controlled frequencies get closer. If the bandwidth-control parameter is too small, system instability may occur. Conversely, if it is too large, the system may exhibit slow convergence.

We here propose a novel cost-effective approach for the compensation of the secondary path in multi-tonal narrowband ANC systems. Rather than using a single global high-order FIR model, we investigate how multiple local lower-order FIR models (called *local secondary paths*) may be employed to obtain the filtered reference signals. A computational analysis establishes that the proposed system reduces the number of required computations with respect to the original system. Simulations show that the proposed system offers comparable convergence speed and noise canceling performance with respect to the basic multi-tonal parallel-form system and that it outperforms Ziegler's and Xiao's systems in situations that are critical for those systems. Furthermore, simulations show that the online modeling of local secondary paths is more reactive to changes in the secondary path than the global online modeling system thanks to the low order of the local estimates (issue (iii) above). This increased reactivity makes the system less prone to instability if the characteristics of the environment change rapidly. Finally, an empirical step size-correction law is proposed to automatically tune the step size of each adaptive filter in the parallel-form narrowband ANC system without resorting to normalized FxLMS or trial and error (issue (iv) above).

The rest of the paper is organized as follows. Section 2 reviews narrowband ANC systems. Section 3 presents the novel ANC scheme, which is evaluated in various simulation tests in Section 4. Section 5 provides a brief computational analysis of the proposed method. Finally, some conclusions are provided in Section 6.

2. Narrowband ANC systems

2.1. The basic parallel-form multi-tonal narrowband ANC system

The basic narrowband ANC system based on FxLMS was introduced by Glover in [9] back in 1977 and is depicted in Fig. 1. The disturbance is a multi-tonal signal, defined as follows:

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