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On-line Frequency Estimation Based on Cascade Adaptive Notch Filter and Application to Active Noise Control

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Abstract

For ANC systems applied to aircrafts or passenger ships, engines from which reference signals are usually measured are located so far from seats where main part of controllers are placed. It can make feedforward ANC scheme difficult to implement or very costly. Feedback ANC algorithms which do not require reference signals and use error signals alone to update the filter, are usually sensitive to measurement noise and impulse noise.

In this paper, reference signal needed for the feedforward control is not measured directly but generated with the estimated frequencies. Cascade adaptive notch filter (ANF), which has the low computational burden, is used to implement ANC system in real time. Several ANFs of order 2 are connected in series to estimate multiple sinusoids. Computer simulations and experiments in the laboratory for verifying efficacy of the proposed algorithm are carried out.

1. Introduction

For active control of sound and vibration two types of control strategy have been widely applied. The first one is a feedforward control method, which requires both a reference signal and an error signal, and can attenuate broadband noise as well as narrowband noise. The measured reference signal, which is correlated with the impending primary noise is used to derive the control input. If the correlation between the reference and the error signal is perfect, it is theoretically possible to make the error signal zero, which can be a very attractive feature. However, if the correlation is only partial, the system only cancels the primary noise components that are correlated with the reference signal. Because of its high stability and performance robustness, it has been used in many applications [1]. The second one is a feedback control method, which requires the error signal alone to attenuate periodic noises. Systems with difficulty in obtaining suitable references or active control systems with narrowband disturbance typically use feedback control in order to avoid the problems associated with obtaining a reference signal for use in a feedforward LMS configuration. It is well known that a certain level of noise reduction can only be achieved over a limited bandwidth and the smaller the error signal is driven, the higher the control gain must be, and the less stable will be the system [2].

Active control of harmonic noise has received a great deal of attention because the rotating or reciprocating machinery such as engines or fans induce the harmonic noise. As mentioned above, we can obtain a good performance for the harmonic noise using a feedforward control method only when a reference is available. For ANC applied to passenger ships or aircrafts, engines from which reference signals are usually measured are located so far from seats where main part of controllers is placed that the scheme might be difficult to implement or costly. Among various feedback methods that do not require reference signals, internal-model-control (IMC) technique [3] that alters its feedback structure into feedforward one has a superior performance over other feedback methods for the harmonic noise. However, the scheme is sensitive to measurement noise and unexpected transient disturbance (impulse noise) such as a sneeze, clapping hands and so on. Moreover, error signals may increase suddenly due to an impulse noise with a large level of power, which can derive the adaptive algorithm unstable.

In this paper, a new indirect feedback ANC algorithm is proposed for multi-tonal noise. Firstly, we estimate noise signals in the controlled field using IMC technique from the error signals and then estimate its frequencies in real-time. Secondly, we generate the sinusoidal signals with the estimated frequencies and use it as reference signals of the conventional feedforward ANC algorithm. If the noise frequencies are exactly estimated, the scheme will be identical to the conventional normalized feedforward method that measures multi-tone directly, except that smaller order of the adaptive controller may be used because the reference signal of the proposed method has no measurement noise.

We propose on-line frequency estimation algorithm with computational efficiency to generate reference signals for the feedforward ANC in real-time. Among the various methods of frequency estimation [4-6] it is well known that adaptive notch filter (ANF) based method has good tracking capability, low computational complexity and high accuracy [7]. Especially, Linearized minimal parameter estimation method [8] using ANF with constrained poles and zeros has the improved threshold signal-to-noise ratio (SNR) and the convergence rate. However, the method might be difficult to apply to the ANC in real-time because it requires both matrix calculation to adapt coefficients of the ANF and root-finding technique of polynomial equation to estimate frequencies from the updated coefficients of the ANF.

Cascade adaptive notch filter (ANF), which has the low computational burden, is used to implement ANC systems in real time. Several ANFs of order 2 are connected in series to estimate multiple sinusoids. Computer simulations and experiments in the laboratory for verifying the efficacy of the proposed algorithm are carried out.

2. On-line frequency estimation method

ANF with constrained poles and zeros

A transfer function of ANF of order 2 is

$$N(z) = \frac{A(z^{-1})}{A(\rho z^{-1})} = \frac{1 + a(n)z^{-1} + z^{-2}}{1 + \rho a(n)z^{-1} + \rho^2 z^{-2}}, \tag{1}$$

where ρ, called a pole contraction factor, is a positive real number close to but smaller than 1 and is in relation to the bandwidth of the notch. Note that the filter notches a single-tone and the locations of zeros and poles are directly related as follows:

$$P = Z / \rho, \tag{2}$$

where P is the pole and Z is the zero of $N(z)$.

We can estimate the coefficient, $a(n)$ using recursive maximum likelihood method (RML) [7] via the famous stochastic Gauss-Newton algorithm for an ARMA process. The algorithm has several advantages in the area of accuracy, numerical robustness, stability, convergence speed, computational efficiency and linear phase [7]. However, it is a nonlinear recursive least square (RLS) problem which has a local minimum due to nonlinearity.

Linearized minimal parameter estimation method improves convergence rate and threshold SNR by linearizing the estimation structure of the notch filter using the constraint of poles and zeros [8]. Figure 1 shows the block diagram of the method.

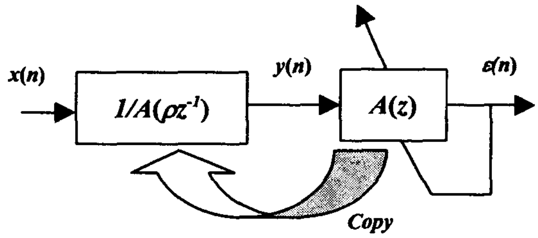


Figure 1. The block diagram of Linearized minimal parameter estimation method

In Figure 1, $x(n)$ is an input signal and $\varepsilon(n)$ is an error of the ANF. The basic concept of the method is to separate the numerator and the denominator of the ANF and update only the numerator, which is possible by the property of constrained poles and zeros as seen in Figure 1. The denominator can be easily obtained from ρ and the numerator $A(z^{-1})$ to be updated in the previous step.

When the ANF makes an input signal $x(n)$ of single-tone into a whitening signal, which is a desired action of it, the frequency of the input signal $x(n)$ becomes the central notch frequency of the notch filter as follows:

$$f(n) = \frac{1}{2\pi}\cos^{-1}\left(-\frac{a(n)}{2}\right). \tag{3}$$

Cascade ANF for multi-tone

In general, the ANF of order $2p$ is used to estimate the frequencies of p sinusoids. It requires both matrix calculation to adapt p coefficients of the ANF and root-finding technique for polynomial equation of order p to estimate frequencies from the updated coefficients of the ANF.

To reduce the computational burden in real-time implementation, we use a cascade ANF for the frequency estimation of multi-tone. The cascade ANF is composed of p notch filters of order 2 in series to estimate the frequencies of p sinusoids. Each section of the notch filters notches one frequency component of sinusoids, sequentially. Figure 2 shows the block diagram of the cascade ANF. Note that all the sections of the filter are adapted with the error $\varepsilon_p(n)$ of the last section. It is to avoid the conflict in each notch filter. Each section is adapted by linearized minimal parameter estimation method [8].

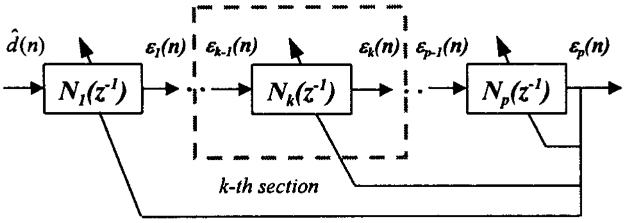


Figure 2. Block diagram of cascade ANF

The algorithm is derived as follows:

$$\varepsilon_k(n) = N_k(q^{-1})\varepsilon_{k-1}(n) \tag{4}$$

$$\begin{aligned}\tilde{\varepsilon}_k(n) &= \frac{1}{A_k(\rho q^{-1})}\varepsilon_{k-1}(n) \\ &= \varepsilon_{k-1}(n) - \rho a_k(n-1)\tilde{\varepsilon}_k(n-1) - \rho^2\tilde{\varepsilon}_k(n-2)\end{aligned} \tag{5}$$

$$\varepsilon_k(n) = N_k(q^{-1})\varepsilon_{k-1}(n) \tag{6}$$

$$\Phi_k(n) = \lambda\Phi_k(n-1) + \tilde{\varepsilon}_k(n-1)^2 \tag{7}$$

$$z_k(n) = \lambda z_k(n-1) + \tilde{\varepsilon}_k(n-1)E_k(n) \tag{8}$$

$$a_k(n) = -\Phi_k(n)^{-1}z_k(n) \tag{9}$$

$$f_k(n) = \frac{1}{2\pi}\cos^{-1}\left(-\frac{a_k(n)}{2}\right) \tag{10}$$

As shown in equation (4)-(10), neither matrix calculation nor root-finding algorithm is needed and it reduces the computational burden significantly.

We estimated the tonal frequencies of noisy signal measured in the cabin of a passenger ship to obtain more realistic results. According to spectrum analysis of the signal, frequency component in range of 80Hz~180Hz are dominant.

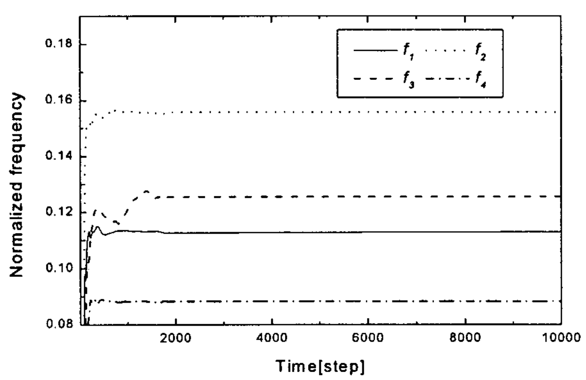


Figure 3. Frequency estimation result

Figure 3 shows the frequency estimation result. Four dominant frequency components were estimated very well as shown in Figure 3.

3. ANC based on noise frequency estimation

Consider the following two steps for the frequency estimation based ANC [8].

Firstly, we estimate the frequencies of the tonal components in noise signal, $\hat{d}(n)$ that needs to be canceled in the controlled field by the method proposed in section 2 and define a reference signal as follows:

$$r(n) = \sum_{k=1}^{p}\sin\left(2\pi\sum_{i=0}^{n}\hat{f}_k(n-i)\right), \tag{11}$$

where p is the number of the estimated frequencies and $\hat{f}_k(n-i)$ is the k^{th} estimated frequency of $\hat{d}(n-i)$. It is identical to the k^{th} frequency of $d(n-i)$, if the model of cancellation path is exact and therefore, $\hat{d}(n-i)$ is equal to $d(n-i)$.

Secondly, we adapt the controller filter $W(z)$ with the generated reference signal. The adaptation is carried out with *filtered-x* LMS algorithm, which is popular in the feedforward ANC scheme. Therefore, without measuring reference we can expect to obtain the performance of the conventional feedforward control, which measures coherent reference, assuming accurate estimation of the frequencies. Figure 4 shows the block diagram of the approach.

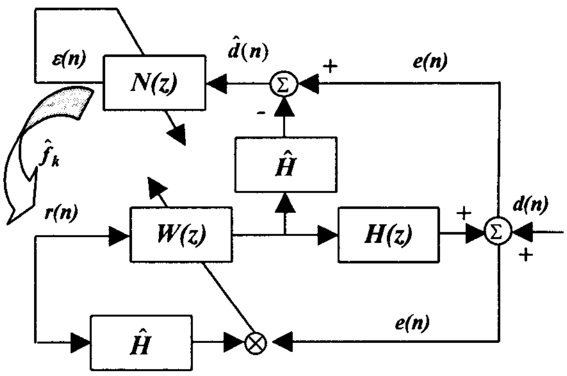


Figure 4. Block diagram of the ANC based on noise frequency estimation

4. Experiments

Feasibility of the proposed ANC scheme in the application to a passenger ship was verified by experiments in the laboratory where noise signal measured in the cabin of a passenger ship was generated with a loud speaker. For the experiments, TMS320C40 DSP board in connection with a notebook computer by local network was used with 1kHz sampling frequency.

To obtain a satisfactory performance two microphones and two speakers were placed near ears of a person taking a seat as shown in Figure 5.

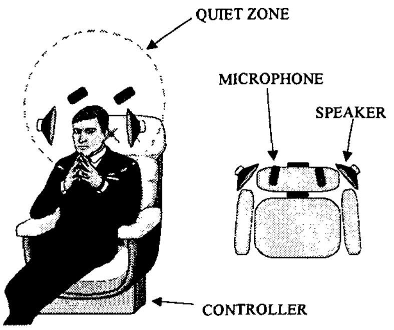
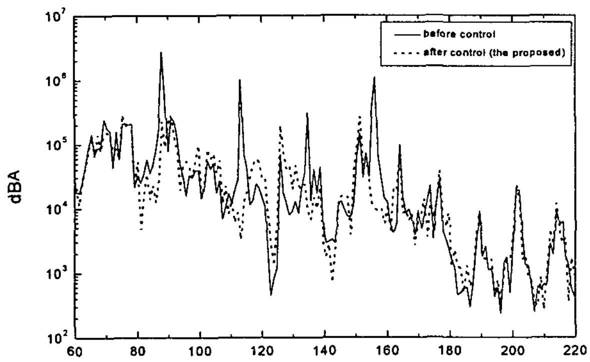
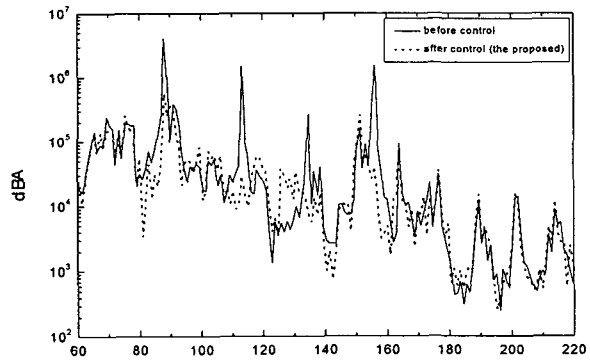


Figure 5. Experimental setup of MIMO ANC systems



(a) Microphone I



(b) Microphone II

Figure 6. Experimental results of the proposed algorithm (filter legnth=70, step size=0.15)

Figure 6 shows the A-weighted steady state power spectra of the error microphone signals before and after real-time control. We used constraint *filtered-x* LMS algorithm as the feedforward control algorithm. The notch filter estimated four dominant frequencies exactly and the frequency components were reduced by about 10-20 dB.

5. Conclusion

We proposed an ANC scheme for the harmonic noise reduction, which does not use reference signals. The proposed scheme is composed of two parts. The first part is an on-line frequency estimation. The second part is the conventional feedforward control.

We proposed a new frequency estimation algorithm with the improved convergence rate, threshold SNR and computational efficiency based on the real-time cascade ANF. We generate the sinusoidal signal with the estimated frequencies, which is used as the reference signal of the feedforward ANC. We used the cascade ANF for low computational burden in real-time implementation. We showed the validity of the proposed algorithm for ANC of a passenger ship or multi-tonal noise applications through the experiments in the laboratory.

6. References

[1] Colin H. Hansen and Scott D. Snyder, *Active control of noise and vibration*, pp. 374-543, E & FN SPON, 1997

[2] S. M. Kuo and D. Vijayan, "Adaptive algorithms and experimental verification of feedback active noise control systems," *Noise Control Eng*. **42**, pp. 37-46, 1994

[3] S. E. Forsythe, M. D. McCollum and A. D. McCleary, "Stabilization of a digitally controlled active isolation system," *Proc. Recent Adavances in Active Control of Sound and Vibration*, pp. 879-889, 1991

[4] D. G. Childers, *Modern Spectrum Analysis*. New York. IEEE Press, 1978

[5] S. B. Kesler, *Modern Spectrum Analysis II*. New York. IEEE Press, 1986

[6] S. M. Kay and S. L. Marple, "Spectrum analysis-A modern perspective," *Proc. IEEE* **69**, pp. 1380-1419, 1981

[7] Arye Nehorai, "A Minimal Parameter Adaptive Notch Filter With Constrained Poles and Zeros," IEEE, *Transactions on Acoustics, Speech, and Signal Processing*, **33(4)**, pp. 983~996, 1985

[8] Sunmin Kim, "Active Noise Control Algorithm Based on Noise Frequency Estimation," *Proceedings of the 12th KACC*, Korea, pp. 321-324, 1997