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LONG TERM PROVEN AND OPTIMIZED HIGH-PRECISION 225 HZ CARRIER FREQUENCY TECHNOLOGY IN A MODERN AND UNIVERSAL DATA ACQUISITION SYSTEM

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Abstract: The maximum resolution when measuring transducers, which operate on the strain gage principle, is physically limited. The legendary high precision instruments of the DMP series with a high accuracy class of 0.0005 (5 ppm) reach this physical limit. Close to the accuracy class of the DMP series, the "…38"-devices of HBM archive the 0.0025 (25 ppm).

HBM introduces a new amplifier in this "…38" series, the QuantumX MX238B. The 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 in a modular and compact data acquisition system.

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

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 [1]. For the electrical measurement of mechanical quantities using strain gauges, 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 HBM offers a class of legendary high precision amplifiers.

In 1980 HBM introduced the DMP series with the DMP39 and a class accuracy of 5 ppm [2]. The first instrument of the DMP series was developed in close collaboration with the German National Metrology Institute (NMI), the Physikalisch Technische Bundesanstalt PTB, to realize an instrument beyond the demands of industry to explore the technically possible at that time [3]. In 1992 the successor DMP40 was released.

Since 2013 the actual device of the DMP series is the DMP41 with the innovative and patented background-calibration [4] [5]. For a better traceability of mechanical quantities in industrial applications, there is also the requirement of building up measuring chains of a total uncertainty of only 100 ppm. The total uncertainty should not be evenly distributed to transducer and amplifier. The demands on the amplifier are significant higher. Therefore a necessity for amplifiers with a class accuracy of 25 ppm is also given.

In the class accuracy of 25 ppm HBM introduced therefore 1982 the first amplifier of the "…38" series with the DK38, followed by the ML38 (MGC family) in 1995 (ML38B in 2005). In 2016 HBM introduced a completely new design of a "…38" device as a member of its prosperous data acquisition module family QuantumX.

HBM just introduces a completely new precision amplifier of the "…38" series, called MX238B (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, like the other amplifiers of the "…38" series. In most calibration applications two channels have to be compared (device under test and reference in a calibration machine).

In respect to the predecessor ML38, important analog measuring parameters were substantially improved. The principal measurement method and the carrier frequency have remained nearly the same for the MX238B. The advantages of the 225 Hz carrier frequency method and the patented background-calibration of the DMP41 have already been discussed in an earlier publication [6].

Both channel of the MX238B are completely synchronous and independent as well as galvanically isolated to each other. In the MX238B amplifier the measurement method and the accuracy of the DMP and "... 38" series have been combined with the modern possibilities of the QuantumX family. It is now possible to measure synchronous multiple type of signals of very different accuracy-bandwidth combinations with one single data acquisition system. For the first time the patented background-calibration procedure of the DMP41 is used in the "...38" series.

Figure 1: New preciscion amplifierMX238B in the QuantumX family

2. ANALOGE FRONTEND AND DIGITAL SIGNAL PROCESSING

Measurement signals need to be made available with increasing precision and, at the same time, with high stability to fully utilize the potential of static and quasi-static measurements in calibration tasks. For the new compact QuantumX MX238B two-channel precision module with an accuracy class of only 0.0025, the knowledge and the insights from the high precision amplifier DMP41 were taken over into the new amplifier. Compared to the current DMP41 series, there are only a few main differences in the measurement and the signal processing technology. The design of the measuring front end of the DMP41 series has already been shown in a previous publication and explained there in detail [7]. Figure 2 shows a simplified bock diagram of a single measuring channel of the new MX238B.

In order to reach the required noise suppression and zero stability, the sensors are supplied with a low carrier frequency of 225 Hz [8] [9]. To obtain a very frequency- and amplitude stable bridge excitation voltage, the 225 Hz sine wave voltage is digitally generated. All figures stored in a sine-wave table are transmitted 225 times per second to a digital-to-analog converter (DAC). The output waveform is smoothed and converted into a symmetrical bridge excitation voltage referenced to ground. The nominal excitation voltage is fed to an output stage. The bridge excitation voltage has no significant harmonics.

As well as all HBM high precision amplifiers, also the Quantum 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 [10] [11]. The output stage regulates voltage drops across the cable from the supply voltage to the transducer. Internally, the measurement signal inputs (diagonal) and the sense lines of the supply voltage inputs are implemented identically. The input impedance of the amplifier is very high to avoid a loading of the transducer by the amplifier and the voltage drop across the cables can be compensated by the ratiometric measurement method [12]. The line effects and their compensation possibilities were explained in detail in a previous publication [13].

The connected sensor divides the excitation voltage down depending on the mechanical load in a certain ratio (mV/V). The resulting measuring signal is first amplified in the amplifier, digitized by a 24-bit A/D converter, band pass filtered (not shown), demodulated and then low pass filtered. The amplifier stage is constructed using low-noise operational amplifiers in order to reach the required resolution.

In respect to the DMP41 series, the bandpass filtering and demodulation is performed now completely digital. Therefore it is possible to change the demodulation principal from rectangular to a sinusoidal demodulation. This also reduced the amount of required hardware and space. Because of the ratiometric measurement method the stability of the measurement depends only on the resistance ratio of some precision resistors, small changes are additionally corrected by the auto-calibration cycles (now background-calibration cycles). As internal calibration source the inductive divider is changed to a precision resistive divider with active temperature compensation. This new resistive divider is described in the next section in detail. The legendary inductive divider out of the DMP41 series offers measuring technology advantages, but can be replaced by a special resistive divider with active compensation for the MX238B series.

The measurement signal is adjusted in the DSP (Digital Signal Processor) in accordance with the auto-calibration values and the selected filter. The patented HBM background-calibration ensures uninterrupted measurement, even during the comparison with the internal calibration signal. This method has proven itself in the DMP41 for years. Table 1 shows a comparison of the major analog parameters of the DMP41, the predecessor ML38B and the new QuantumX MX238B. In all shown parameters, the MX238B is significant better than the ML38B. For the highest precision, the DMP41 is still top of class.

	DMP41	ML38B	MX238B
Accuracy Class *(Divider Principal)*	5 ppm *(inductiv)*	25 ppm *(inductiv)*	25 ppm *(resistive)*
Short-Term Drift	< 5 ppm/24h *(typ. < 2 ppm/24h)*	< 20 ppm/24h	< 10 ppm/24h
Long-Term Drift	< 5 ppm/a *(typ. < 2 ppm/a)*	< 25 ppm/a	< 15 ppm/a
Zero-Point Drift	< 2 ppm/10K *(typ. < 1 ppm/10K)*	< 10 ppm/10K	< 5 ppm/10K
Gain Drift	< 5 ppm/10K *(typ. < 2 ppm/10k)*	< 20 ppm/10K	< 10 ppm/10K
Linearity	< 5 ppm *(typ. < 2 ppm)*	< 20 ppm	< 10 ppm
Bandwidth *(-3 dB)*	0.04 … 40 Hz	0.03 … 10 Hz	0.01 … 50 Hz

Table 1: Comparison of HBM high preciscion amplifiers

The combination of the already proven technology of the high-end class devices and new approaches like a more sophisticaled signal processing and a resistive divider lead to a very precise and still miniaturized and flexible amplifier with modern interfaces and possibilities.

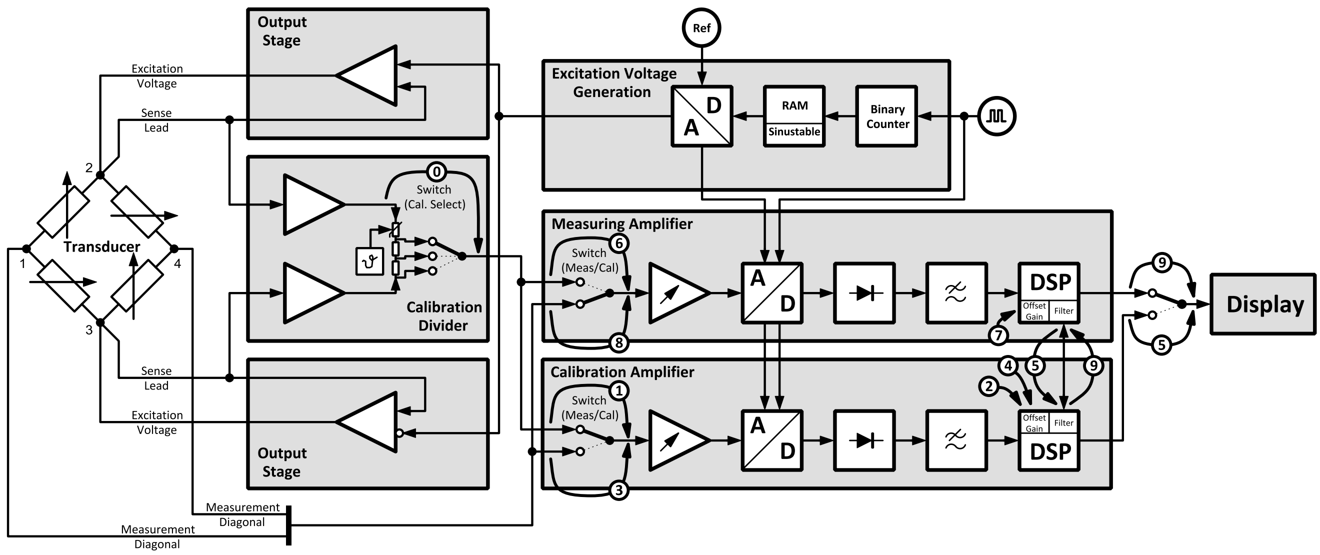

Figure 2: Simplified block diagram of a DMP41 channel with an additional calibration amplifier

3. NEW INTERNAL CALIBRATION REFERENCE

In the field of high precision amplifiers a periodically auto- or background-calibration is necessary. The goal is to keep the high class accuracy constant over temperature and lifetime. An internal calibration divider attenuates the sensed excitation voltage by a certain factor and provides the required reference signal in mV/V. This ratio must be very accurate, temperature- and long-term stable.

The required temperature and long-term stability could not be achieved only by using high precision resistors in earlier devices. Due to the alternating voltage by using the carrier frequency method an inductive divider was used. Through the inductive division method, the temperature drift is extremely low and the long-term stability is ensured. Figure 3a shows a simplified circuit of an inductive calibration divider. This specially designed divider provides the required dividing ratios by the number of windings and generates the calibration signal V_{cal} out of the sensed excitation voltage V_{sens}. This is very temperature- (< 2 ppm / 10 K) and long-term stable (< 2.5 ppm / 36 years) - *a winding cannot disappear!*

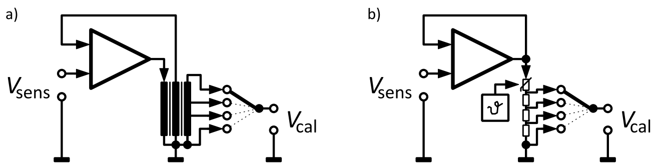

Figure 3: Circuit of the internal calibration dividers

For almost ideal inductive dividers relatively large cores and twisted wires are used. This results in a big housing. The losses of the primary winding's copper resistance are compensated by a current-free sensor winding. In this way, the magnetic flux is controlled and the division ratio is exactly represented by the winding ratio alone. Different taps on the secondary side provide reference signals for all measuring ranges. The accuracy and stability of the precision measuring amplifier depends entirely alone on this inductive component. This method of generating the required reference signals has been proven for decades in the predecessors of DMP41. The long term stability is monitored at a pair of devices and remains within a range of 2.5 ppm since 1981.

Due to the progressive miniaturization, also in the area of high precision measuring amplifiers, a new resistive calibration divider is now used for the first time in this amplifier class (MX238B). In addition to the design of the new calibration divider, numerous measurements were necessary to prove the new concept. When relative performance along with absolute performance is a requirement, the preferred solution is a network of resistors.

The long-term stability of a calibration divider is the main parameter. A time-dependent drift of the calibration divider cannot be compensated inside the device. For this reason, the focus is placed on the long-term drift. The lowest possible long-term drift is achieved by use matched discrete resistors based on the bulk metal foil technology, which are located together in a hermetically shielded ceramic housing.

The hermetic sealing and with dry nitrogen flooded housing prevents the ingress of moisture and oxygen. A sealed metal header offers good thermal dissipation and sharing of temperatures between resistors. This assembly ensures the same environmental conditions for all the resistors. The hermeticity, the location of the chips within the package, the "heat sink" effect of the package itself and the wired bonding help to preserve uniform conditions inside the divider. The result is the excellent load life stability and better performance during temperature changes and moisture exposure.

In addition to the very good temperature drift of the divider, in the high precision amplifier MX238B is in addition an active temperature compensation implemented. Figure 3b shows a simplified circuit of a resistive calibration divider with temperature compensation. In the production process, the remaining temperature response of the calibration divider is determined for each individual measuring amplifier. The specific temperature dependency is then stored in the device. For each background-calibration cycle, the used calibration tab is adapted to the current temperature. This procedure results in a further reduction of the temperature influence. The principal of the background-calibration, first used in DMP41, is described in an earlier publication and can be transmitted to the new amplifier. Figure 4 shows the warm-up phase of the MX238B. Each minute a background-calibration is performed without interrupting the measuring. After 20 Minutes there is no adjustment through the background-calibration visible.

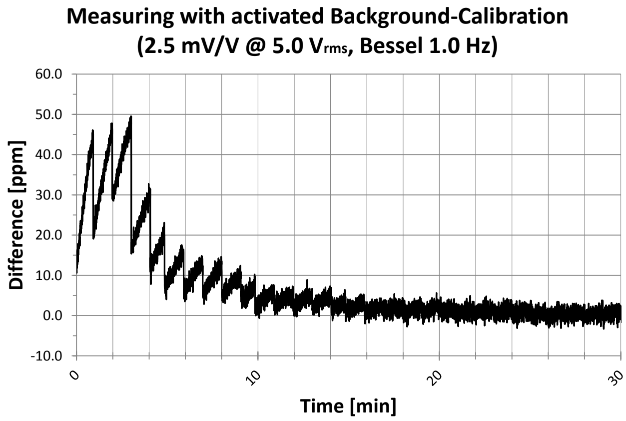

Figure 4: QuantumX MX238B warm-up phase

After a warm-up phase of one hour, a static measuring is started. Figure 5 shows a short-term measuring for 24 h with a BN100A and an MX238B. The measuring is extremely stable and there is no disturbance through the background-calibration visible. There is also no influence of the change in the ambient temperature visible (in this measurement approximately 4 K).

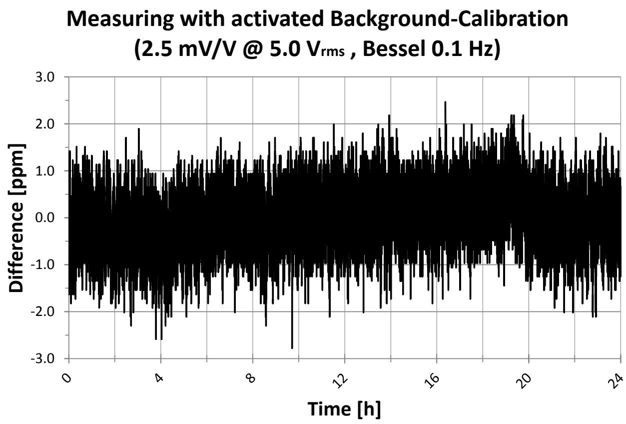

Figure 5: QuantumX MX238B short-term measuring over 24 h

The gap to the previous inductive divider can thus be closed almost completely. As the short-term stability over 24 h is excellent, we suppose that the long-term stability will be also very good. However for this just introduced device, there are no long-term measurements available so far. We will monitor the long-term stability in the same way, as we perform on a measuring chain consisting out of BN100 and DMP39 for the inductive divider for now approximately 36 years.

4. LINEARITY AT THE PHYSICAL LIMIT

Amplifiers for strain gauge measurements like the new QuantumX MX238B have to be verified periodically. Therefore these amplifiers are calibrated with a strain gauge bridge calibration standard. These bridge calibration standards are simulating defined voltage ratios as reference values in mV/V. For the MX238B with a carrier frequency of 225 Hz the worldwide most accurate bridge simulator is the BN100A from HBM [14].

A classic bridge calibration standard simulates defined voltage ratio as reference values and has therefore to be calibrated before the measurement for each used reference value. The expanded uncertainty for this calibration is typical 0.00001 mV/V at the level of international metrological institutes (NMI) for a value of 2.5 mV/V and an excitation voltage of 5 V_{rms} [15]. For further dissemination in calibration laboratory level the expanded uncertainty increases typically to 0.00002 mV/V. For the measurement of the linearity error of modern high precision amplifiers like the DMP41 or the new MX238B with an excellent linearity, this measuring uncertainty is insufficient. In this case the bridge calibration standard has the major uncertainty. For measuring the linearity of high precision amplifiers another solution is evaluated therefore.

At the IMEKO World Conference in Prague in 2015 an alternative improved calibration procedure for strain gauge amplifiers was shown by the Slovenian National Building and Civil Engineering Institute (ZAG) [16]. This publication shows a way to measure the linearity of strain gauge amplifiers, without the necessity of calibrating the simulator first. The uncertainty is nearly complete independent from the simulator and depends only on the stability and reproducibility of the measured values by the amplifier.

The published method is applicable for indicating instruments where it is possible to combine single unknown artefacts with a negligible error over time. If only the linearity of an amplifier should be measured, not even a single artefact has to be calibrated before. To characterize the linearity of our new high precision amplifier we were developing in cooperation with the ZAG such a simulator to evaluate this measuring principal and it's uncertainty.

The calibration method is quite simple. Quantities of stable artefacts X_n, in our case tabs of a resistive divider which provide mV/V signals, are measured as $A(X_n)$ in any possible combinations (not all routings are technically possible). From the difference of the measured values of possible combinations and calculated results from the single artefacts the linearity error $\xi(X_n)$ of the system can be estimated (1).

$$A(X_1 + X_2) = A(X_1) + A(X_2) + \xi(X_1 + X_2) \qquad (1)$$

For the case that the amplifier has an ideal linear behavior ξ is equal to zero, because the sum of the single measured artefacts has to be equal to the measured sum of the artefacts. If ξ is not equal to zero, the used amplifier has a non-linearity. Important is, that the single artefacts have not to be calibrated before for this measurement. The artefacts have only to stay stable for the duration of the measurement and must be combinable without error. The demands to the classic bridge calibration standards (BN100A for the MX238B) are much higher. A bridge calibration standard has to be stable from the point of calibration at the NMI to the point of the measurements of the amplifier with a typical recalibration periods of a year.

Figure 6 shows a simplified circuit diagram of the first linearity test unit at HBM, called "LinChecker". It is quite similar to the simulator designed by the Slovenian National Building and Civil Engineering Institute (ZAG). The "LinChecker" uses a standard resistive voltage divider with a very low temperature coefficient.

Over tabs different voltage drops over single or different combinations of resistors can be fed to an amplifier. Different polarities are also possible. The shown output network keeps the output impedance constant for all tabs and simulates in all combinations a transducer with a constant impedance of 350 Ω [17]. The current of all resistors is also constant during the measurements, there will be no influence on the current by changing the tabs. The divider circuit is completely passive, only resistors with a low temperature coefficient and mechanical switches (relays) are used.

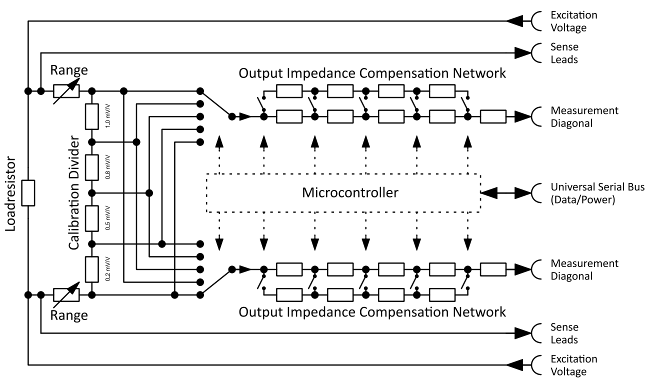

Figure 6: Simplified circuit diagram of the linearity test unit "LinChecker"

The switches are remote controlled over USB. A fully automated measuring process is realized in a windows application in C#/.NET. The benefit is to have the possibility to perform many repeatable measurements under different conditions to evaluate the behavior of this new measuring procedure. Depending on the quantity of combinations and the selected filter a complete measurement takes around one hour. To perform many measurements to average the results, a remote controlled device is therefore essential.

By using the method of least squares a fit can estimate the linearity of the amplifier. The least-square fit function type depends on the characteristic of the typical linearity of the amplifier. The linearity correction fitting is critical and a wrong fitting function will increase the uncertainty. A cubic correction $\Delta a(x)$ with A, B, C and D will result to a sufficient regression estimation (typical linearity error of an amplifier) (2).

$$\Delta a(x) = Ax^3 + Bx^2 + Cx + D \qquad (2)$$

The number of unknown variables (A, B, C and D) is reduced by approximating the error by a simple function and therefore the system will be over determined, because of the high quantity of combinations (28 possible combinations).

For the calculation of the measurement uncertainty method "Type A" according to GUM (Guide to the Expression of Uncertainty in Measurement by the Bureau International des Poids et Mesures (BIPM)) is used [18]. The measuring uncertainty u can be calculated out of N measurements with the measured values $a_{i,\mathrm{meas}}$, the calculated sum value $a_{i,\mathrm{calc}}$ out of the single artefacts, the fitted linearity error of the amplifier $\Delta a(x)$, the number n of fitted parameters in the equation of the linearity and the expansion factor $k = 2$ (3) [19].

The parameter n is equal to four, because of the chosen cubic fit with four unknown parameters for the linearity error. A statistical weight has not to be included in the uncertainties, because the uncertainties of the readings are independent of the amplitude and therefore similar over the complete rang.

$$u = k\sqrt{\frac{1}{N-n}\sum_{i=1}^{N}\left(a_{i,\mathrm{meas}} + \Delta a\left(a_{i,\mathrm{calc}}\right) - a_{i,\mathrm{calc}}\right)^2} \qquad (3)$$

To confirm the combinatorial method the linearity error and measuring uncertainty are compared to the classical method with a bridge calibration standard. Figure 7 shows a calibration of the MX238B with a BN100A, which is traced to the German NMI (Physikalisch Technische Bundesanstalt PTB). The expanded uncertainty of the NMI of 4 ppm is shown for each value. Actually the uncertainty has to be additionally increased with the factor of around two for laboratory measurements. A further increase of the measurement uncertainty was not taken into account.

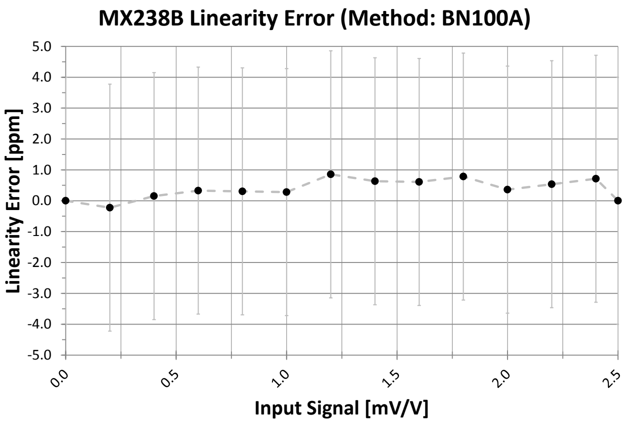

Figure 7: Linearity error of the MX238B using BN100A

Figure 8 shows now the linearity error of the same amplifier MX238B using the new combinatorial method. The low distribution of the measured values around the fitted linearity error of the amplifier gives a low expanded measurement uncertainty of only 0.9 ppm. The measurement is randomly performed and repeated ten times. The measurement uncertainty for is measurement is reduced by the factor of 4.4 in respect to the NMI without the need of any calibration for the "LinChecker" bridge simulator. Both ways to measure the linearity error match very well, expect the improved measurement uncertainty.

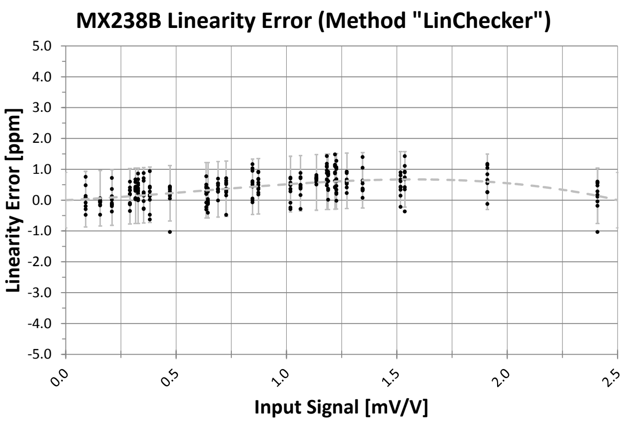

Figure 8: Linearity error of the MX238B using "LinChecker"

The measuring with the combinatorial method is repeated in this case ten times after each other and averaged by using the cubic fit. Because of the long measuring time of several hours, a possible drift of the amplifier is compensated. For every single linearity measuring a linear fit is used in addition to calculate the linearity error independent of the actual amplifier gain and offset.

Figure 9 shows again the classic measurement procedure with the same bridge calibration standard BN100A and a DMP41. The linearity error of the DMP41 is nearly equal to the measurement of the MX238B, but now with an opposite sign. The expanded measurement uncertainty is the same like for the MX238B, because the uncertainty of the bridge calibration standard is not affected by the used amplifier.

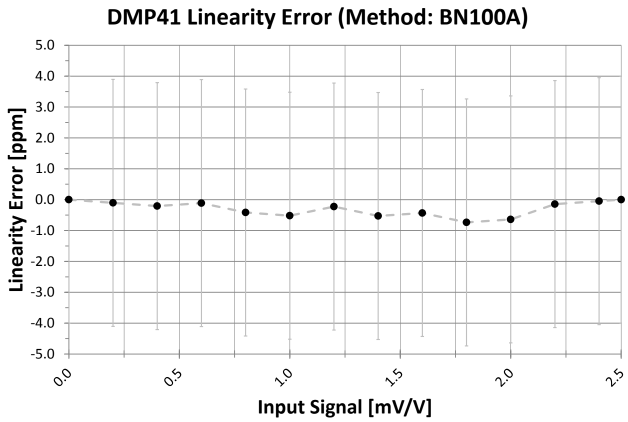

Figure 9: Linearity error of the DMP41 using BN100A

With this inverted linearity error of the DMP41 a corresponding proof exists, that the linearity error is not a part of the stimulus. Figure 10 shows this linearity error of the DMP41 with the combinatorial method. The most limiting factor of the combinatorial method is the quality and stability of the amplifier itself. The shown measurement with the DMP41 has therefore now a significant lower expanded uncertainty of only 0.5 ppm (reduction of 8).

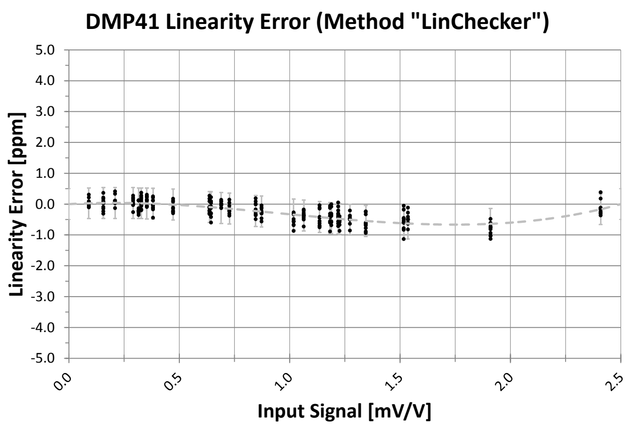

Figure 10: Linearity error of the DMP41 using "LinChecker"

Only with this low uncertainty of the combinatorial method the very low linearity of high precision strain gauge amplifiers like the DMP41 and MX238 can be proven. The uncertainty of the classic method is not sufficient for linearity measurements. The combinatorial approach is generally failsafe due to the high redundancy in the measurements. Large errors will usually lead to an unexpectedly high measurement uncertainty. Therefore also a randomized measuring sequence is chosen, because otherwise in an ascending or descending sequence a drift of the single artefact values will lead to an in reality not existing linearity error. Small errors in the combinations will lead to a higher uncertainty. To characterize the performance of the amplifier in addition to the linearity the absolute error is very important. Therefore the combinatorial method can be combined with the classic bridge calibration standard. The benefit of the combination of these two measurements is shown in the publication of the ZAG.

5. CONCLUSION

In general the market requests more accuracy for measured signals. HBM adds therefore with the new compact full bridge amplifier MX238B a high precision module into the universal DAQ system QuantumX, as a DAQ system solution for all test and measurements tasks. The analog parameters could be further increased related to the predecessors of the "…38" series. Features of the high end amplifier DMP41 were adapted now to the QuantumX system (e.g. patented background-calibration).

For the first time of the "…38" series the internal reference was changed from an inductive to a resistive divider technique. The now used resistive divider with active temperature compensation can perform the requested tasks with sufficient accuracy. However, for the highest precision amplifier, build to measure at the physical limit, the legendary inductive divider of the DMP41 is still unavoidable. The factory adjustment and later on the calibration of the new amplifier MX238B stays the same and is performed with the bridge calibration standard BN100A.

With the modern and state of the art digital signal processing in the FPGA/DSP, it is possible to realize powerful digital filtering to get a much higher bandwidth for the MX238B. Figure 11 shows the implemented Bessel filters. The maximum bandwidth of 50 Hz is defined by the -3 dB cut-off frequency and is selectable for the Bessel and Butterworth filter. The limitation of the maximum bandwidth is off course the carrier frequency technology.

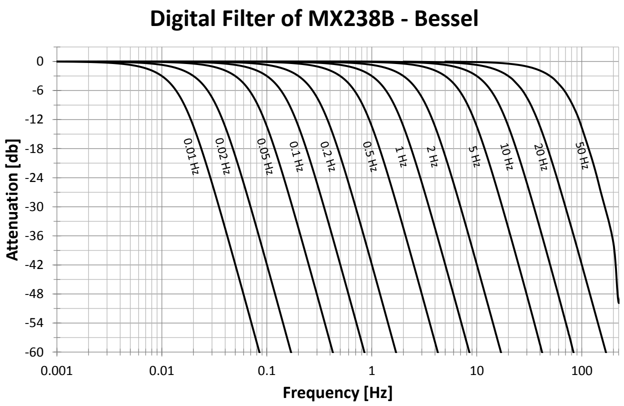

Figure 11: Bessel filter of the QuantumX MX238B

Both channels of the MX238B measure among each other simultaneously and can be also synchronized with all other modules of the QuantumX family (Precision Time Protocol PTPv2, Firewire IEEE1394b). This makes it now possible to combine the legendary 225 Hz precision measurement technology together with many other physical measuring quantities in one single DAQ system.

For instance the QuantumX MX840B can measure up to 15 different transducer technologies. Additional the QuantumX MX410B is a suitable amplifier for dynamic calibration purpose. The introduction of the MX238B also offers the ability to process and display multiple signals of very different accuracy-bandwidth combinations at the same time and closes the gap by using the variety of the complete QuantumX family. In the appendix a short overview of the complete QuantumX family from HBM is shown and represents the entire variety and potential of this data acquisition system.

With the shown combinatorically method it is now possible to determine the linearity error of high precision amplifiers for strain gauge measurements, because of the much lower uncertainty. For only measuring the linearity not even any calibration is needed.

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APPENDIX: OVERVIEW QUANTUMX FAMILY

- **MX879B**
  32 channel multi I/O module (addition 8 analog outputs), real-time response to measurement results

- **MX878B**
  8-channel analog outputs for durability testing

- **MX238B**
  2-channel highly precise measuring amplifier for force, torque, pressure measurement, meets the high standards of precision in calibration tasks and laboratory

- **MX403B**
  4-channel amplifier for voltages up to 1 000 V, compliance IEC 61010 measuring instrument standard

- **MX430B**
  4-channel precise measuring amplifier for force, torque, pressure measurement

- **MX410B**
  4-channel highly dynamic universal amplifier (100 kS/sec per channel, 40 kHz bandwidth)

- **MX471B**
  4-channel CANbus module with high-speed CAN

- **MX440B**
  8-channel universal amplifier for cost-effective entry in professional measurement acquisition, 15 different sensor and transducer types

- **MX460B**
  4-chanel dynamic and precise pulse and frequency measurement module

- **MX809B**
  8-channel reliable measurement of temperatures or voltages at a high potential, compliance IEC 61010 measuring instrument standard

- **MX840B**
  8-channel universal amplifier of HBM's QuantumX data acquisition system, 15 different sensor and transducer types

- **MX1609TB/MX1609KB**
  16-channel thermocouple modules, including automatic transducer identification

- **MX1601B**
  16-channel universal amplifier for standard signal, attractive price per channel

- **MX1615B/MX1616B**
  16-channel amplifier suitable for strain gauge bridges and experimental stress analysis, unrivaled channel density

- **CX27B**
  Real-time data transmission with EtherCAT fieldbus standard

- **CX22B/CX22B-W**
  Stand-alone data recorder, analyzes and stores acquired measurement.

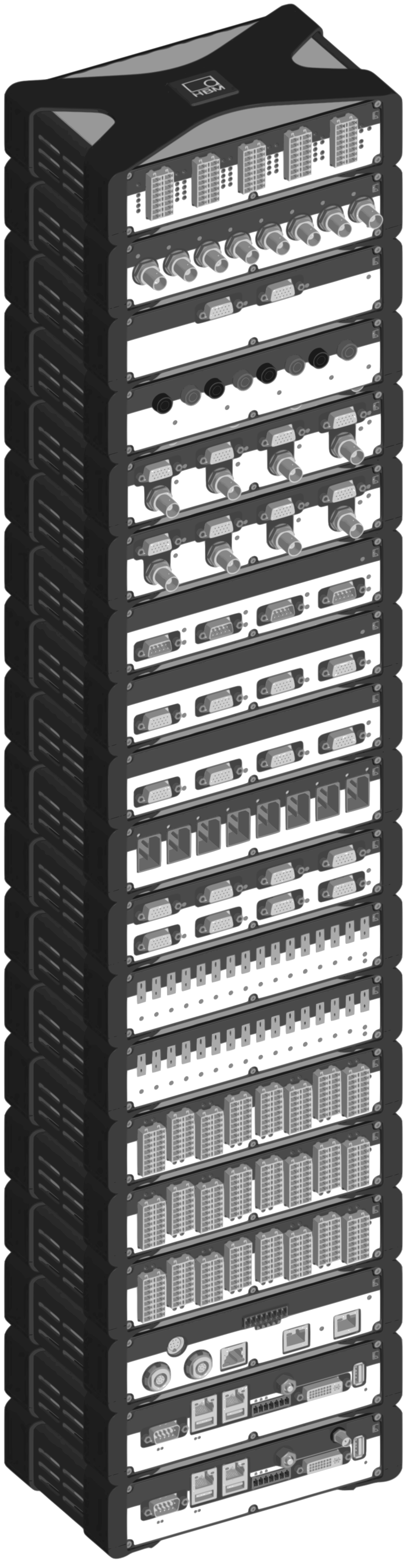

Figure 12: Complete QuantumX family (2017)