Signal Processing 98 (2014) 396–409

Contents lists available at ScienceDirect

Signal Processing

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

Multichannel self-optimizing narrowband interference canceller

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ARTICLE INFO

Article history:
Received 6 February 2013
Received in revised form
29 November 2013
Accepted 3 December 2013
Available online 11 December 2013

Keywords:
Active noise and vibration control
Time-varying processes
Adaptive signal processing

ABSTRACT

The problem of cancellation of a nonstationary sinusoidal interference, acting at the output of an unknown multivariable linear stable plant, is considered. No reference signal is assumed to be available. The proposed feedback controller is a nontrivial extension of the SONIC (self-optimizing narrowband interference canceller) algorithm, developed earlier for single-input, single-output plants. The algorithm consists of two loops: the inner, control loop, which predicts and cancels disturbance, and the outer, self-optimization loop, which automatically adjusts the gain matrix so as to optimize the overall system performance. The proposed scheme is capable of adapting to slow changes in disturbance characteristics, measurement noise characteristics, and plant characteristics. It is shown that in the important benchmark case – for disturbances with random-walk-type amplitude changes – the designed closed-loop control system converges locally in mean to the optimal one. The algorithm, derived and analyzed assuming a single-tone, complex-valued disturbance with known frequency, can be extended to cope with a range of realistic applications, such as real-valued disturbances, multitone signals, and unknown frequency.

1. Introduction

Narrowband interferences (acoustic noise and/or vibration) usually originate from rotation of an engine, compressor, fan, or propeller. In the range of small frequencies (below 1 kHz) such interferences are difficult to eliminate using passive methods, but can be efficiently removed using active noise control (ANC) techniques, i.e., by means of destructive interference. Vaguely speaking, the idea is to generate acoustic waveform that, in the area/point of interest, has the same shape as the disturbance waveform, but opposite polarity [1]. Multichannel ANC systems are becoming increasingly popular as they allow one to create larger (and spatially diversified) quiet zones compared to single-channel systems, albeit at the expense of higher equipment cost and increased computational requirements. Commercial applications of such systems include reduction of propeller-induced interior noise in aircrafts [2,3], active noise [4,5] and vibration control systems for cars [6], active noise-cancelling mufflers [7], and active noise barriers [8], among many others.

Most of the existing multichannel solutions are based on the classical filtered-X least mean squares (FXLMS) approach [1,9] or its modifications obtained by replacing the LMS adaptive filters with faster converging ones, such as recursive least squares (RLS) [10] or affine projection (AP) [11] – for comparison of different variants see e.g. [12]. In all cases mentioned above impulse response coefficients of all secondary paths, linking actuators with sensors, are supposed to be constant and known. In practice this means that the controlled acoustic/vibration field should be identified prior to starting the ANC algorithm, and that it should be re-estimated each time the spatial configuration of the system (positions of actuators and sensors) changes. To exert full control over the system in the presence of nonstationarities, on-line plant

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0165-1684/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.sigpro.2013.12.001

identification is required. A special random perturbation technique is often used [13] for this purpose. Unfortunately, auxiliary noise disturbs operation of the ANC system, which results in performance degradation.

Another conceptually different solution to the multivariable narrowband disturbance rejection problem, based on the "phase-locked" loop structure, was presented in [14]. However, in order to use this technique characteristics of the controlled plant (complex gains at given frequencies) need to be known *a priori*.

An entirely new approach to narrowband disturbance cancelling was recently proposed in [15,16] (for complex-valued disturbances) and in [17] (for real-valued disturbances). The developed scheme, called SONIC (self-optimizing narrowband interference canceller), combines the coefficient fixing technique, used to "robustify" self-tuning minimum-variance regulators [18–20], with automatic gain tuning. It can be used to control nonstationary plants subject to nonstationary narrowband disturbances and compares favorably, both in terms of cancellation quality and computational complexity, with the FXLMS scheme.

The main contribution of this study is development and analysis of a multivariate version of SONIC controller. Similar to the univariate case, the extended controller can cope with plant modelling errors and locally converges in mean to the optimal one. Several useful extensions, e.g. frequency adaptive version of the controller, are proposed in the paper. Finally, good behavior of the proposed algorithm is confirmed with simulations and practical experiments.

2. Problem statement

Consider the problem of cancellation of an n-dimensional complex-valued narrowband disturbance:

$$\mathbf{d}(t) = \boldsymbol{\alpha}(t)e^{j\omega_0 t} \tag{1}$$

where $t = \ldots, -1, 0, 1, \ldots$ is a discrete, normalized time, $\omega_0 \in [-\pi, \pi)$ is a known angular frequency, and $\boldsymbol{\alpha}(t) = [\alpha_1(t), \ldots, \alpha_n(t)]^{\mathrm{T}}$ denotes the unknown time-varying vector of complex-valued "amplitudes", acting at the output of a multidimensional stable plant governed by

$$\mathbf{y}(t) = \mathbf{L}_{\mathrm{p}}(q^{-1})\mathbf{u}(t-1) + \mathbf{d}(t) + \mathbf{v}(t) \tag{2}$$

where $\mathbf{y}(t)$ is the n-dimensional output signal, $\mathbf{u}(t)$ is the n-dimensional input (cancellation) signal, $\mathbf{v}(t)$ is an n-dimensional wideband noise, and $\mathbf{L}_{\mathrm{p}}(q^{-1}) = [L_{kl}(q^{-1})]$, $k = 1, 2, \ldots, n$, $l = 1, 2, \ldots, n$ denotes the $n \times n$-dimensional transfer function (q^{-1} denotes the backward shift operator) which will be further assumed unknown and possibly time-varying.

We will look for a feedback controller allowing for cancellation, or near cancellation, of the sinusoidal disturbance, i.e., controller generating the signal $\mathbf{u}(t)$ that minimizes the system output in the mean-squared sense – in the control literature such devices are usually termed as minimum-variance (MV) regulators. It will not be assumed that a reference signal, correlated with the disturbance, is available. For this reason the designed system will be a purely feedback canceller, not incorporating any feedforward compensation loop.

3. Control of a known plant

We will look for a steady-state MV regulator, i.e., for a control rule which guarantees that

$$\lim_{t \to \infty} \mathrm{E}[\mathbf{y}(t)\mathbf{y}^{\mathrm{H}}(t)] \longrightarrow \min.$$

We will start from a very simple controller that requires full prior knowledge of the plant and disturbance. Then we will gradually step back from restrictive assumptions to make our design work under more realistic conditions.

3.1. Stabilizing controller

Suppose that the controlled plant is time-invariant, and that its transfer function $\mathbf{L}_{\mathrm{p}}(q^{-1})$ is known. Since the disturbance is a narrowband signal, so must be the cancellation signal, with angular frequency ω_0 and complex amplitude chosen so as to enable destructive interference at the plant's output. In a case like this Eq. (2) can be approximately written down in the form:

$$\mathbf{y}(t) \cong \mathbf{K}_{\mathrm{p}}\mathbf{u}(t-1) + \mathbf{d}(t) + \mathbf{v}(t) \tag{3}$$

where

$$\mathbf{K}_{\mathrm{p}} = \mathbf{L}_{\mathrm{p}}(e^{-j\omega_0}), \quad \det(\mathbf{K}_{\mathrm{p}}) \neq 0$$

denotes the nonsingular matrix of plant gains at the frequency ω_0.

Should the disturbances be measurable and known ahead of time, the MV controller could be expressed in the form:

$$\mathbf{u}(t) = -\mathbf{K}_{\mathrm{p}}^{-1}\mathbf{d}(t+1). \tag{4}$$

When $\mathbf{d}(t+1)$ is unknown, it can be replaced in (4) with the one-step-ahead prediction, evaluated recursively by a simple gradient algorithm. This leads to the following control rule:

$$\widehat{\mathbf{d}}(t+1|t) = e^{j\omega_0}[\widehat{\mathbf{d}}(t|t-1) + \mathbf{M}\mathbf{y}(t)] \tag{5}$$

$$\mathbf{u}(t) = -\mathbf{K}_{\mathrm{p}}^{-1}\widehat{\mathbf{d}}(t+1|t) \tag{6}$$

where $\mathbf{M} = [\mu_{kl}]$, $k = 1, 2, \ldots, n$, $l = 1, 2, \ldots, n$ denotes a matrix of complex-valued adaptation gains, chosen so as to guarantee stability of the closed loop.

To arrive at stability conditions, the time-varying amplitude in (1) will be rewritten in the form:

$$\boldsymbol{\alpha}(t) = \boldsymbol{\alpha}(t-1) + \mathbf{e}(t)$$

where $\mathbf{e}(t)$ denotes the one-step amplitude change. Using this notation, one can rewrite $\mathbf{d}(t)$ in the form:

$$\mathbf{d}(t) = e^{j\omega_0}\mathbf{d}(t-1) + \tilde{\mathbf{e}}(t) \tag{7}$$

where $\tilde{\mathbf{e}}(t) = e^{j\omega_0 t}\mathbf{e}(t)$. Denote by $\mathbf{c}(t) = \mathbf{d}(t) - \widehat{\mathbf{d}}(t|t-1)$ the cancellation error. After combining (3) with (6) and (7), one arrives at

$$\begin{aligned}
&\mathbf{y}(t) = \mathbf{c}(t) + \mathbf{v}(t) \\
&\mathbf{c}(t) = e^{j\omega_0}(\mathbf{I} - \mathbf{M})\mathbf{c}(t-1) - \mathbf{M}\tilde{\mathbf{v}}(t-1) + \tilde{\mathbf{e}}(t)
\end{aligned} \tag{8}$$

where $\tilde{\mathbf{v}}(t) = e^{j\omega_0}\mathbf{v}(t)$.

It is clear from (8) that when the processes $\{\mathbf{v}(t)\}$ and $\{\mathbf{e}(t)\}$ are bounded in the mean-squared sense, so is the output signal, provided that $\mathbf{M}$ belongs to the set of