Design and performance evaluation of smart vibration sensor for industrial applications with built-in MEMS accelerometers

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***Abstract*—Paper deals with design and experimental evaluation of performance of a smart vibration sensor for industrial applications based on two built-in MEMS accelerometers and signal pre-processing using a low power microcontroller. Sensor contains one single axis low noise broadband MEMS accelerometer with analog output and one tri-axial low noise MEMS accelerometer with a narrower frequency range and digital SPI interface. Data from both MEMS devices are processed using TI MSP430 microcontroller. The smart sensor has digital output interface, which allows easier connection to the subsequent data processing system and ensures higher immunity to electro-magnetic interference. The smart sensor is intended for measurements of overall vibration velocity in frequency range defined in ISO standard up to 1 kHz while applications above ISO frequency range up to 10 kHz for acceleration measurement used in bearing diagnostics are also expected. Performance parameters of each sensing device built-in inside the common housing have been evaluated in two steps. The first step dealt with precise measurement of metrological parameters of each device including nominal value of vibration sensitivity in the main axis, its frequency dependence and transverse sensitivity with cross-axial excitation. These measurements were performed on the accredited calibration system SPEKTRA CS18, which offers outstanding measurement uncertainty, and achieved results confirmed the correctness of the design of the whole system and its critical parts. The second step was intended for evaluation of the sensor in practical application, where comparison between both internal sensing systems and external reference accelerometer was performed on test stand with industrial actuators to perform real vibration measurement task. Also this step indicated suitability of the designed sensor for these range of applications. Further and more detailed evaluation is expected in the near future when complete signal processing and autodiagnostic features will be implemented in the system thanks to utilization of two separated sensing elements.**

Keywords*—MEMS accelerometers, vibration sensing, digital MEMS, low noise MEMS.

I. Introduction

Accelerometers are the most used sensors in the vibration based condition monitoring in the present days. Electrodynamic and eddy current sensors are used in the minor occurrence. There is a lot of accelerometer types at the industrial field, starting with single axis analog output sensors (with IEPE or charge output), through sensors commonly called transmitters (sensors with build-in electronics for simple signal processing, e.g. RMS value calculation) and ending by smart sensors with digital output (mainly RS-485, versions of industrial Ethernet, CAN bus etc.) with a small part of intelligence inside the sensor. The last mentioned types are capable to do any advanced methods for vibrodiagnostics, such as frequency analysis of the time signal, trending of the values or any other features. All industrial accelerometers consists of one sensing element, based on piezo-electrical principal. This fact leads to very low operational safety because of no redundance of the accelerometers and only one measuring direction, mostly in the rotational axis of the sensor, or in the direction of the mounting stud. The very common and mostly used case for vibration sensing in the industrial environment is only a simple, single axis, accelerometer with piezo-electrical sensing element and analog IEPE output.

Micro Electro Mechanical Systems (MEMS) accelerometers take place at the market of vibration sensing in the last few years. Before this, MEMS accelerometers were used only at the consumer electronics for non critical tasks (toys, mobile phones, laptops etc.) or at the high signal applications, such as car airbags control electronics, where their parameters were sufficient for this purpose. Their main disadvantage was relatively high internal noise, which made them unuseful for sensitive applications, like vibrodiagnostics.

Our Smart Vibration Sensors consists of two independent sensing elements - MEMS accelerometers. Both elements are from the low-noise category. One is uniaxial, with analog output and frequency range up to 11 kHz. Second element is triaxial, with digital SPI output interface and frequency range up to 1 kHz. It also contains temperature measuring element. Signals from both accelerometers are processed by small and simple RISC processor MSP430i2041 [1] produced by Texas Instruments. This microcontroller processes signals from the accelerometers and transfers values out through RS485 interface at the speed of 3.6 MBd to supervised system. Currently, there is no advanced signal processing inside the processor due to its limited performance (see later). Complete sensor can be built in the small aluminum case of the dimensions roughly comparable to the small industrial IEPE accelerometers (dimensions of the cylinder are approx. ϕ 15 mm and height 25 mm).

II. Used MEMS accelerometers

There are a lot of MEMS accelerometers at the market in the present days. There are sensing elements with different:

- axes of sensitivity (one axis or three axes),
- frequency range (or self resonance of the sensor) - from hundreds of Hz up to small tens of kHz,

- dynamic range (from e.g. 2 g up to tens of g),
- noise density
- package size

Crucial parameter for application in Smart Vibration Sensor is noise density of the accelerometer. There are a lot of types with high noise density (e.g. around 100 $\mu g/\sqrt{Hz}$) on the market, which are not suitable for small signals measurement, mainly in the ISO band (vibration velocity in the frequency range 10 Hz . . . 1 kHz defined by ISO10816 standard). But there are several types, which are called low-noise (or ultra low-noise) accelerometers with the noise density of approx. 30 $\mu g/\sqrt{Hz}$. Key parameters of the accelerometers can be seen in the Tab. I. There are only low noise (ADXL355, ADXL1002) and very low noise (VS1002) accelerometers listed in the table and compared to the standard piezo type (PCB356B18).

Table I
PIEZO AND MEMS ACCELEROMETERS COMPARISON.

	PCB356B18	ADXL355	ADXL1002	VS1002
Range [g]	±5	±2/±8	±50	±2
Axis [-]	3	3	1	1
Res. [kHz]	20	2.4	21	1.2
Sens. [mV/g]	1000	400/100[a]	40	1350
Output [-]	IEPE	SPI	Voltage	Voltage
Temp. [°C]	-30/+80	-40/+125	-40/+125	-55/+125
Noise [$\mu g/\sqrt{Hz}$]	1.2	25	25	7
Size [mm]	20x20x20	6x6x2	5x5x2	9x9x4

[a]Dependent on the selected range.

As it was mentioned above, the major parameter for selection of the accelerometers is its noise density. There can be seen from Tab. I roughly three groups of typical accelerometers from the noise point of view. The first group, with the lowest noise around 1 $\mu g/\sqrt{Hz}$, is group consisting of standard, piezo, accelerometer. The second group is the set of low-noise accelerometers, with own noise of 25 $\mu g/\sqrt{Hz}$. Accelerometers from this group have been selected as a sensing elements for Smart Vibration Sensor. The last group with noise level of approx. 7 $\mu g/\sqrt{Hz}$, consists of ultra low-noise MEMS accelerometer. Their noise density can be seen as very suitable for measuring applications and also very comparable to the standard piezo accelerometers. But the previous research shown, that the main advantage of ultra low-noise MEMS is present in case when low frequency signals are measured, especially around (or bellow) 1 Hz. But their price is almost 5 times higher than low-noise accelerometers.

Finally, there are two independent MEMS accelerometers used in the Smart Vibration Sensor. Main reason for this is **redundancy of the sensing elements**. Signal from both accelerometers is compared in appropriate axis and in case of any higher deviation, supervised system can decide, how to deal with it. This can be used as a very important information in the vibrodiagnostic-sensitive application or as an informational parameter in vibration non-critical application. The second reason for using two accelerometers is **a number of axes**. One, primary sensor, is uniaxial, with analog output and higher frequency range (up to 11 kHz) ADXL1002. Secondary sensor is triaxial, with digital output and lower frequency range (up to 1 kHz) ADXL355. In fact, user has very detailed information about machine vibration signal in the wide frequency range in main measurement direction (e.g. vertical) and has also additional overview information about two other directions (e.g. horizontal and axial). Thanks to the triaxial measurement, a supervised system has detailed information about sensor yaw and can recalculate randomly turned sensing axes of the sensor to the orthogonal coordinate system related to the measured machine (or related to the Earth).

III. PRACTICAL DESIGN OF SMART VIBRATION SENSOR

Whole device is a combination of analog circuits, digital parts and microcontroler. Following chapters will shortly describe electrical connection, embedded software, needed adjustment of the sensor and also simple supervised system.

A. HW design

There can be seen block schematics of the Smart Vibration Sensor in the Fig.1.

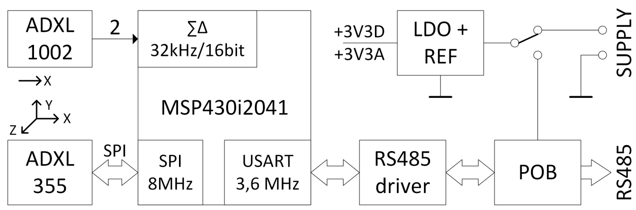

Figure 1. Block schematics of the Smart Vibration Sensor

The sensor consists of the above mentioned accelerometers, the simple microcontroller (MCU) MSP430i2041, a RS485 bus driver, possibility of Power Over Bus (POB) feature and other necessary components needed for sufficient function of the complete sensor.

1) Digital accelerometer ADXL355 [2] - is a triaxial accelerometer with the digital SPI or I2C interface (SPI is used in our case). It also consists of a temperature sensor. Output is 20 bits for acceleration data and 12 bits for temperature measurement. Its dynamic range can be selected by initial SPI commands (±2/4/8 g) as well as measuring frequency range (max. up to 1 kHz). The accelerometer has also other digital interface signals (INT1, INT2 and DRDY), which can be used for additional communication with microcontroller. The device has internal reference circuits, thus no special requirements for supply voltage are needed.
2) Analog accelerometer ADXL1002 [3]- is an uniaxial accelerometer with an analog interface. Its dynamic range is ±50 g, sensitivity 26 mV/g (for 3.3 V supply voltage) and dynamic range up to 11 kHz. The accelerometer requires a stable and noise free power source, thus simple LC filter is applied at the power supply pin.
Signal from the accelerometer is split into two inputs an internal analog to digital converter in MCU. The first branch has gain of 0.3 and MCU is able to measure the whole dynamic range of the accelerometer using this input. The second branch has unity gain set by the hardware, but the second pin of the differential

input of the converter is connected to the half of supply voltage. Thanks to this, DC bias voltage level from accelerometer's output is subtracted from the measuring signal and only dynamic changes are measured. There is a programmable gain amplifier with amplification factor of 16 inserted in the signal chain, thus the smaller signals (approx. up to 2 g) can be measured with the higher accuracy. The MCU makes a decision, which converter input will be selected according to the level of the input signal and to prevent the saturation of converter.

3) MCU MSP430i2041 consists of a powerful 16-bit RISC CPU, a power-management module (PMM) with a built-in voltage reference and a voltage monitor, four 24-bit sigma-delta ADCs, a temperature sensor, a 16-bit hardware multiplier, two 16-bit timers, one eUSCI-A module and one eUSCI-B module, a watchdog timer (WDT), and 16 I/O pins [1]. The internal oscillator is used for clock generation and the internal analog reference as a base for A/D conversion.. Both of them have to be adjusted in manufacturing process of the Smart Vibration Sensor. The MCU provides:
   - communication with the digital accelerometer via SPI bus at 8 MHz data rate,
   - analog to digital conversion using internal $\Sigma - \Delta$ 24 bit converter (with ENOB of 16 bits at a sample rate of 32 kSa) - for details see [1],
   - measurement of the internal voltage of the whole system,
   - simple signal processing and data frame preparation,
   - transfer of complete message frame out of the processor in the format suitable for RS485 driver,
   - timing of the ADXL355 digital accelerometer to ensure time synchronization with the MCU and valid data reading
4) RS485 driver - commercial device SN65HVD75 is used as a RS485 driver. It simply converts USART compatible interface to RS485 half duplex interface. There is a version with 20 Mbps data rate used. The sensor has two possibilities how to connect power supply to it. The first option (currently used) is to connect voltage source +5 V/10 mA directly to the supply rails of the sensor. The sensor is thus connected to the supervised system by four wires (RS485+, RS485-, Vcc, GND). The second option is to use Power Over Bus circuits at both sides (power injector and receiver). In that case sensor is connected only by two wires serving as data and power lines together. This feature is not used in current sensor design due to the need of relatively high values of inductors, which will not fit into the sensor housing.
5) Other components - other needed components for sufficient function, such as blocking capacitors, an EMI filter, POB circuits, bus terminators etc. are used in the schematic. Their functionality is obvious thus they don't need any detailed explanation.

All components are with industrial temperature range -40°C up to +125°C, so the sensor can be used within industrial environment conditions. Also the built-in sensor measures internal temperature and the MCU transmits this information to the supervised system. A receiver can e.g. ignore vibration values in case of the sensor temperature is higher than +125°C and prevent false alarm based on incorrect vibration value due to exceeded temperature of the sensor.

Photography of the printed circuit board of the sensor prototype can be seen in Fig. 2.

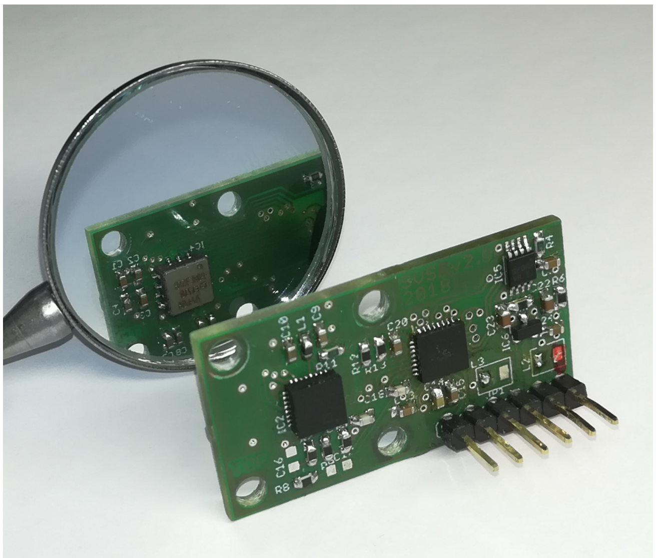

Figure 2. Photography of the Smart Vibration Sensor PCB.

B. Embedded software design

Embedded software for the internal processor MSP430i2041 is written in C language with small parts of code written in assembler. A complete project is made in Code Composer Studio provided by Texas Instruments. The flowchart of initial phase of software can be seen in the Fig. 3. There are initialized all necessary peripheral modules immediately after power up or reset. Mainly GPIOs, a timer for generating interrupt with the period of 31.25 μs, UCSI peripherals as the SPI (UCSI B as SPI master, with baud rate 8 MHz) and the serial bus (UCSI A as USART gate, in format 8N1 at bus speed 3.686 MHz), analog to digital converter (mainly its internal

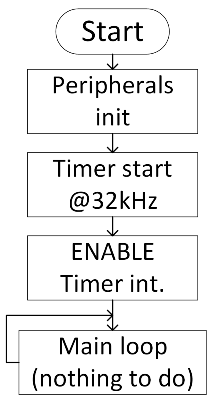

Figure 3. Flowchart of embedded software of Smart Vibration Sensor.

reference, gain of the inputs, oversampling ratio 32x) and finally both accelerometers (mainly dynamic and frequency range and chip enable). As soon as all necessary peripherals are initialized, the timer is started and interrupt requests from the timer are enabled. The processor runs in the infinite loop afterwards and waits for the interrupt request from the timer each 31.25 μs.

This time has been selected mainly from the request of sampling frequency of the A/D converter (32 kSa/s) and for necessity of measurement of the analog signal from the wideband accelerometer in the frequency range at least up to 11 kHz. Also the ADXL355 output data rate suits this speed - the MCU reads out ADXL355 SPI registers with frequency of 4 kHz (what is maximal output data rate of the ADXL355 sensor). A reading from the sensor is done in four cycles (three acceleration data and one temperature data). A structure of the interrupt service routine (ISR) can be seen in Fig. 4.

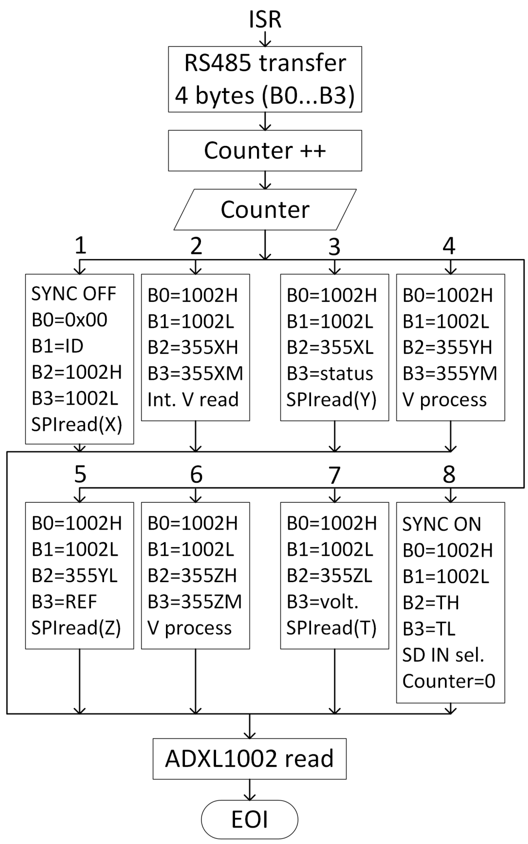

Figure 4. Flowchart of the interrupt service routine.

The ISR of the timer is the most important and the most time critical part of the code. All necessary communication is done during this ISR. Firstly four bytes are transferred via RS485 (B0 ... B3). the transfer is in 8N1 format at baud rate of 3.686 MHz. As soon as the RS485 transfer is done, preparation of the bytes B0...B3 for the next interrupt starts. Depending on the value of the internal counter, appropriate action is performed. Description of the follow-up actions is:

- SYNC ON (OFF) - start (end) of synchronization pulse to the ADXL355. This pulse provides external time synchronization for ADXL355 accelerometer, because it gives the output values based on its internal time base, which does not have to be the same as time at MCU. The ADXL355 is switched to the mode of external synchronization and as soon as it receives synchro pulse, it provides valid acceleration data (with the defined delay). For details please see datasheet [2].
- B0 ... B3 - bytes, which are transferred through the RS485 bus.
- ID - ID of the sensor combining its number and the software version number
- 1002H, 1002L - high (H) or low (L) byte of ADXL1002 acceleration data obtained from the analog to digital converter SD24.
- SPIread(X) - the ADXL355 reading procedure through the SPI bus. The letter in the parenthesis shows the value to be red (acceleration data X, Y, Z and temperature data T).
- 355xy - acceleration data from ADXL355 red in a previous cycle. Letter "x" means axis (X/Y/Z) and letter "y" means byte number in complete 20 bits information (H = high byte, M = middle byte and L = low byte).
- Int. V read - analog to digital conversion of internal voltage needed for later re-calculation of other necessary values. Voltage is then processed in the next steps (V process) and transferred via RS485 in the seventh step (B3=volt.).
- REF - the real reference value of an analog to digital converter transfer for later recalculations.
- TH (TL) - a high (low) byte of temperature measured by the ADXL355
- SD IN sel. - a selection algorithm of ADC inputs for the ADXL1002. A selected input is transferred in the byte status in the B3 in third step.

All procedures in the ISR are very time critical and were tuned to fit the time space for individual operations. It is necessary to keep the sampling rate for the analog output sensor (32 kHz) as well as the readout speed from the digital sensor ADXL355. Any deviation from the periodic time increases spectral noise of the system and leads to missed data when processed by the supervised system.

C. Adjustment of the sensor

A lot of parameters inside the sensor are sensitive to supply voltage change (e.g. asensitivity of the ADXL1002 sensor) or have its own tolerance band (the built-in reference voltage of ADC or a clock setting resistor inside the MCU etc.), thus it is necessary to adjust the sensor immediately after PCB assembly. Following parameters need to be adjusted:

- Analog to digital converter reference voltage - needs to be measured at the REF pin of MCU and inserted into embedded software as an adjustment constant. The reference voltage is transferred to the supervised system for correct recalculations of all values measured by analog to digital converter inside MCU, such as two accelerations from the ADXL1002 and the internal voltage of the system.
- Internal oscillator of MCU - needs to be measured and adjusted to the exact value by writing an appropriate constant to the register of the MCU. A manufacturer

of the chip also provides easier solution. He writes the exact value during manufacturing process to the internal memory of the chip so user can only read out the correction value and use it. The right value is very important for complete system timing, such as a clock speed of SPI bus, a data speed of the RS485 data (necessary for asynchronous transfer to the master device) and for the time synchronization between the MCU and the ADXL355.

- Sensitivities of the elements - because of manufacturing tolerances of the parameters and different supply voltages between sensors, sensitivities of each element should be also checked. This procedure can be done by any specialized calibration equipment, such as the SPEKTRA CS18 calibration system, as described bellow.

D. *Supervised system*

The simple supervised system for data processing from the sensor has been developed yet. It has been done in LabVIEW environment, using compactRIO (cRIO) device with interface for RS485 data reception. The system is capable to receive data at speed of up to 3.686 MHz, decode individual bytes of the message frame, synchronize a complete frame and decode all the information provided by the Smart Vibration Sensor (see section III-B Embedded software design). A captured data stream from the cRIO is sent to the PC application via Ethernet and processed and displayed to user. Most important things are show as numbers (e.g. temperature, ISO velocity from both sensors (ADXL1002, ADXL355X, ADXL355Y and ADXL355Z), internal voltage and reference voltage) or as charts (time signals from both sensors, frequency spectrum from both sensors in acceleration and velocity representation). All bellow mentioned results were measured using this supervised application.

IV. Precise measurement of metrological parameters

Precise measurement of metrological parameters of each sensing element including nominal value of vibration sensitivity in a main axis, its frequency dependence and transverse sensitivity with cross-axial excitation were measured on the sensor prototype using a specialized calibration system SPEKTRA CS18. This system is used for a primary and a secondary calibration of vibration sensors and offers outstanding measurement uncertainty. The device under test (DUT) during measuring process can be seen in Fig. 5. Frequency responses in all three axes were measured in the first step. Measurement was done for constant acceleration and because ADXL355 was set to range ±2 g, acceleration of 0.5 g was selected. Frequency range of the measured sensitivity was selected from 5 Hz and the bandwidth was wider for ADXL1002 (up to 20 kHz) and narrower for ADXL355 (up to 5 kHz) because of their specified frequency ranges and resonances. A tightening torque for sensor mounting to a shaker armature was 2 Nm. The best conditions were available for measurement in Z axis (the results confirm this fact), because measurement sensor was placed just in the middle of the shaker, in the

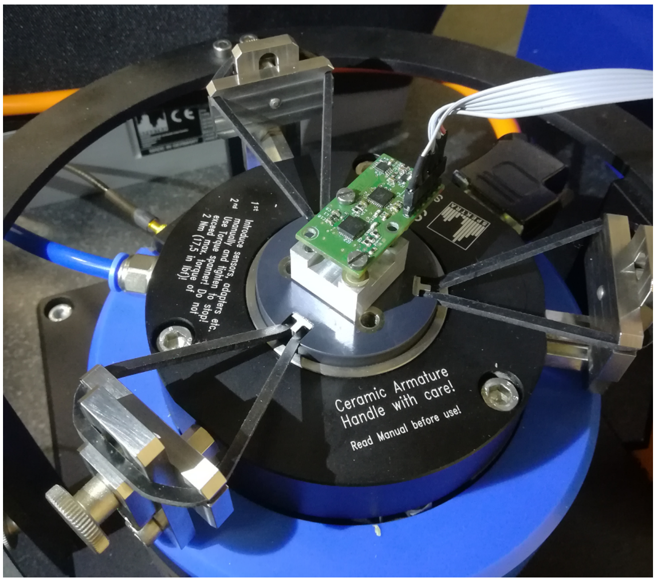

Figure 5. Photo of the SVS during tests on SPEKTRA system (measurement in Z axis is shown).

axis of vibration excitation. Measuring for other axes was not ideal - measured sensing element was not in the axis of the shaker thanks to the shape and dimensions of the mounting holder. The distance from the axis of the shaker and measuring element was approx. 20 mm. This fact can leads to not-ideal shape of the frequency response curve. All frequency responses can be seen in the Figures 6 - 9.

A resonant frequency of the ADXL1002 sensor is at

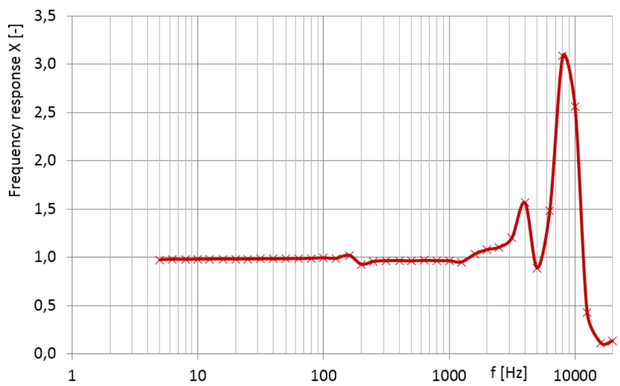

Figure 6. Frequency response of ADXL1002 sensor.

21 kHz, but there can be seen a resonant frequency peak of approx. 8 kHz in Fig. 6. This peak is not a natural frequency of the sensor, but the resonant frequency of the sensor mounting to the shaker.

Frequency responses of the ADXL355 sensor can be seen in Fig. 7 - 9. As mentioned above, a Z axis response is the smoothest one from all measured axes. There can be seen no resonance for the ADXL355 sensor, even if one of the measuring point was relatively close (2.5 kHz) to the value defined by manufacturer (2.4 kHz, see datasheet [2]). This should be caused possibly by internal output filter with 1 kHz cut off frequency.

A transverse sensitivity of the device was also measured.

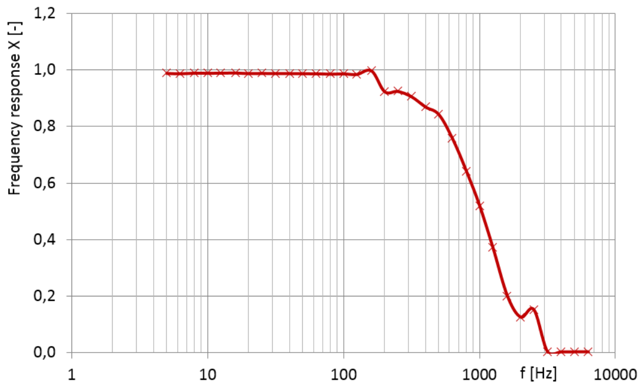

Figure 7. Frequency response of ADXL355 sensor (X axis).

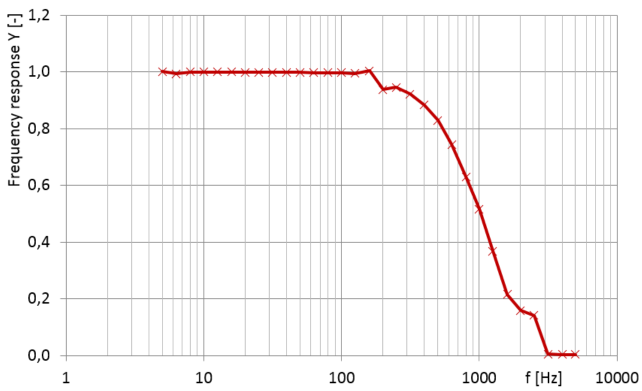

Figure 8. Frequency response of ADXL355 sensor (Y axis).

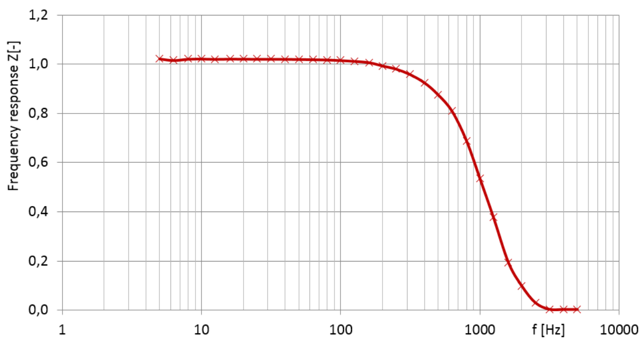

Figure 9. Frequency response of ADXL355 sensor (Z axis).

It was done at fixed frequency of 80 Hz and for acceleration of 0.5 g. Results can be seen in the Tab. II.

All values can be considered as a good results, even if e.g.

Table II
CROSSAXIAL SENSITIVITY OF SMART VIBRATION SENSOR.

Excitation axis	X	Y	Z
ADXL1002	-	2.40 %	1.00 %
ADXL355 X	-	0.87 %	2.50 %
ADXL355 Y	0.61 %	-	0.58 %
ADXL355 Z	2.87 %	1.07 %	-

cross axis sensitivity defined by manufacturer of ADXL355 is 1 %. Any higher values can be caused by non ideal measuring conditions, mainly effect of fastening adapter between sensor and shaker should be considered. These values are expected to be lower during measurement of the final housing of the sensor.

All measured parameters, such as frequency response, sensitivities and cross axis sensitivity, are considered as a very positive and successful values, and with a potential to be a little better for finally packed version of the sensor thereafter.

V. SENSOR EVALUATION IN PRACTICAL APPLICATIONS.

Not only measurement in the laboratory ideal conditions has been carried out. The tests on real machines (stepper actuators test bench) have been done to check the sensor ability to measure on real industrial platform and for analysis of real issues. Measurement was compared to the data acquired with the industrial piezoelectric sensor PCB352C03 for the most typical cases. A comparison was performed based on the overall effective velocity value in the ISO frequency range in the first phase and results in very good conformity. A comparison in the frequency domain has been done in the second phase and these results are discussed in the following section.

A. Test bench description

A test bench consists of two stepper actuators from TG-Drives company. There were two motors assembled on one common aluminum frame and their shafts were mechanically coupled together using a bellows clutch. The original idea was that one motor will serve as a propulsion and the second one as a load with breaking effect. But practical measurement showed not so much interesting results in spectral domain, so practical tests were done with only one actuator, but with a mounted clutch, serving as a simulation of an unbalance and a bent shaft issue together. A detailed photography of the motor can be seen in Fig. 10. The stepper

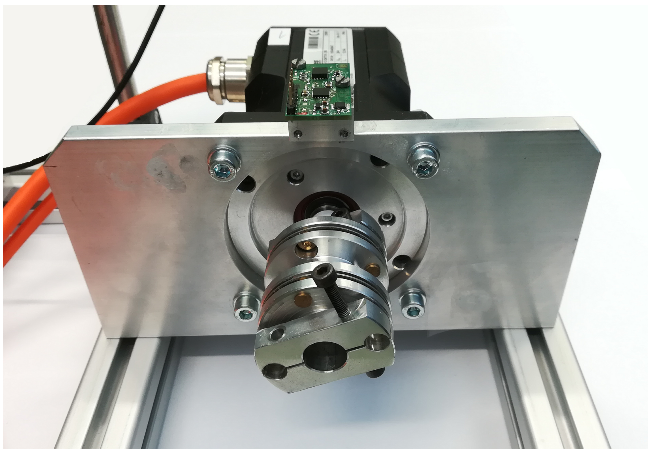

Figure 10. Stepper motor with bellows clutch and SVS.

motor is a 10 pole machine and ran at 1470 RPM during bellow described tests. Thus first harmonic is at 24.5 Hz.

B. Measurement results

The first measuring case was done on the motor with unbalance mounted on the end of the clutch. This setup also caused effect of a bend rotor. Measured spectrum of the overall vibration velocity in ISO band can be seen in

Fig. 11.
There are three curves in the chart. All curves were mea-

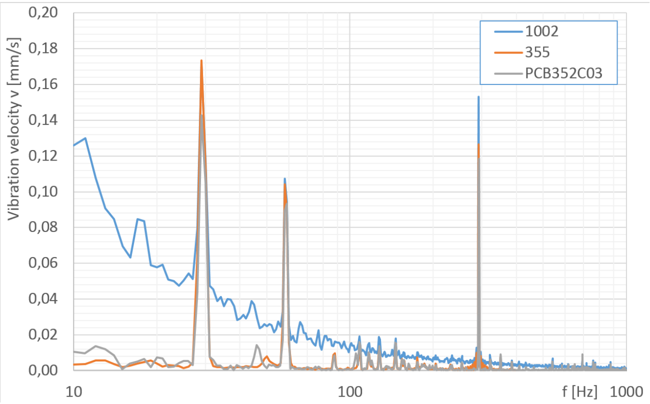

Figure 11. Vibration velocity of the steper motor measured by the SVS and compared with output data measured by a standard accelerometer.

sured in the same direction (vertical). Since absolute values were relatively low (around 0.1 mm/s, what is practically uninteresting value and in industrial condition is very often attributed to surrounding noise), the conformity of all three sensors is almost ideal in frequency domain and very high in amplitude domain.

From Fig. 11 it can be seen, that the noise background for the MEMS sensor ADXL355 and the piezo PCB352C03 are at the same level (around 0.005 mm/s), what is very good result and very useful for practical industrial applications. On the other hand side, the noise of the ADXL1002 seems to be higher, mainly at the lower frequencies. But this is not caused by the internal noise of the accelerometer itself (because internal noise of both accelerometers defined by manufacturer is at the same level 25 $\mu g/\sqrt{Hz}$), but the noise of used analog to digital converter inside the MCU. It can be seen from Fig. 12, that noise level of the ADXL1002 sensor is significantly higher in whole frequency band comparing to the other ones.

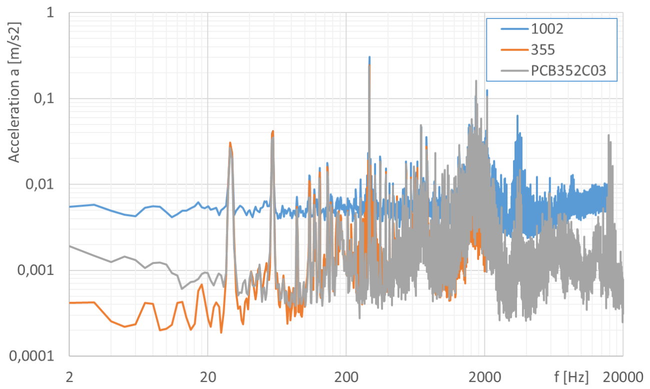

Figure 12. Acceleration spectrum for all three sensing elements.

Figure 12 shows spectrum of a vibration acceleration signal for all three sensors for the same measurement test case as shown in the Fig. 11. Acceleration is measured directly by the sensors and velocity spectrum is then calculated (integrated) from measured acceleration information. This is the reason for higher noise similar to $1/f$ noise shape in the velocity spectrum. But the noise is still low enough (bellow 0.15 mm/s) for practical purposes of vibration sensing.

From the diagnostic point of view, there can be seen three main spectral lines in the Fig. 11 (and also in the Fig. 12). The first harmonic (at frequency approx. 29.5 Hz) is spectral line corresponding to the revolutions of the motor. Its amplitude is also emphasized by unbalance of the rotor (screw mounted in the clutch at the motor shaft). Second spectral line is also harmonic (2nd harmonic at frequency of 59 Hz) and is caused by loose end of the clutch. This simulates bent rotor and causes second harmonic inside the system or in the measured vibrational spectrum. Third spectral line (10th harmonic at frequency of approx. 295 Hz) is caused with high probability by poles of the rotor - the measured motor is the 10 pole machine and this spectral line is exactly at 10 times revolution frequency.

The last measured charts are rather informational. The first cahrt, shown in the Fig. 13, depicts triaxial measurement on the one particular place on the motor. A curve X represents vertical direction, a curve Y represents horizontal and finally a curve Z represents axial direction of the measurement. The great advantage of this solution is in mounting only one sensor to the measuring location and to have at least overview of behavior in all three orthogonal directions. The last curve, representing an ADXL1002 output, is not shown in this figure, because this curve overlaps the ADXL355X curve and its showing would lead to low clarity of the chart.

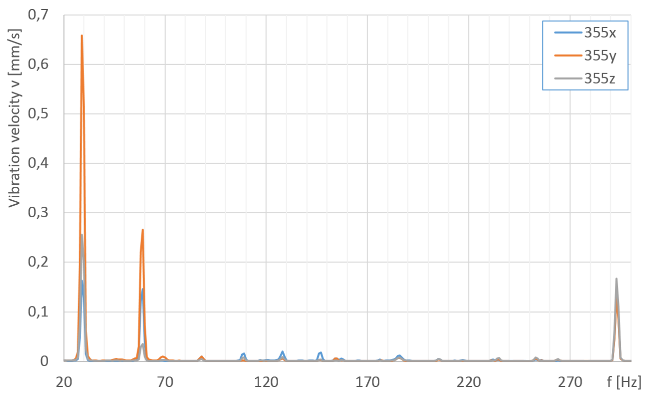

Figure 13. Comparison of triaxial measurement.

The second measurement, displayed in the Fig. 14, shows vibration acceleration spectrum measured on the vibration shaker with sinusoidal excitation signal at 80 Hz and with amplitude level of 0.5 g. Several aspects can be seen there:

- Conformity of all curves - same amplitude and frequency measured by all three sensing elements (80 Hz and 0.5 g)
- Noise level of the sensors - the same result, as mentioned above - ADXL355 and PCB352C03 have roughly the same noise level, but ADXL1002 has significantly higher noise values (almost one order higher). It is not the self noise of the accelerometer, but noise of the ADC in processor.
- Other harmonics can be seen in the spectrum. Not only fundamental harmonic (80 Hz), but also higher ones

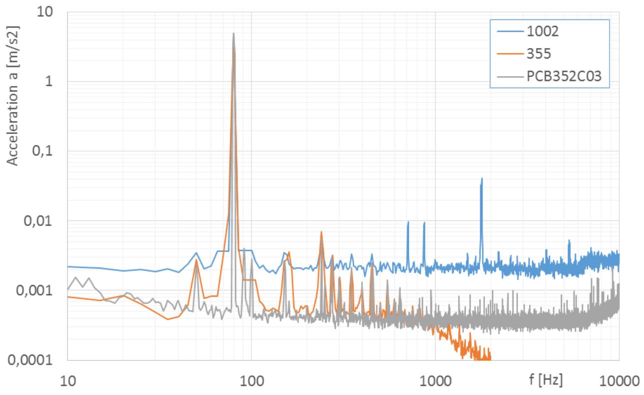

Figure 14. Acceleration spectrum measured on vibration exciter driven with 80 Hz sine wave.

are present in the signal. This is a negative property of used shaker.
- Spectral line on the ADXL1002 curve at approx. 1.8 kHz. The origin of this line is not totally clear at this time, but there are a few potential sources, e.g. disturbance from supply circuits, analog front-end interference or ADC converter grounding, PCB layout etc.
- Decrease of an ADXL355 measured acceleration curve at higher frequencies - the effect of the built-in low pass filter at 1 kHz can be seen there.

VI. Conclusion

This paper deals with design and practical performance evaluation of the Smart Vibration Sensor based on two MEMS sensing utilization. Brief design process is described in the first chapters, including comparison and selection of suitable MEMS sensing devices, as well as hardware and embedded software design process and adjustment of the sensor. Results of measurement of the main parameters of the sensor obtained by the calibration system SPEKTRA CS18 are described and shown. Overall, all assumptions were confirmed by measurement and thus the sensor in its prototype version was confirmed as suitable for industrial applications. Also simple measurement in real conditions using industrial actuators has been done with excellent results (from the noise and signal resolution point of view).

There are also a few of open issues to be solved and improved in the near future. One of them is an improvement of analog circuits for the ADXL1002 sensor for better spectral resolution and sufficient combination of signals from both branches to reach better spectral density of completely assembled signal. Better analog to digital converter could be also considered - the sensor can reach better level of background noise for the ADXL1002 sensors, at least both MEMS sensor can be equal in this parameter.

Actual design of the smart sensor almost reaches the performance limit of the processor used in the system, so not much further enhancement can be made in this design. Any better or powerful type should be used, but it is also a compromise of performance, power consumption, available peripherals, number of general purpose input and output pins and mainly size of the package.

Another thing is to implement diagnostic methods for predictive vibrodiagnostics of the machines as well as auto-diagnostic functions (like both sensors comparison, detection of faulty sensing element etc.). These functions can be implemented in the superior system in the first phase and after successful evaluation on the PC based development system they could be ported to the MCU of the smart sensor. The last thing to implement would be automatic detection of yaw of the sensor for recalculation of individual sensitivities to measuring orthogonal direction of the analyzed machine.

Finally, the PCB of the sensor has to be redesigned to fit it into selected housing. After that, further detailed measurement campaign will be carried out in the calibration laboratory to evaluate sensor performance and afterwards followed by real tests in the industrial environment.

It can be concluded, that designed sensor achieved very good noise properties (which was one of the biggest issue before design), thus could be very useful for industrial applications and competitive to professional piezo accelerometers, while achieving very good price to performance ratio.

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