Mechanical Systems and Signal Processing 98 (2018) 108–123

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

A multi-reference filtered-x-Newton narrowband algorithm for active isolation of vibration and experimental investigations

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ARTICLE INFO

Article history:
Received 23 September 2016
Received in revised form 26 April 2017
Accepted 27 April 2017
Available online 4 May 2017

Keywords:
Ship machinery
Active control
Vibration isolation
MRFx-Newton
Narrowband
Multiple references

ABSTRACT

In engineering applications, ship machinery vibration may be induced by multiple rotational machines sharing a common vibration isolation platform and operating at the same time, and multiple sinusoidal components may be excited. These components may be located at frequencies with large differences or at very close frequencies. A multi-reference filtered-x Newton narrowband (MRFx-Newton) algorithm is proposed to control these multiple sinusoidal components in an MIMO (multiple input and multiple output) system, especially for those located at very close frequencies. The proposed MRFx-Newton algorithm can decouple and suppress multiple sinusoidal components located in the same narrow frequency band even though such components cannot be separated from each other by a narrowband-pass filter. Like the Fx-Newton algorithm, good real-time performance is also achieved by the faster convergence speed brought by the 2nd-order inverse secondary-path filter in the time domain. Experiments are also conducted to verify the feasibility and test the performance of the proposed algorithm installed in an active-passive vibration isolation system in suppressing the vibration excited by an artificial source and air compressor/s. The results show that the proposed algorithm not only has comparable convergence rate as the Fx-Newton algorithm but also has better real-time performance and robustness than the Fx-Newton algorithm in active control of the vibration induced by multiple sound sources/rotational machines working on a shared platform.

1. Introduction

In the isolation of vibration of ship machinery, passive isolation devices can effectively attenuate the broadband components, and active control has also been proposed to suppress the energy-concentrated low-frequency sinusoidal components which have a much higher magnitude [1–5].

Narrowband control algorithms have been developed in both time domain and frequency domain [4–7] to attenuate these sinusoidal components. Unlike broadband algorithms, the convergence rates of these narrowband algorithms are faster and not influenced by the eigenvalue dispersion of the autocorrelation functions of reference signals. Furthermore, the calculation complexity is greatly reduced by using shorter order controllers which improves the tracking ability of these algorithms.

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http://dx.doi.org/10.1016/j.ymssp.2017.04.044
0888-3270/

Narrowband control algorithms can be realized in various ways. In modulation-demodulation narrowband algorithms [5,7], accurate estimation of frequency is required to achieve good real-time performance. Another method to control multi-tonal noise in real time also needs to estimate the vibration signal frequency [6] and then generate a corresponding sinusoidal reference signal. However, the algorithms using this method have unsatisfactory robustness when frequency mismatch occurs [8].

The reference signals are acquired mainly in two ways through the measurement. The most common way is directly from the primary source such as the rotational speed signal of machine. It can guarantee a high correlation between the reference signal and the vibration signals. Moreover, the influence of external noise is relatively small, so the reference signal has high SNR (signal to noise ratio). However, the rotational speed signal is always a simple-frequency signal collected by special equipment and cannot contain all frequencies of vibration caused by the machine [2]. Another way is to measure the broadband vibration signal from sensors and extract the sinusoidal components in the broadband signal with NBPF (narrowband-pass filters) as reference signal [9]. The disadvantage is that the frequency characteristics of narrowband-pass filter must be considered in the algorithm.

For an MIMO system, the MIMO coupling should be addressed. The MIMO Fx-LMS (filtered x least mean square) algorithm can achieve good suppression effect, but the convergence rates are low due to the coupling effect between multiple actuators. This problem has been solved by the Newton algorithm and transform-domain algorithms [1,2,7]. Fast convergence of the Newton algorithm is realized through inverse secondary-path filtering in controller adapting [1]. But they all need to transform signals at first, which makes it more complex in computation and cannot be implemented in real time. Most recently, Li et al. [9] proposed time-domain MIMO Fx-Newton algorithms in which a 2-order inverse secondary-path filter is used in the Newton algorithm. This algorithm can be implemented in time-domain directly.

In engineering applications, multiple rotational machines may share a common vibration isolation platform, and multiple sinusoidal components may be excited at very close frequencies (with slight difference) located in the same narrowband. It is difficult to separate and control these sinusoidal components in the error signal with a narrowband algorithm with one controller. Theoretically an ideal band-pass filter with enough narrow passband may solve this problem, but the implementation is not feasible. Widrow [4] proposed multiple-reference adaptive algorithms for such cases, and developed adaptive filters for multiple reference signals generated by several primary sources. Hu [10] also constructed a noise canceller with multiple references and Liu [11] used multiple references to implement the multiple-source multiple-harmonic (MSMH) algorithm for solving multiple primary sources problem which can be solved by one reference in NBPF algorithms. However, their algorithms are broadband algorithms in which the convergence rate is slow and a long order controller is needed. Furthermore, they use multiple reference signals mainly to obtain the effective vibration information of each vibration source. In other words, if one sensor can get all of the primary vibration signal, the single reference algorithm can also achieve the effect of their algorithm. The narrowband algorithm can overcome the shortcomings of broadband algorithms but it brings a new problem. It is unsatisfactory in dealing with the control of multiple vibration spectrums in the same narrowband which is always caused by multiple sources. In this paper, a new multiple reference narrowband Newton algorithm is proposed to solve this problem. Besides the advantages of the narrowband algorithm, it can effectively solve the vibration control problem of vibration spectrums in the same narrowband generated by different sources at the same time.

In this study, a multi-reference filtered-x Newton narrowband algorithm (the MRFx-Newton algorithm) is proposed to separate and control multiple sinusoidal components in the vibration signal, especially for those at very close frequencies, and MIMO coupling is also considered. Experiments with a double-deck floating-raft vibration isolation system loaded with two air compressors and a shared raft are also conducted to verify the feasibility and test the performance of the proposed algorithm. The convergence and performance of the proposed algorithm are also compared with the Fx-Newton algorithm proposed by Li et al. [9].

This paper is organized as follows: firstly, a brief background introduction and related previous studies are summarized in Section 1. In Section 2, the proposed MRFx-Newton algorithm is introduced, including how the algorithm is evolved from the Newton algorithm in the frequency domain when one narrowband-pass filter cannot separate the different vibration spectrums (Section 2.1), and how the algorithm is implemented in the time domain (Section 2.2). Then the system description, experimental setup (Section 3.1) and narrowband division (Section 3.2) are introduced in Section 3. In Section 4, the experimental results are analyzed and discussed, and the conclusion is given in Section 5.

2. The MRFx-Newton algorithm design

The proposed multi-reference Fx-Newton algorithm is developed based on the method proposed by Li et al. [9]. In their method, multiple targeted sinusoids are extracted from a measured broadband reference signal. By taking the Hilbert transform (with all-pass characteristics), "$-\pi/2$" phase shift of the reference signal is realized (i.e. generating the corresponding orthogonal signal). Then, the fast secondary path filtering and good convergence performance can be achieved.

In this study, instead of one reference signal, multiple independent reference signals are considered for attenuating multiple sinusoids in the same narrowband. Fast convergence of the Newton algorithm for an MIMO system (with L actuators and L error sensors) is also achieved by the inverse secondary-path filter [1,3,9] (detailed analysis can be found in [9]).

In this section, the principle of the MRFx-Newton algorithm is concisely illustrated in the frequency domain. Then, more efficient implementation of the algorithm in the time domain is also presented in detail.