A New Generation of Hall Sensors Including Delta-Sigma Modulators

80% of all current measurements within motor control are done with a shunt resistor. The voltage drop across the shunt is converted to a digital signal with a delta-sigma modulator. Hall sensors are mainly used in high current applications, where the power consumption inside the shunt resistor is getting too big. To generate the lowest overhead in development, the shunt and hall module should just be exchangeable. Therefore, the hall sensor should provide a bit-stream output of a delta-sigma modulator by maintaining low noise at a low price. The delta-sigma modulator ADS1208 from TI makes this possible.

In motor control, up to 10 signals need to be monitored. Therefore, it is most important to keep the costs for the sensors and their analog-to-digital conversion low. The cheapest method to measure currents is adding a resistor (shunt) into the current path and to measure the voltage drop across the resistor. A delta-sigma modulator is used to convert this voltage drop into a bit-stream. There are several reasons to use modulators instead of conventional analog-to-digital converters (ADC).

First of all, the voltage drop needs to remain as small as possible (typically +/-250mV) to minimize the power loss \( P = I \times V \) in the shunt and delta-sigma modulators are very robust in respect to noise and offset. Even such low voltages can be converted to high resolutions. Also, the shunt and the modulator are often at a floating potential, so that the digital output (bit-stream) of the modulator must be galvanically isolated. The bit-stream is a two wire interface, a data and a clock signal, and only one wire if Manchester encoding is used. Therefore, its isolation is most cost effective. Finally, the bit-stream needs to be decimated with a digital filter to receive a higher resolution output at a lower data rate. The filter structure can be adjusted to the applications needs in respect of resolution and speed. It can include over-current protection or a pure integrator to receive the integral of the current that was applied to the motor during one cycle of the control loop. The filter is usually implemented inside a FPGA or an ASIC. To make the use of modulators easier, TI is currently developing a flexible filter structure (AMC1204).

![Diagram of current measurement using the ADS1202 or ADS1203 type modulators](image)

Figure 1: Current Measurement using the ADS1202 or ADS1203 type modulators
Unfortunately, the shunt measurement is not usable in all applications. The power loss (P=I*V) inside the shunt, will heat up the resistor and cause a drift of its value causing gain and linearity errors. Therefore, the hall sensor is mostly used in high current applications.

Figure 2 shows a typical solution for the electronics inside a hall sensor. A current source, which can be implemented with a reference voltage and an operational amplifier, is used to apply a DC current to the hall element. An external magnetic field is generating a hall voltage \( V_{HH} \), which is in the range of +/-100mV. This voltage needs to be corrected in offset, gained up and shifted to a common mode voltage, so that the output fits to a standard voltage range (for example a bipolar input range of +/-2.5V around common mode voltage of 2.5V: 2.5V +/-2.5V). The user can now add a delta-sigma modulator in his application (ADS1204 from TI) to transfer the output of the sensor into a bit-stream that interfaces to the digital filter of the shunt solution.

![Figure 2: Possible electronic circuit of a hall sensor](image)

All these necessary components of the hall sensor add up in price. While a shunt solution can be implemented with approximately $3-4, the hall solution would cost around $6-7 (including the modulator). The new modulator ADS1208 is optimized to reduce the count of components and therefore the costs by improving the performance.

The ADS1208 has the current source already included, which is sourced out of the pin I_OUT (see figure 3). The voltage between the supply pin AVDD and the I_ADJ pin is internally regulated to the voltage at the REFOUT pin divided by 5 (equals 0.5V). The current is defined to this voltage divided by the resistor value of \( R_1 \). Therefore in the application, the current can be adjusted to a required value:

\[
I_{out} = \frac{V_{refout}(T)}{5 * R_1(T)}
\]

This current at I_OUT is applied to the Hall element. The resistor \( R_1 \) can also be chosen to have a certain temperature characteristic to compensate drifts of the hall element itself, which are expressed with \( a(T) \) in equation (1). The actual Hall voltage \( (V_{HH}-V_{IN}) \) is directly proportional to the applied current and to the magnetic field that should be sensed:

\[
V_H = V_{HH} - V_{IN} = B * \frac{x * v_{refout}(T)}{R_1(T)} * a(T)
\]  

Finally, the hall voltage is converted into a digital bit stream with a delta-sigma modulator that is included inside the ADS1208. The analog input range of the ADS1208 is adjusted to the typical output voltage of a hall element (+/-125mV with REFIN=2.5V). Gaining up the input signal with internal or external amplifiers would cause additional noise. Especially the common mode noise, which is very essential in motor control.
Delta-sigma modulators have the ability to convert low voltage inputs with high accuracy and low noise. Therefore, the ADS1208 can achieve above 80dB in SNR with no missing codes.

**Figure 3: Hall module using the ADS1208**

The input voltage range of the delta-sigma modulator is proportional to the voltage at the pin REFIN, which is normally shorted to REFINOUT. The bit-stream output of the ADS1208 needs to be filtered with an external digital low pass filter to receive a low noise, higher resolution digital output word, which is here called \( F_{\text{data}} \). The value of \( F_{\text{data}} \) is proportional to the input voltage divided by the voltage \( v_{\text{refin}} \).

\[
F_{\text{DATA}} = y \cdot \frac{V_{\text{INP}} - V_{\text{INN}}}{v_{\text{refin}}} = y \cdot \frac{V_{\text{INP}} - V_{\text{INN}}}{v_{\text{refout}}}
\]  

(2)

With the hall sensor being directly connected to the modulators input, \( V_{\text{inp}} - V_{\text{inn}} \) is equal to \( V_H \) in formula (1). Therefore:

\[
F_{\text{DATA}} = \frac{y}{v_{\text{refout}}(T)} \cdot B \cdot x \cdot V_{\text{refout}}(T) \cdot a(T) = B \cdot \frac{y \cdot x \cdot a(T)}{R_1(T)}
\]

(3)

Formula (3) shows that the reference drift is canceled out (\( V_{\text{refout}}(T) \)). In case that the Hall element itself has also a temperature drift \( a(t) \), a combination of resistor and thermistor can be chosen for \( R_1(T) \) to cancel out that temperature dependency.

The absolute accuracy of modulators is usually described with the (integral) linearity, the offset and the gain. While the non-linearity is usually in the range of 0.01-0.02% of the full-scale range (%FSR) and the offset around 0.15-0.3%FSR, the gain error is much higher (1-3%FSR). Also the drift of the gain error is very significant (typically 0.4%FSR, -40°C to 85°C).
The above equations show that the ADS1208 is increasing the system performance by reducing the gain error (trimming R1) and the gain error drift (cancellation of the reference drift, compensation of the hall element’s drift with a thermistor for R1). In addition, the offset can be calibrated at room temperature by trimming the resistors R3 and R4.

A sigma delta modulator is usually implemented in a switched capacitor design. These designs are precharging an input capacitor $C_{\text{samp}}$ (also called sampling capacitor) to the input voltage, disconnect the input from the capacitor and are then processing the charge to further capacitors with the help of operational amplifiers. The sampling capacitor is then discharged and reconnected to the input. This cycle is repeated with every system clock (the ADS1208 has an internal clock generator, but can also run with an external clock).

\[
C_{\text{samp}} = \frac{\Delta Q}{\Delta V} = \frac{I_{\text{in}} \Delta t}{\Delta V} \quad (4)
\]

Formula (4) takes into account that recharging the input capacitor with every clock cycle (cycle time $\Delta t = 1/f_{\text{clk}}$) from 0V to the input voltage ($=\Delta V = v_{\text{in}} - 0V$) will require an average current $I_{\text{in}}$. In other words, the equivalent input impedance of the modulator is:

\[
R_{\text{in}} = \frac{V_{\text{in}}}{I_{\text{in}}} = \frac{1}{f_{\text{clk}} \cdot C_{\text{samp}}} \quad (5)
\]

The high output impedance $R_{\text{h}}$ (several kOhms) of hall sensors has two effects. First, the output impedance of the hall sensor and the equivalent input resistance from the modulator form a voltage divider $R_{\text{h}}/(R_{\text{h}} * R_{\text{in}})$ causing an essential gain error that can drift with frequency and temperature. Furthermore, the bandwidth that is formed by the output impedance of the hall element and the input capacitor of the modulator is limited, so that the capacitor cannot be fully recharged within the sampling time (typically one half of a clock cycle). This generates a significant non-linearity.

To overcome these problems and to make the above gain adjustment effective, operational amplifiers are added to the inputs inside the ADS1208. These amplifiers work in a unity gain configuration to avoid common mode effects. They are also calibrated in offset to keep the offset specification tight (including drift).

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