IMPROVING THE CHARACTERISTICS OF A HIGH-PRECISION MEASURING AMPLIFIER BY A POWERFUL DIGITAL SIGNAL PROCESSING

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Abstract: The maximum resolution when measuring transducers, which operate on the strain gage principle, is physically limited. In addition to a very good analogue measurement technology, the quality of the measured signals can be further improved by a correct and powerful digital signal processing.

The new amplifier QuantumX MX238B maintains the well-known and proven 225 Hz carrier frequency technology combined with the patented background-calibration function of the high-precision amplifier DMP41 and in addition with a powerful digital signal processing. This paper explains the digital signal processing and the achieved improvements.

Keywords: precision instrument, strain gauge, physical limit, high resolution, high stability, auto- and background-calibration, digital signal processing

1. INTRODUCTION

The resistance of a strain gauge changes under mechanical load. If several strain gauges are combined to a bridge circuit the ratio of the bridge output to the bridge excitation voltage is nearly proportional to the mechanically applied force. For the electrical measurement of mechanical quantities using strain bridges, it is the ratio of the voltages expressed in mV/V, which has great importance. The measured mechanical quantities are captured using transducers and are mapped into the unit mV/V.

Therefore a classes of different legendary high-precision amplifiers is offered. In 1980 the DMP series was introduced with the DMP39 and a class accuracy of 5 ppm [1]. Since that time, findings from previously released measuring amplifiers are continuously considered in the development of new measuring amplifiers like the new MX238B of the QuantumX family.

Figure 1 shows the new amplifier MX238B. The MX238B is a compact two channel high-precision amplifier with a class accuracy of 25 ppm. The advantages of the 225 Hz carrier frequency method and the used patented background-calibration of the DMP41 have already been discussed in an earlier publication [2] [3]. The background-calibration ensures uninterrupted measurements, even during the comparison with the internal calibration signal. This method has proven itself in the DMP41 for years. But even with almost the same analog measuring principals, further improvements can still be achieved.

The trend of digitalization is progressing also in the measurement technology. In the case of measuring amplifiers, digitization keeps moving forward to the sensor. This allows a progressive miniaturization, but above all, also a higher accuracy and general improvement of the measurement properties can be achieved. The MX238B maintains the well-known and proven 225 Hz carrier frequency technology in a modular and compact data acquisition system with a powerful digital signal processing [4].

Figure 1: New precision amplifier MX238B in the QuantumX family
For end users, a measuring amplifier is usually a black box. A large part of the signal processing, nowadays mainly digital, is hidden from the user. In addition to the classic specifications in the data sheet, the realization of the measuring amplifiers has an impact on the quality of the measured data. There can be significant differences in the digital signal processing by various measuring amplifiers from different manufacturers.

In the following sections it will be shown which components are necessary in the digital signal processing in order to realize measuring amplifiers with a high accuracy. The mainly digital signal processing steps are explained in detail. Error influences are shown, which can be significantly reduced by a modern digital signal processing. The understanding of the digital signal processing is important for the selection of a suitable precision amplifier in addition to the specifications in the data sheet.

The signal processing will be explained in the context of a QuantumX MX238B measuring amplifier with a carrier frequency of 225 Hz, but can also be transferred in the same way to the four channel 600 Hz carrier frequency measuring amplifier QuantumX MX430B.

2. ANALOG FRONTEND AND EXTENDED DIGITIZATION

Figure 2 shows a simplified block diagram of a single measuring channel of the MX238B (and MX430B for the carrier frequency method). All analog input channels are galvanically isolated from each other and build up identically [5]. For this reason, the following explanations can be reduced to one single channel.

The high-precision amplifiers operate typically using a carrier frequency. In order to reach the required noise suppression, zero- and display-stability, the sensors are supplied with a low carrier frequency of 225 Hz. To obtain a very frequency- and amplitude-stable bridge excitation voltage, the 225 Hz sine wave excitation is digitally generated. The discrete amplitude values for one period are stored in a lookup table. All values stored in this table are transmitted 225 times per second to a 16-bit low-noise digital-to-analog converter (DAC). At the output of the converter occurs an almost ideal and highly stable sine wave.

It is very important to create the nearly ideal sinusoidal carrier frequency in order to obtain only a very few harmonics in the spectrum. Figure 3 shows the distribution of the harmonics of the bridge excitation voltage. All harmonics of this bridge excitation voltage are attenuated more than 97 dB. If a bridge excitation voltage contains significant harmonic components, these are attenuated differently depending on the frequency response of the transducer or the bridge calibration standard. On the other hand a different harmonic distribution at the amplifier input lead to different measured values depending on the demodulation method (rectangular or sinusoidal). In addition to optimizing the demodulation technique, the most harmonic excitation voltage increases the robustness of the amplifier with respect to transducer or bridge calibration standard influences. Due to the digital generation of the supply voltage, it is also possible to balance the offset of the bridge excitation voltage for each individual device to a minimum (advantage when connecting inductive bridge calibration standards).
As well as the DMP41, the MX238B operates with a six-wire circuit to eliminate the cable influences, two sense leads from the excitation voltage of the transducers are fed back to the output stage (not shown) [7]. The output stage regulates voltage drops across the cable from the supply voltage to the transducer [8] [9]. The connected sensor divides the excitation voltage down depending on the strain level in a certain ratio (mV/V). The resulting measuring signal is amplified and then digitized. The amplifier stage is constructed using low-noise operational amplifiers in order to reach the required resolution (SNR). The input impedance of the amplifier is very high to avoid a loading of the transducer by the amplifier [10]. The sensitivity remains constant regardless of the internal resistance of the sensor.

Compared to the DMP41 measuring amplifier, the MX238B is digitizing the signal straight after the amplification stage and the signal processing is realized purely digitally. In this way analogous influences of the previously analog circuit parts are eliminated. The entire control of the amplifier section and the data acquisition is realized in real time via a specially developed DSP, realized in an FPGA (Field Programmable Gate Array). The second identical measuring amplifier connected in parallel takes over the measuring task during a device-internal background calibration (like a bypass). This feature has no negative influence on the measurement and is automatically executed by default. There is no longer a freezing during the live measurement. Measurements could be done on the physical limit without any interruption.

3. COMPENSATED DELTA-SIGMA CONVERTER

Delta-sigma converters are used to digitize the analog input signal of strain gauge based amplifiers. The amplified analog measuring signal is converted by the delta-sigma modulator into a digital data stream of 1s and 0s. The 1s density of the output data stream is proportional to the analog input signal. Oversampling and noise shaping are used to reduce the quantization noise in the frequency band of interest. Additionally oversampling reduces alias effects and thus the need and the influence of analog filters.

The purpose of internal digital filters in delta-sigma converters is to filter the noise-shaping of the modulator out and convert the 1-bit data stream at high sampling rates \( f_m \) into a data stream with a lower data rate and a higher amplitude resolution (decimation \( M \)). Usually a SINC filter structure with an order of \( N \) is implemented in a delta-sigma converter for these purposes (2).

\[
|H(f)| = \left| \frac{M \cdot \sin \left( \frac{\pi f}{f_m} \right)}{M \cdot \sin \left( \frac{\pi f}{f_m} \right)} \right|^N
\]  

(2)

For choosing the order of the SINC filter, it is necessary to know the order of the delta-sigma modulator providing the data. The order should be at least higher than the order of the delta-sigma modulator in order to prevent excessive aliasing of out-of-band noise from the modulator. The combination of the delta-sigma modulator and the digital decimation filter forms a delta-sigma A/D converter [11].

Implementing these filters in hardware is very attractive, because they do not require the use of digital multipliers. They can be efficiently implemented by cascading stages of accumulators operating (integrators), operating at the high input modulator frequency \( f_m \), followed by stages of cascaded differentiators operating at the lower output data rate \( f_s \). This architecture utilizes simple wrap-around arithmetic and it is inherently stable. Figure 4 shows a fifth order SINC decimation filter running at a modulator rate of 2.56 MHz with a decimation of 64, which is the operation mode of the delta-sigma converter used in the MX238B.
The big disadvantage of this simple SINC filter in delta-sigma converters is the high attenuation in the passband of the measuring signal. Already a low attenuation for low frequencies leads to an error much higher than the class accuracy. The carrier frequency method with the two side bands and a high sample rate of the delta-sigma modulator with 40 kSps reduces this effect significantly, but it is necessary to compensate this dynamic error in addition by a compensation filter.

4. DIGITAL SINUSOIDAL DEMODULATION

For carrier frequency amplifiers, the measuring signal must be demodulated after the amplification. The digitalized signal demodulator unit consists of three main parts (bandpass, demodulator and low-pass filter) with the already amplified and digitized transducers output voltage as the input signal. This part of the signal processing was previously implemented analogously for devices in this accuracy class (DMP41, ML38,…). High computing power in the smallest space allows now a progressive digitalization in modern amplifiers also in this part of the signal path. The demodulator unit has the function to rectify the alternating voltage signal with the correct sign (phase). The sign is of importance because of the direction of the measured mechanical quantity (e.g. tensile or compressive force) [12]. In a first step, all signal components outside the measuring signal frequency range are filtered out with a digital bandpass filter. Already at this point disturbing static or higher frequency signal components are eliminated [13] [14]. Without this elimination the following demodulator stage modulate DC components (like offset voltages, thermocouple voltages,...) which leads to a signal component at the carrier frequency.

A digital demodulator follows the bandpass. The demodulator transfers the measuring signal that was modulated in the transducer back into the frequency range of the physical measuring signal of the sensor $f_s$. A modulation is mathematically a multiplication of a measured input signal $f_m$ with a carrier $f_d$ as demodulations signal in the time domain (corresponds to a convolution in the frequency domain) [15].

$$ f_d(t) = f_m(t)f_d(t) \quad F_d(\omega) = \frac{1}{2\pi} \{ F_m(\omega) \ast F_d(\omega) \} \quad (3) $$

Shifting the demodulation into the digital signal processing branch opens up new possibilities. A previously unrealizable demodulation with a sine signal is now possible with high resolution and accuracy. A digital sinusoidal demodulation has the advantage that there are no intermodulation products with the harmonics of the excitation voltage or used bridge calibration standard. This leads to a much more robust behavior to various transducers and bridge calibration standards regarding to their frequency and phase response and also to their internal circuit linearity.

After the demodulation, a powerful digital low-pass filter is necessary which filters out the two sidebands at twice the carrier frequency. The two sidebands arise due to the carrier frequency method (due to the process). This low-pass filter is implemented in the MX238B as a symmetric FIR filter (linear phase finite impulse response filter) and is not configurable by the user. For a causal discrete-time FIR filter $H(z)$ of order $N$ ($n$ real coefficients $h_i$), each value of the input sequence from the demodulator $z$ is a weighted sum (weighted by filter coefficients) of the most recent input values. This computation is also known as discrete convolution and is inherently stable.

$$ H(z) = \sum_{i=0}^{N-1} h_i \cdot z^{-i} \quad (4) $$

In addition to the standard task of this demodulator low-pass filter, analog and digital frequency characteristics of the signal path in front of the demodulator are additionally compensated with this filter (inverse filter ingredient). This includes the low-pass filters on the analogue side and on the digital side the previous mentioned SINC filter of the delta-sigma converter which are compensated in this way. Figure 5 shows the frequency response of the implemented FIR filter of the MX238B.
The result of this FIR filter is a smooth frequency response in the passband band and a very high suppression of the side bands from the carrier frequency procedure. Both sidebands are further damped by the following application filters and thus below the noise level. The amplifier has from this point on an almost ideal behavior in the frequency domain and is useful for slower dynamic measurements and calibrations up to 50 Hz for the MX238B.

5. USER SCALING AND APPLICATION FILTER

A scaling unit is performed directly after the demodulation unit. First, the measured value is mapped into the electrical mV/V unit (adjustment and intrinsic error compensation). Factory adjustment data, dynamic captured data from the background calibration process and the actual temperature are included in this error correction. Also at this point, the temperature influence of the calibration divider is digitally actively compensated.

For the calibration channel, a self-error correction is additionally performed. Therefore at runtime, the intrinsic errors (e.g. linearity error) of both amplifiers are determined relative to one another and the calibration amplifier is adapted to the same characteristics as the actual measuring channel. Thus it is irrelevant for measurements or calibrations on which internal amplifier the actual measuring path is performed. The offset-, gain- and linearity-error of the measuring channel remain constant during all the time.

After scaling in the mV/V unit, the digitized reading is now also balanced in the amplitude. No further corrections are necessary anymore. The user can select an optional scaling to different physically units or select between different powerful filters on high data rates depending on the application [16]. There are various Bessel and Butterworth filters to choose from. Figure 6 shows the available filter curves for the Bessel characteristics. With these filters can the signal bandwidth be limited and the noise be reduced depending on the application.
6. COMPENSATION MATRIX CALCULATION

In the field of industrial testing the number of applications for multicomponent transducers (MCTs) is increasing very fast and is getting more and more important. Multicomponent measurements in force and torque applications usually mean to measure more than one force or moment in different directions. Due to the individual loads, the crosstalk of the individual components can be determined. The result is a compensation matrix for crosstalk for a MCT (5). The QuantumX device family can internally compute this compensation, using a 6x6 matrix to eliminate that crosstalk before output. Also, measurement signals of different types of modules can be calculated synchronous by the compensation matrix and can be provided on an analog output in real-time.

\[
\begin{pmatrix}
F_x \\
M_y
\end{pmatrix} =
\begin{pmatrix}
K_{11} & \cdots & K_{16} \\
K_{61} & \cdots & K_{66}
\end{pmatrix}
\begin{pmatrix}
V_{F_x} \\
V_{M_y}
\end{pmatrix}
\]  

(5)

7. CONCLUSIONS

This publication shows the possibilities of modern signal processing and which signal processing steps are required for a precise and robust carrier frequency amplifier. Relevant details of the digital signal processing used aren’t published in any datasheet. For this reason, the components of digital signal processing for the new precision measuring amplifier MX238B of the QuantumX family were shown. If a user of a precision measuring amplifier attaches great importance to high accuracy and robustness against parasitic influences, it is necessary to select a corresponding measuring amplifier. This publication is intended to support the user in their decision. Even with quasi-static and dynamic measurements, it is important to ensure a smooth frequency response of the measuring amplifier, which can only be achieved by powerful digital signal processing. There exists a legendary, well known long-term re-calibration record over 38 years for the ultra-high precision amplifier DMP series, which certifies a drift of only 2 ppm over decades [17] [18]. Figure 7 shows finally the started long-term re-calibrations for the new QuantumX MX238B amplifier, which certifies also an excellent stability of the new internal resistive and hermetically sealed calibration divider.

![Figure 7: Long-term stability of the MX238B](image-url)
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