A SIMPLE FEEDBACK NARROWBAND ACTIVE NOISE CONTROL WITH INTEGRATED CIRCUIT DESIGN

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The miniaturization of active noise control is necessary for most applications. For low order analog control and integrated circuit design, a simple proportion-integration-differentiation method is proposed for narrowband noise reduction. The case study for transformer noise control is illustrated with integrated circuit design in 0.18 μm CMOS technology, which shows the effectiveness of the proposed method.

Keywords: active noise control, analog feedback control, integrated circuit design

1. Introduction

The miniaturization of active noise control (ANC) system is necessary for most applications, especially for ANC headphone for limited assembly space [1], multi-channel ANC system for easy and simple installation[2], etc.. As well known, digital control and analog control are two typical active control strategies. Compared to digital controllers, analogy controllers have advantages of low cost and easy integrated design for miniaturization.

The key point to design a feedback controller is to obtain good noise attenuation at the specified frequency bands with sufficient stability at the cost of the smallest noise amplification at other bands. Most design methods are to translated the performance requirements into various design criteria and constraints for optimization problem, such as $H_\infty[3, 4]$, $H_2[5]$, $H_2/H_\infty[6]$ and waterbed flatten method [7] etc.. In general, the optimization design is suited to be implemented by digital controller or high order analog controller, which brings analog implementation complication, as well as difficulty to integrated circuit design.

For low order analog control and integrated circuit design, a simple proportion-integration-differentiation (PID) method is proposed for narrowband noise reduction. Firstly, the design method is given. Then, a case study for transformer noise control is illustrated with integrated circuit design to show the effectiveness of the proposed method.

2. Design method

A block diagram of a feedback ANC system is shown in Fig. 1, where $H(s)$ is the Laplace-domain transfer function of the feedback controller, $G(s)$ is the transfer function of the plant, $d(t)$ is the disturbance signal, and $e(t)$ is the residual error signal [8].
The transfer function from the disturbance to the error signal is equal to

\[ S(s) = \frac{E(s)}{D(s)} = \frac{1}{1 + G(s)H(s)}. \]  

This transfer function is also known as the sensitivity function of the system. Let \( s = j\omega \) in Eq. (1), the frequency response of the sensitivity function can be written as

\[ S(j\omega) = \frac{1}{1 + G(j\omega)H(j\omega)}. \]  

where \( G(j\omega) \) is the frequency response of the secondary path, \( H(j\omega) \) is the frequency response of the controller, and \( G(j\omega)H(j\omega) \) is the open-loop frequency response of the control system.

From the definition of the sensitivity function, it is clear that the control system has disturbance attenuation for \( |S(j\omega)| < 1 \) and disturbance amplification for \( |S(j\omega)| > 1 \). The noise reduction \( NR \) is defined as \(-20\log_{10}|S(j\omega)|\), and can be calculated according to the following equation

\[ NR = 20\log_{10} |1 + G(j\omega)H(j\omega)|. \]  

A narrowband analog design method is proposed for low order analog control and integrated circuit design. The schematic diagram of the proposed method is shown in Fig. 2, which consists of four parts: one or more band-pass filter, gain adjustor, adder and PID control. Band-pass filter is used to give the basic noise attenuation performance, where the filter number and center frequency value depend on the noise attenuation frequencies and quality factor is suggested to be 20 for narrowband noise reduction. The gain of the system can be set according to the maximum noise reduction and the amplitude-frequency response of the secondary path. To compensate the secondary path delay, integration is suggested to be at low frequency end and differentiation is suggested to be at high frequency end to ensure the system stability and reduce the disturbance amplification.

The band-pass filter and gain adjustor can be implemented by the circuit shown in Fig. 3. Part A is a two-order band-pass filter and the transfer function can be expressed by Eq. (4)
\[ A(s) = \frac{V_o(s)}{V_i(s)} = \frac{A_0 \omega_p s}{s^2 + \omega_p^2 s + \omega_p^2} \]  

where center radian frequency \( \omega_p = \sqrt{\frac{R_1 + R_2}{R_1 R_2 C_1 C_2}} \), gain at center frequency

\[ A_0 = \frac{R_2 R_3 C_2 A_{VF}}{R_1 R_2 (C_1 + C_2) + R_2 R_3 C_2 + R_1 R_3 C_2 (1 - A_{VF})} \]

quality factor

\[ Q_p = \frac{\sqrt[4]{R_1 + R_2}}{R_1 R_2 (C_1 + C_2) + R_2 R_3 C_2 + R_1 R_3 C_2 (1 - A_{VF})} \]

and feedback gain \( A_{VF} = 1 + \frac{R_p}{R_4} \). Assuming

\[ R_1 = R_2 = R_3 = R, C_1 = C_2 = C \], we have \( A_0 = \frac{A_{VF}}{4 - A_{VF}} \), \( \omega_p = \frac{\sqrt{2}}{R C} \), \( Q_p = \frac{\sqrt{2}}{4 - A_{VF}} \). Part B is gain adjustor, and the gain \( K = R_m / (R_m + R_n) \).

\[ H(s) = k \frac{a T_s + 1}{b T_s + 1} \]

where \( a = \frac{R_1 + R_2}{R_2} \), \( T_1 = (R_1 / R_2) C_1 \), the radian frequency at maximum lead phase \( \omega_{m1} = \frac{1}{T_1 \sqrt{\alpha}} \),

\( a = \frac{1 + \sin(\varphi_{m1})}{1 - \sin(\varphi_{m1})} \) (maximum lead phase \( \varphi_{m1} \)), \( T_2 = R_4 C_2, b = \frac{R_4 + R_4}{R_4}, \) the radian frequency at maximum lag phase \( \omega_{m2} = \frac{1}{T_2 \sqrt{b}}, b = \frac{1 + \sin(\varphi_{m2})}{1 - \sin(\varphi_{m2})} \) (maximum lag phase \( \varphi_{m2} \)), \( k = \frac{b}{a} = 1 + \frac{R_6}{R_5} \).

**Figure 3:** Circuit of band-pass filter and gain adjustor.

PID control can be implemented by the circuit shown in Fig. 4, the transfer function can be expressed by Eq. (5)

\[ H(s) = k \frac{a T_1 s + 1}{b T_2 s + 1} \]

where \( a = \frac{R_1 + R_2}{R_2}, T_1 = (R_1 / R_2) C_1, \) the radian frequency at maximum lead phase \( \omega_{m1} = \frac{1}{T_1 \sqrt{\alpha}}, \)

\( a = \frac{1 + \sin(\varphi_{m1})}{1 - \sin(\varphi_{m1})} \) (maximum lead phase \( \varphi_{m1} \)), \( T_2 = R_4 C_2, b = \frac{R_4 + R_4}{R_4}, \) the radian frequency at maximum lag phase \( \omega_{m2} = \frac{1}{T_2 \sqrt{b}}, b = \frac{1 + \sin(\varphi_{m2})}{1 - \sin(\varphi_{m2})} \) (maximum lag phase \( \varphi_{m2} \)), \( k = \frac{b}{a} = 1 + \frac{R_6}{R_5} \).

**Figure 4:** Circuit of PID control.
The detailed design process of the proposed method is given as following.

1) Obtain the frequency response of the secondary path $G(j\omega)$.

2) According to the objective of noise attenuation, set the filter number, center frequency and set the quality factor is 20.

3) Calculate the system gain by Eq.(3) on the basis of the maximum noise attenuation, the secondary path amplitude and the band-pass filter gain at the center frequency.

4) Set the maximum lead phase $\varphi_{m1}$, the maximum lag phase $\varphi_{m2}$ and corresponding radian frequency $\omega_{m1}$ and $\omega_{m2}$, where $\varphi_{m1}$ and $\varphi_{m2}$ are suggested to be in $30^\circ$ - $70^\circ$, the maximum lag frequency is at the low frequency end and the maximum lag frequency is at the high frequency end of the objective frequency range.

5) Check the system stability by the Nyquist plot of the open-loop frequency response $G(j\omega)H(j\omega)$. If the system is unstable, back to step 3) to adjust the lag frequency, the lead frequency, lag phase, lead phase and the system gain further until the system is stable.

6) Calculate noise reduction by Eq. (3) and check the maximum noise reduction, the noise amplification and noise attenuation frequency band. If the attenuation performance can not meet the objective, back to step 3) to adjust the lag frequency, the lead frequency, lag phase, lead phase and the system gain further until the performance is qualified. In general, the noise amplification should be less than 6 dB to ensure the system robustness.

The above mentioned parameters can be adjusted by manual mode or program mode.

3. Case study

As well known, the transformer noise is characterized by the fundamental and harmonic frequencies of the power line [9]. If the frequency of the power line is 50 Hz, the transformer noise is 100 Hz, 200 Hz and 300 Hz harmonic noise with about 10 dB higher than background noise. The objective of this case is to reduce 100 Hz, 200 Hz and 300 Hz harmonic noise with the maximal attenuation about 15 dB.

The plant is set up in an anechoic chamber, where the error microphone is located about 20 cm away from the control loudspeaker. The frequency response of the secondary path (the loudspeaker and acoustic path) is shown in Fig. 5, which has a flat response in the frequency range 100 - 500 Hz.
According to the objective of noise attenuation, set the filter number is 3, center frequencies are 100 Hz, 200 Hz and 300 Hz, respectively. The quality factors of three filters are set to be 20. The maximum noise reduction at center frequency is 15 dB.

Set the maximum lead phase \( \varphi_{m1} \) is 58° and corresponding frequency is 1000 Hz. Set the maximum lag phase \( \varphi_{m2} \) is 65° and corresponding frequency is 50 Hz. According to the above set value, the circuit parameters can be calculated by Eqs.(4) and (5).

The frequency response of the analog controller is shown in Fig.5, which has lead phase at high frequency band, lag phase at low frequency band and peak amplitude at frequencies 100 Hz, 200 Hz and 300 Hz. The Nyquist plot of the open-loop frequency response is shown in Fig. 6, where the plot does not surround the Nyquist point (-1, j0), and shows the system is stable.

The noise reduction calculated by Eq. (3) is shown in Fig.7, where noise attenuation up to 13.0 dB is achieved at frequencies 100 Hz, 200 Hz and 300 Hz, and the noise amplification is limited below 5.8 dB. The performance meets the objective well.

Based on one low noise Op Amps [10], the analog controller is designed with 0.18 \( \mu \)m CMOS technology, where the capacitors are external connection. The layout area is 1.3 mm \( \times \) 0.9 mm, which is good for miniaturization of active noise control system.

![Fig 6: The frequency response of the controller.](image1)

![Fig 7: The Nyquist plot of the open-loop frequency response from 50 -1000 Hz.](image2)
4. Conclusion

For low order analog control and integrated circuit design, a simple PID control method is proposed for narrowband noise reduction. The detailed implementation of the proposed method is given. The case study for transformer noise control is to reduce 100 Hz, 200 Hz and 300 Hz harmonic noise with the maximal attenuation about 15 dB. The simulation results show the effectiveness of the proposed method. For miniaturization of the analog controller, the integrated circuit design is developed with the layout area 1.3 mm×0.9 mm in 0.18 μm CMOS technology.

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