DIGITAL SENSOR NETWORK USING DELTA-SIGMA MODULATION FOR HEALTH MONITORING OF LARGE STRUCTURES

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Abstract. This Structural health monitoring represents one of the primary applications for new sensor technologies. When the number of accelerometers or other vibration sensors installed in structures increases significantly, a problem arises to the transfer and processing of a huge amount of data. Obviously, this can be only solved by using digital equipments. Therefore, the demand for sensors with digital outputs shall increase as many measurements are required to interface with digital equipments.

Delta-sigma (ΔΣ) modulation has become quite popular for achieving high resolution of analog to digital conversion. The oversampled delta-sigma modulator is a noise shaping quantizer. The main purpose of noise shaping is to reshape the spectrum of quantization noise so that most of the noise is shifted to the area that is far away from the frequency band of interests.

In this study, a promising digital sensor using a delta-sigma modulator structure is proposed. By extensive simulations and experiments, it is investigated and verified that the higher the oversampling frequency, the broader the bandwidth and the higher signal-to-noise ratio (SNR). Consequently, our proposed digital method can achieve higher resolution compared to any analog method. In addition, the method widens dynamic range as well.
1. INTRODUCTION

Structural health monitoring represents one of the primary applications for new sensor technologies. When the number of accelerometers or other vibration sensors installed in structures increases significantly, a problem arises in the transfer and processing of a huge amount of data. Obviously, this can be only solved by using the networked digital equipments. Therefore, the demand for sensors with digital outputs has become more significant as many measurements are required to interface with digital equipments.

In this study, a digital sensor using delta-sigma modulation is examined. The delta-sigma modulation method converts analog signals to the series of one bit digital signals. This method can achieve very high resolution of the signal.

2. DELTA-SIGMA MODULATION [1] [2] [3]

The delta-sigma (ΔΣ) modulation has become quite popular for achieving high resolution of analog to digital conversion. One significant advantage of the method is that analog signals are converted using only 1-bit analog-to-digital converter (ADC). The oversampled delta-sigma A/D modulator is a noise shaping quantizer. The main purpose of noise shaping is to reshape the spectrum of quantization noise so that most of the noise is filtered out of the relevant frequency band.

2.1. FIRST ORDER DELTA-SIGMA MODULATION

First of all, the basic composition of the first order ΔΣ modulator is shown in Figure 2.1.

![Figure 2.1 Basic composition of the first order ΔΣ modulator](image)

The principle is as follows. The input analog signal is integrated in the beginning. The plus and minus of the integrated value is judged, ‘1’ or ‘-1’ is output respectively. It is delayed by one sample, and the digital-to-analog conversion is done, and the output signal is subtracted from the integrator by the output signal at the same time as the following input analog signal...
input to the integrator. Such an operation is matched to the synchronous clock, and the quantization value comes to follow to the average input by this feedback. Those differences are accumulated in the integrator, and it is corrected as a result.

The output of the $\Delta \Sigma$ modulation is obtained as one bit signal. It depends on the quantizer to assume the threshold to be ‘0’. Therefore, the output can be made to a multi bit by increasing the threshold. The output of the $\Delta \Sigma$ modulation is assumed to be one bit signal in this paper.

Figure 2.2 shows the block diagram of Figure 2.1.

![Figure 2.2 Block diagram of the first order $\Delta \Sigma$ modulator](image)

The conditional expression of the $\Delta \Sigma$ modulator becomes as follows.

<Condition 1>

The quantizer should work for the integrator output as threshold ‘0’.

$$Q(W_i) = \begin{cases} +1 & (W_i \geq 0) \\ -1 & (W_i < 0) \end{cases}$$ \hspace{1cm} (1)

<Condition 2>

The operation feedback from the quantizer is from the range of the input to the large range in the stationary state. Therefore, it is necessary to decide the value of the feedback gain so that the input may fill the expression (2.2).

$$-A \leq X_i \leq +A$$ \hspace{1cm} (2)

When it meets these requirements, the first order $\Delta \Sigma$ modulator can be correctly operated. Therefore, the difference equation of the first order $\Delta \Sigma$ modulator can be requested from Figure 2.2.

$$W_i = X_{i-1} + W_{i-1} - A \cdot Q(W_{i-1})$$ \hspace{1cm} (3)
\[ Y_i = Q(W_i) \]

This expression becomes the fundamental equation in the simulation of the first order \( \Delta \Sigma \) modulation.

### 2.2. SECOND ORDER DELTA-SIGMA MODULATION

The second order \( \Delta \Sigma \) modulator becomes a composition in which one number of integrators is increased to the first order \( \Delta \Sigma \) modulator. Therefore, this composition is shown in Figure 2.3.

![Block line chart of the second order \( \Delta \Sigma \) modulator](image)

Figure 2.3 Block line chart of the second order \( \Delta \Sigma \) modulator

In the same way, the difference equation of the second order \( \Delta \Sigma \) modulator can be requested from Figure 2.3.

\[
V_i = X_{i-1} + V_{i-1} - A \cdot Q(W_{i-1})
\]

\[
W_i = V_{i-1} + W_{i-1} - A \cdot Q(W_{i-1})
\]

\[ Y_i = Q(W_i) \] (4)

This expression becomes the fundamental equation in the simulation of the second order \( \Delta \Sigma \) modulation.

### 3. SIMULATION

MATLAB was used for simulations. When the signal wave form was evaluated, a power spectrum density of the signal was requested in the frequency domain. And it used it as a method of evaluating the numerical value compared with S/N. It is shown that the original signal and the noise signal are assumed to be \( s(t) \) and \( n(t) \) by the following expressions compared with S/N.
\[
S/N = 10 \log \left( \frac{\frac{1}{T} \int_0^T s^2(t) dt}{\frac{1}{T} \int_0^T n^2(t) dt} \right) \text{ [dB]}
\]  

3.1. FIRST ORDER DELTA-SIGMA MODULATION

The input signal is assumed to be a signal consists of puts the white noise and the sine wave. The sine wave frequency was set to 100Hz and the sampling frequency was assumed to be 10kHz.

The signal integrated with the first integrator is first fed back and it is straightened one after another. The straightened signal becomes \(W\), and this signal is shown in Figure 3.1. Output \(Y\) that is 1bit final signal in passing through the quantizer can be obtained, and this signal is shown in Figure 3.2.

The power spectrum density of 1bit output signal is shown in Figure 3.3. It has the peak around the frequency 100Hz of the sine wave. It is understood that the noise has been shifted to the high frequency region well recognized. Thus, the noise shaping characteristic of the \(\Delta\Sigma\) modulation is understood.
Figure 3.3 Power spectrum density of 1bit output signal

This high frequency can be removed by inserting the low-pass filter in the circuit. Then, because the output signal is 1bit signal, it is necessary to convert it to a multi bit signal. The conversion is expressed in the form.

\[ X_i = \frac{1}{N} \sum_{k=1}^{N} Y_{i-k} \]  

As a next step, it is necessary to apply the digital low-pass filter put this multi bit signal. \( SINC^3 \) digital filter was used this time. The filtering process is represented by

\[ y(k) = \sum_{n=0}^{3N-1} h(n)x(n-k) \]  

The coefficients of the digital filter \( h(n) \) are selected due to the necessary decimation ratio, as given below.

\[ h(n) = \frac{n \cdot (n+1)}{2} \quad (1 \leq n \leq N) \]

\[ h(n) = \frac{N \cdot (N + 1)}{2} + (n + N) \cdot (2N - 1 - n) \quad (N \leq n \leq 2N) \]

\[ h(n) = \frac{(3N - n - 1) \cdot (3N - n)}{2} \quad (2N \leq n \leq 3N) \]
In Figure 3.4, the final signal and its power spectrum are shown.

![Signal and Power Spectrum](image)

**Figure 3.4 The signal after the low-pass filter and power spectrum density**

### 3.2. SECOND ORDER DELTA-SIGMA MODULATION

In order to improve the noise shaping capability, the second order delta-sigma modulation method was tested. The signal integrated with the first integrator is first feedback and it is straightened one after another. The straightened signal becomes $V$, and this signal is shown in Figure 3.5. The signal should be fed to the integrator again. The signal integrated with the second integrator is fed back and it is straightened one after another. The straightened signal becomes $W$, and this signal is shown in Figure 3.6. Output $Y$ as the 1bit signal in passing through the quantizer can be obtained. This signal is shown in Figure 3.7. The power spectrum density of $Y$ is shown in Figure 3.8.

The noise is shifted to the high frequency. Therefore, it is understood that the second order $\Delta\Sigma$ modulation has a good noise shaping characteristic.
4. EXPERIMENT AND EVALUATION

4.1. EXPERIMENT METHOD

Figure 4.1 shows the outline of the experiment.
4.2. EXPERIMENT

The ΔΣ modulator used in this experiment is "ADS1201", and is shown in Figure 4.2. The digital filter is shown in Figure 4.3 and an analog low-pass filter is shown in Figure 4.4.
4.3. EVALUATION

Table 4.1 shows the results.

The difference between the simulation and the experiment is relatively large for analog filters. Thus, it is recognized that the experiment contains large noise. On the other hand, the difference is very small between the simulation and the experiment for digital filters. Thus, it can be said that the simulation and the experiment are made well for delta-sigma modulation.

Table 4.1 S/N

<table>
<thead>
<tr>
<th></th>
<th>Simulation</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>First-order modulator</td>
<td>122.9</td>
<td>70.9</td>
</tr>
<tr>
<td>Second-order modulator</td>
<td>107.8</td>
<td>70.9</td>
</tr>
</tbody>
</table>

5. CONCLUSION

In this study, it has aimed at all digitization of the sensor network. It is necessary to establish digital processing. Especially, it is necessary to do the processing from 1bit signal obtained from the sensor. Therefore, a promising digital sensor using a delta-sigma modulator structure is proposed. By extensive simulations and experiments, it is investigated and verified that the higher the oversampling frequency, the broader the bandwidth and the higher signal-to-noise ratio (SNR). Consequently, our proposed digital method can achieve higher resolution compared to any analog method. In addition, the method widens dynamic range as well.
REFERENCES