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Analysis and compensation of reference frequency mismatch in multiple-frequency feedforward active noise and vibration control system

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A B S T R A C T

In the field of active noise and vibration control (ANVC), a considerable part of unwelcome noise and vibration is resulted from rotational machines, making the spectrum of response signal multiple-frequency. Narrowband filtered-x least mean square (NFXLMS) is a very popular algorithm to suppress such noise and vibration. It has good performance since a priori-knowledge of fundamental frequency of the noise source (called reference frequency) is adopted. However, if the priori-knowledge is inaccurate, the control performance will be dramatically degraded. This phenomenon is called reference frequency mismatch (RFM). In this paper, a novel narrowband ANVC algorithm with orthogonal pair-wise reference frequency regulator is proposed to compensate for the RFM problem. Firstly, the RFM phenomenon in traditional NFXLMS is closely investigated both analytically and numerically. The results show that RFM changes the parameter estimation problem of the adaptive controller into a parameter tracking problem. Then, adaptive sinusoidal oscillators with output rectification are introduced as the reference frequency regulator to compensate for the RFM problem. The simulation results show that the proposed algorithm can dramatically suppress the multiple-frequency noise and vibration with an improved convergence rate whether or not there is RFM. Finally, case studies using experimental data are conducted under the conditions of none, small and large RFM. The shaft radial run-out signal of a rotor test-platform is applied to simulate the primary noise, and an IIR model identified from a real steel structure is applied to simulate the secondary path. The results further verify the robustness and effectiveness of the proposed algorithm.

1. Introduction

In the fields of aircraft, watercraft, automobile, machinery, etc., the suppression of unwelcome noise and vibration has drawn much attention and effort from researchers and engineers, since over-vibrations of machine may deteriorate working

Abbreviations: ; ALC, adaptive linear combiner; ANVC, active noise and vibration control; FXLMS, Filter-x least mean square algorithm; IC, ICs, initial condition, initial conditions; MF, MFs, mismatch frequency, mismatch frequencies; MFC, mismatch frequency component; NFXLMS, narrowband FXLMS algorithm; PF, PFs, primary frequency, primary frequencies; PFC, primary frequency component; RFM, reference frequency mismatch; RF, RFs, reference frequency, reference frequencies; RFC, reference frequency component

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Nomenclature

Roman symbols

$d(n)$	primary noise
$e(n)$	error signal
$s(n)$	impulse response function of secondary path
$\hat{s}(n)$	impulse response function of secondary path model
$y(n)$	ALC output
$\mathbf{A}_p$, $\mathbf{B}_p$	vectors of primary coefficients
$\mathbf{F}_p$	vector of real primary frequencies
$\mathbf{F}_r$	vector of real reference frequencies
$G(z)$	open loop transfer function of narrowband FXLMS
$H(z)$	closed loop transfer function of narrowband FXLMS
$\mathbf{P}_p$	vector of amplitudes of primary noise
$\underline{\mathbf{P}}_p$	diagonal matrix of amplitudes of primary noise
$\mathbf{P}_s$	vector of amplitude ratios of secondary path
$\underline{\mathbf{P}}_s$	diagonal matrix of amplitude ratios of secondary path
$S(z)$	z-domain transfer function of secondary path
$\hat{S}(z)$	z-domain transfer function of secondary path model
$\mathbf{X}_{pa}(n)$, $\mathbf{X}_{pb}(n)$	vectors of primary base sinusoids
$\mathbf{X}_{ra}(n)$, $\mathbf{X}_{rb}(n)$	vectors of reference base sinusoids
$\hat{\mathbf{X}}_{ra}(n)$, $\hat{\mathbf{X}}_{rb}(n)$	vectors of filtered reference base sinusoids
$\mathbf{X}_{ra,rec}(n)$, $\mathbf{X}_{rb,rec}(n)$	vectors of rectified reference base sinusoids
$\mathbf{W}_a(n)$, $\mathbf{W}_b(n)$	vectors of ALC coefficients
$\hat{\mathbf{W}}_a(n)$, $\hat{\mathbf{W}}_b(n)$	vectors of filtered ALC coefficients

Greek symbols

μ_a, μ_b	step-sizes of adaptive linear combiner
μ_c	step-size of adaptive digital oscillator
$\Delta\mathbf{\Omega}$	vector of normalized mismatch frequencies
$\Delta\underline{\mathbf{\Omega}}$	diagonal matrix of normalized mismatch frequencies
$\Delta\mathbf{F}$	vector of real mismatch frequencies
$\mathbf{\Phi}_p$	vector of phases of primary noise
$\mathbf{\Phi}_s$	vector of phase differences of secondary path (model)
$\underline{\mathbf{\Phi}}_s$	diagonal matrix of phase differences of secondary path (model)
$\mathbf{\Omega}_p$	vector of normalized primary frequencies
$\mathbf{\Omega}_r$	vector of normalized reference frequencies
$\underline{\mathbf{\Omega}}_r$	diagonal matrix of normalized reference frequencies

condition, reduce structural strength, debase the reliability and lower the safety. A considerable part of the unwelcome noise and vibration is resulting from rotational machines, such as engines, propellers, compressors, motors, etc., whose fundamental frequency are usually low ($<$ 200 Hz), time-varying and un-precisely-known [1,2]. Generally, there will be more than one noise source and each source will be more than one harmonic, making the spectrum of response signal multiple-frequency [3]. It is hard to reduce such noise and vibration by traditional passive noise and vibration control (PNVC) methods. Fortunately, active noise and vibration control (ANVC) technology which has developed since 1970s is considered as a very promising approach to suppress such noise and vibration [3–10].

The basic idea of ANVC is to generate an equal-but-opposite secondary noise or vibration to counteract the primary one. There are two main topological structures for ANVC, i.e., feedback and feedforward, where the feedforward structure takes priori knowledge (the reference signal) into consideration and will generally have a better performance [11]. The most famous feedforward algorithm for ANVC is the filtered-x least mean square (FXLMS) algorithm, whose reference signals are filtered by a secondary path model to compensate for the influence of the secondary path. Narrowband FXLMS (NFXLMS) is a variant of FXLMS algorithm [4,11], which takes more priori knowledge (i.e., the primary noise is narrowband) into account. Therefore, its controller can be simplified and the performance can be further improved by using non-vibrational/non-acoustic reference sensor to avoid the "feedback effect" [11]. The *narrowband* assumption is tenable, since a considerable part of unwanted noise and vibration is generated by rotational machines in real application. As a consequence, the study of narrowband noise and vibration control with applications is very active. For example, there is control on finite element (FE) plant [3], control on real-life plant [12] or even control in noise and vibration reshaping application [13].

The most commonly used parallel structure of NFXLMS is shown in Fig. 1. For each frequency component, two orthogonal sinusoids are generated as base signals. The controller is an adaptive linear combiner (ALC) of those two sinusoids. The least mean square (LMS) algorithm estimates the best coefficients of the ALC by minimizing the squared error signal. The sinusoids generator is one of the most important parts of the NFXLMS algorithm. It can be achieved by lookup table technique or digital oscillator, in which digital oscillator method requires fewer computations [11,14]. Among different types of digital oscillators, the "biquad" form (direct form) oscillator requires the least computations (one multiplication) with equal (constant) amplitude output [14]. Since the "biquad" form oscillator has no quadrature output, two oscillators (cosine and sine) are required for NFXLMS algorithm.

Traditional NFXLMS algorithm has very good performance for periodic noise and vibration reduction if the frequency of digital oscillators (called reference frequency) is exactly equal to that of the noise source. Otherwise, the control performance will be dramatically degraded. This phenomenon is called reference frequency mismatch (RFM) [1]. The RFM phenomenon indeed exists in reality, due to aging and fatigue accumulation of the reference sensor.

The influence of RFM on NFXLMS can be explained in frequency domain. The closed-loop transfer function of the