Digital Filter Design Based on Single Chip Microcomputer

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Abstract—In the paper, 2-order low-pass filter and 2-order band-stop filter were respectively designed based on Butterworth Filter Design Instrument developed on Laboratory Virtual Instrument Engineering Workbench (LabVIEW). Two kinds of digital filters were transplanted into single chip microcomputer (SCM) 8051 to suppress interference signals in the detection of building vibration with frequency of 1-10Hz, and 10Hz interference signal in the output signals of CD series magnetoelectric speed sensor, respectively. The performance of the filters was tested based on Signal Generator and Filtering results indicator developed on LabVIEW. The filters transplanted into the 8051 SCM showed good filtering performances by comparing signal waveforms and total harmonic distortions (*THD*) before and after filtering. The engineering application problems were solved successfully by the designed filters.

Keywords-Butterworth digital filter; single chip microcomputer; Suppressing noise signal; total harmonic distortion; low-pass filter; band-stop filter

I. INTRODUCTION

Digital filter is widely used to filter noise signal in the output signals of sensors in intelligent sensor system because of its good performance in suppressing noise signals and obtaining useful signals. Meanwhile, compared with analog filter, digital filter is less influenced by environment and works steadily. The single chip microcomputer (SCM) has some advantages, such as low cost, small size and high reliability. Therefore, digital filter realized based on SCM has certain practical value in some cases.

In the paper, 2-order low-pass filter [1] with sampling frequency of 300 Hz and 2-order band-stop filter with sampling frequency of 200Hz were designed and transplanted into 8051 SCM to suppress noise signals [2] in the detection of building vibration frequency (1-10Hz) [3] and 10Hz interference signal in the output signals of CD series magnetoelectric speed sensor.

II. OBTAIN THE MATHEMATICAL MODEL OF THE FILTER

A. Introduction of Butterworth Filter Design Instrument

In the paper, Butterworth Filter [4] Design Instrument developed by Laboratory Virtual Instrument Engineering Workbench (LabVIEW) was used to obtain the mathematical model of the digital filter. Fig. 1 is the panel of Butterworth Filter Design Instrument.

In Fig. 1, Butterworth Filter Design Instrument has the following five modules:

- Filter Parameters Setting: set the filter type, order, low cutoff frequency, high cutoff frequency.
- Parameters setting of input signal: set number of samples, sampling frequency, useful signal amplitude, interference signal amplitude and so on.
- Butterworth Coefficients: display coefficients of the designed filter, including reverse coefficients and forward coefficients.
- The amplitude-frequency characteristic curve: show the amplitude-frequency characteristic curve of the designed filter.
- Filtering result indicator: show useful signal waveform, waveform with interference signal, waveform after filtering and the total harmonic distortion (*THD*) before and after filtering.

Generally, signal waveforms in the time domain and *THD* are important performance indexes. *THD* is applied to represent the distorted degree of composite signal including noise compared to useful signal. And *THD* is defined as:

$$THD = \sqrt{\sum_{n=2}^{\infty} A_n^2} \Big/ A_1 \qquad (1)$$

In (1), $\sqrt{\sum_{n=2}^{\infty} A_n^2}$ is total harmonic root mean square(RMS)；A_1 is fundamental wave RMS.
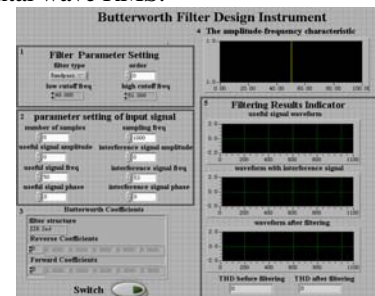

Figure 1.   The panel of butterworth filter design instrument

Set parameters according to measurement requirements and run Butterworth Filter Design Instrument. Record reverse coefficients and forward coefficients if the filtering

performance meets the requirements. Otherwise, change the parameters and try again. Mathematical model of the designed filter could be obtained by putting the filter coefficients into the backward differential equation (2).

$$y(n) = \sum_{r=0}^{M} b_r x(n-r) - \sum_{k=1}^{N} a_k y(n-k) \qquad (2)$$

In equation (2), $x(n)$ is the input signal, $y(n)$ is the output signal. b_r and a_k are separately the forward coefficients and reverse coefficients of the filter. a_0, the coefficient of $y(n)$, is omitted because it equals 1.

B. Obtain the Mathematical Model of Low-pass Filter Applied in Building vibration Frequency(1-10Hz) Detection.

Buildings especially high-rise buildings vibrate obviously because of earthquake or external force, therefore, detection of vibration frequency is important for the safety of person and the buildings. Usually the vibration frequency is 1-10Hz. However, the output signals of the sensor contain a variety of interference signals, such as 50 Hz interference signal and other high-frequency harmonic signals. It is almost unable to measure the vibration frequency accurately. Therefore, 2-order low-pass filter with cutoff frequency of 10Hz was designed to get the useful signals in the paper.

Set the following filter parameters in Butterworth Filter Design Instrument: 1024 sampling points, sampling frequency of 300Hz, 2-order low-pass filter, low cutoff frequency of 10Hz. The useful signal was set as follows: amplitude of 1V and frequency of 1Hz. At the same time, set the interference signal parameter: amplitude of 1V and frequency of 50Hz. Then ran the Butterworth Filter Design Instrument. *THD* decreased from 1.0119 before filtering to 0.059271 after filtering. By comparison, the performance of 2-order low-pass filter met the requirements of the problem. Recorded filter coefficients as follows:

Forward Coefficients b_r = [0.0095 0.0191 0.0095];
Reverse Coefficients a_k = [-1.7056 0.7437];
The amplitude-frequency characteristic curve is shown in Fig. 2.

After getting the filter coefficients, simulating test of frequency characteristic was needed by *freqz* function in MATLAB [5]. Actually a_0 was not included in reverse coefficients a_k obtained by Butterworth Filter Design Instrument, therefore, in the MATLAB simulation, reverse coefficients would be replaced by a_k = [1 -1.7056 0.7437]. Fig. 3 shows the 2-order low-pass filter amplitude-frequency characteristic curve simulated in MATLAB, which also met the requirements of the problem.

Put the reverse coefficients a_k and the forward coefficients b_r into (2). Then the mathematical model of 2-order low-pass filter was obtained as shown in (3).

$$y(n) = 0.0095x(n) + 0.0191x(n-1) + 0.0095x(n-2)$$
$$+ 1.7056y(n-1) - 0.7437y(n-2) \qquad (3)$$

C. Obtain the Mathematical Model of Band-stop Filter Applied in 10Hz Interference Signal Suppression of CD Series Magnetoelectric Speed Sensor

CD series magnetoelectric speed sensor is widely used in mechanical vibration detection because of high sensitivity, low internal resistance and so on. However, when the CD series magnetoelectric speed sensor works in low frequency domain, composite signal including interference signal of 10Hz is outputed, which affects the measurement accuracy. Therefore, 2-order band-stop filter with low cutoff frequency of 8Hz and high cutoff frequency of 12Hz was designed to remove interference signal of 10Hz.

Set the following filter parameters in Butterworth Filter Design Instrument: 1024 sampling points, sampling frequency of 200Hz, 2-order band-stop filter, low cutoff frequency of 8Hz and high cutoff frequency of 12Hz. The useful signal was set as follows: amplitude of 1V and frequency of 19Hz. At the same time, set the interference signal parameter: amplitude of 1V and frequency of 10Hz. Then ran the Butterworth Filter Design Instrument. *THD* decreased from 1.83735 before filtering to 1.07992 after filtering. By comparison, the performance of 2-order band-stop filter met the requirements of the problem. Recorded filter coefficients as follows:

Forward Coefficients b_r = [0.9150 -3.4876 5.1534 -3.4876 0.9150];
Reverse Coefficients a_k = [-3.6428 5.1462 -3.3325 0.8372];
The amplitude-frequency characteristic curve is shown in Fig. 4.

In the MATLAB simulation, reverse coefficients a_k were replaced by a_k = [1 -3.6428 5.1462 -3.3325 0.8372]. Fig. 5 shows the 2-order band-stop filter amplitude-frequency characteristic curve simulated in MATLAB, the frequency characteristic met design requirements.

Put the reverse coefficients a_k and the forward coefficients b_r into (2). Then the mathematical model of 2-order band-stop filter was obtained as shown in (4).

$$y(n) = 0.9150x(n) - 3.4876x(n-1) + 5.1534x(n-2) - 3.4876x(n-3) + 0.9150x(n-4)$$
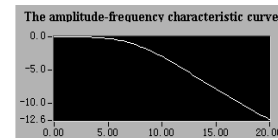$$+ 3.6428y(n-1) - 5.1462y(n-2) + 3.3325y(n-3) - 0.8372y(n-4) \qquad (4)$$

Figure 2. The amplitude-frequency characteristic curve of 2-order low-pass filter
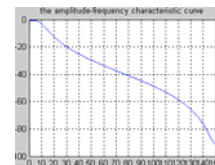

Figure 3. The amplitude-frequency characteristic curve of 2-order low-pass filter in Matlab
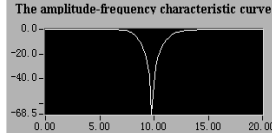
Figure 4.   The amplitude-frequency characteristic curve of 2-order band-stop filter
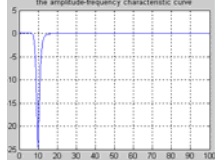

Figure 5.   The amplitude-frequency characteristic curve of 2-order band-stop filter in Matlab

III.   TRANSPLANT FILTER MATHEMATICAL MODEL INTO 8051 SCM

A.   The Hardware Structure Design of Filtering System Based on 8051 SCM

In the paper, the filtering system was mainly composed by 8-bit A/D conversion chip ADC0809 for signal acquisition, 8-bit 8051 SCM for digital processing, and 8-bit D/A conversion chip DAC0832 for analog signal output after filtering. Block diagram of filtering system based on 8051 SCM is shown in Fig. 6 .

B.   The Program Flow Chart of Filtering System Based on SCM

Transplanted the mathematical model (3) of 2-order low-pass filter and the mathematical model (4) of 2-order band-stop filter into 8051 SCM. Program flow chart is shown in Fig. 7. The port P1.3 is the selector of two digital filters. When port P1.3 is at high level, 2-order band-stop filter is selected; otherwise, 2-order low-pass filte is selected.

According to (2), historical input $x(n\text{-}r)$ and historical output $y(n\text{-}k)$ are needed to calculate the output $y(n)$, and $y(n)$ will be converted into historical output of the next moment. In order to solve the problem of limited resources of 8051 SCM, the data $y(n\text{-}k+1)$ should be replaced by $y(n\text{-}k)$ ($k \in (1, N)$), and the data $x(n\text{-}r+1)$ also by $x(n\text{-}r)$ ($r \in (1, M)$) after finishing calculating everytime. Then acquiring and processing signals are conducted. By this way, the floating point algorithm is optimized in the 8051 SCM platform.

IV.   PERFORMANCE TESTING AND EVALUATION

After transplanting the filter model into SCM, filtering performance needed to be tested.

A.   Set up Performance Testing System

The performance testing system was set up based on Signal Generator and Filtering results indicator developed on LabVIEW.

The block diagram of performance testing system is shown in Fig. 8.

In Fig. 8, the Signal Generator was used to produce the desired composite signal including noise, show useful signal waveform and waveform with interference signal on the panel, and calculate *THD* of the signal before filtering. The filtering results indicator was used to show the signal waveform after filtering and calculate *THD* of filtered signal. Fig. 9 shows the panel of Signal Generator and Filtering result indicator.

The composite signal including noise produced by Signal Generator was converted into analog signal through the D/A channel of multifunctional data acquisition card Lab-PCI-6024 (produced by National Instruments). Then the analog signal was filtered in digital filtering system based on 8051 SCM. The output signal of filtering system was converted into digital signal through the A/D channel of Lab-PCI-6024 and shown on the panel of Filtering results indicator.

B.   Filtering Results and Performance Evaluation

1)   Performance evaluation of building vibration frequency detection.

Fig. 10 shows the waveforms and *THD* before and after filtering. The useful signal was set in Signal Generator as follows: amplitude of 1V and frequency of 1Hz. Then set the interference signal parameter: amplitude of 1V and frequency of 50Hz. The number of samples was 1024, and sampling frequency was 1000Hz. As input voltage range of ADC0809 was 0-5V, 2V DC offset was added to composite signal.

In Fig. 10, signal waveform after filtering was smooth with the amplitude of about 1V and the frequency of about 1Hz. The 50Hz interference signal was eliminated well. Meanwhile, the *THD* decreased from 1.0119 before filtering to 0.1059 after filtering. By comparison, the filtering performance was obvious.

2)   Performance evaluation of 10Hz interference signal suppression of CD series magnetoelectric speed sensor.

Fig. 11 shows the waveforms and *THD* before and after filtering. The useful signal was set in Signal Generator as follows: amplitude of 1V and frequency of 19Hz. At the same time, set the interference signal parameter: amplitude of 1V and frequency of 10Hz. The number of samples was 1024, and sampling frequency was 1000Hz. As input voltage range of ADC0809 was 0-5V, 2V DC offset were added to the composite signal.

In Fig. 11, the signal waveform after filtering was approximately sine wave, with the amplitude of about 1V and the frequency of about 19Hz. The 10Hz interference signal was eliminated well. The *THD* decreased from 1.8373 to 1.0951. By comparison, the performance of the filter was obvious.

V.   CONCLUSION

In order to suppress interference signal in the detection of building vibration frequency (1-10Hz) and 10Hz interference signal in the output signals of CD series speed sensor, 2-order low-pass filter with cutoff frequency of 10 Hz and 2-order band-stop filter with low cutoff frequency of 8Hz and high cutoff frequency of 12Hz were respectively designed based on Butterworth Filter Design Instrument. After

simulating test on MATLAB, qualified filter models were transplanted into 8051 SCM. Through practical test, the *THD* decreased from 1.0119 before filtering to 0.1059 after filtering in the problem of suppressing interference signals in building vibration detection. In the problem of 10Hz interference signal in the output signals of CD series speed sensor, the *THD* decreased from 1.8373 to 1.0951. The interference signals were suppressed greatly and the filtering results completely met the actual requirements. A new design method of the filters is provided for filtering online under complex environment, and for establishing convenient, reliable and cheap measuring systems.

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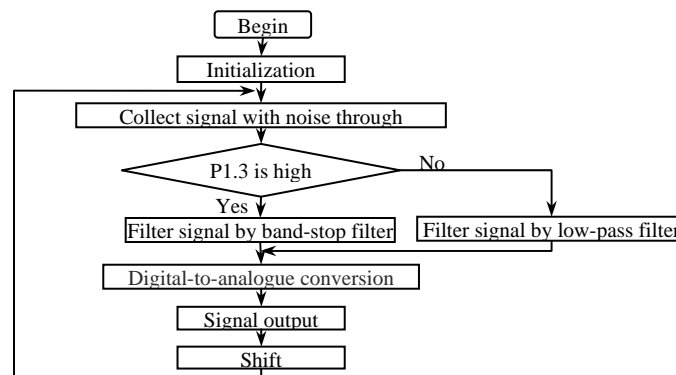Figure 6.   Block diagram of filtering system based on SCM

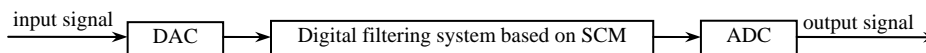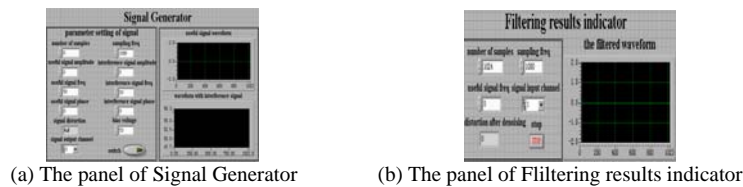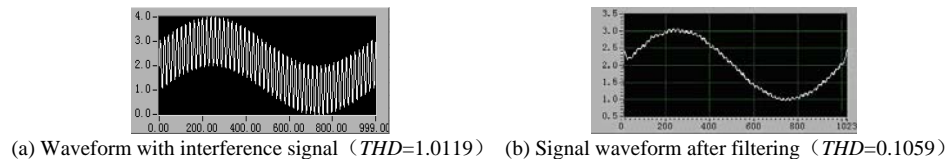Figure 7.   Program flow chart of SCM filtering system

Figure 8.   The block diagram of performance testing system

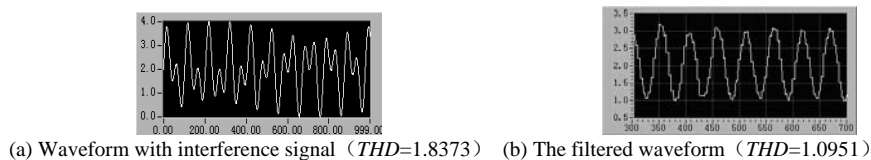(a) The panel of Signal Generator   (b) The panel of Flitering results indicator

Figure 9.   The panel of Signal Generator and Filtering results indicator

(a) Waveform with interference signal（*THD*=1.0119）   (b) Signal waveform after filtering（*THD*=0.1059）

Figure 10. Waveform and distortion comparison before and after filtering

(a) Waveform with interference signal（*THD*=1.8373）   (b) The filtered waveform（*THD*=1.0951）

Figure 11. Waveform and *THD* comparison before and after filtering