BINP CAPACITIVE AND ULTRASONIC HYDROSTATIC LEVEL SENSORS

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INTRODUCTION

Slow ground motion study for future accelerator projects and alignment of large accelerator machine components with high accuracy are important tasks now. One of the prevalent tool for solution of these tasks are Hydrostatic Level Sensors designed to work into the Hydrostatic Levelling System, which is based on principle of communicating vessels. All water level measuring sensors are linked to its neighbours by a system of tubes. So the principle is based on the equilibrium of the pressure of liquid in communicating vessels.

Since 2001 year BINP took part in development and fabrication of Hydrostatic Level Sensors in the network of team-work with FNAL and SLAC. At the beginning BINP developed capacitive HLS sensors and then in 2005 ultrasonic HLS sensors.

Last year in accordance with the program of collaboration between BINP and SLAC high-resolution capacitive (SASE) and ultrasonic (ULSE) hydrostatic level sensors for the Linac Coherent Light Source (LCLS) Undulator Alignment System were developed and fabricated. The LCLS is the SLAC program aimed at the development of a coherent X-ray source. The capacitive sensors will be used at LCLS in combination with ultrasonic sensors, in order to provide accurate measurement of alignment with possibility of absolute calibration of the sensors. On each girder of the Undulator it will be installed one ultrasonic sensor and three capacitive sensors. The detailed view of the sensor's installation is presented on Fig. 1. The sensor of number 1 is of ULSE type, the other sensors (number 2 to 4) are of SASE type.

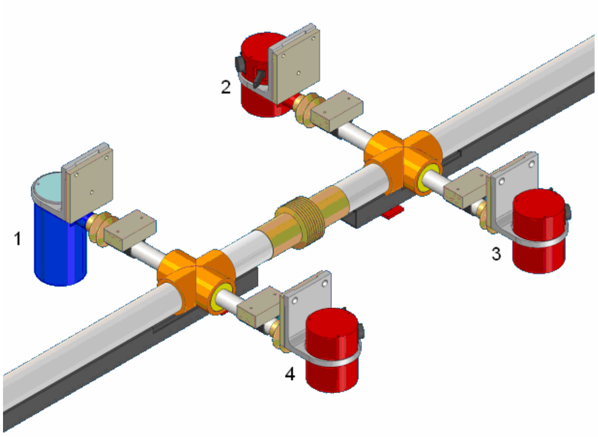

Figure 1: The detailed view of the sensor's installation.

For the placement of the sensors on the girders special brackets designed by SLAC will be used. Mechanical parts of the sensors were fabricated with possibility to fit the brackets. All sensors will be connected into hydrostatic levelling system with pipes half-filled with water. The electronics of the sensors has equal interface regardless of the sensor's type.

CAPACITIVE LEVEL SENSOR

General Description

Capacitive level sensor (SASE) is designed to work into the Hydrostatic Levelling System for monitoring of the LCLS Undulator vertical position. The water level working range is +/- 2.5 mm relative to the middle of the water communication pipe. The repeatability of the sensor is 1 µm with an accuracy of 5 µm over 5 mm measurement range. The digitizing period is 2 seconds.

SASE works on principal of capacitance-based sensing. The principal is to create a capacitor, the liquid surface being one electrode, the sensor electrode placed in air medium upper of water surface being the second electrode of capacitor, the capacitance of which is measured in order to derive the distance between these two electrodes.

A method used for measurement is to convert variable capacitance into frequency, after that to convert the frequency to digital form. The developed circuit uses the idea presented at the work of N.Toth and Gerard C.M. Meijer [1]. General idea of the converter is an RC-generator with oscillating frequency determined by it's internal parameters. The detailed description of the specific realization of the method presented at our report on IWAA04 [2].

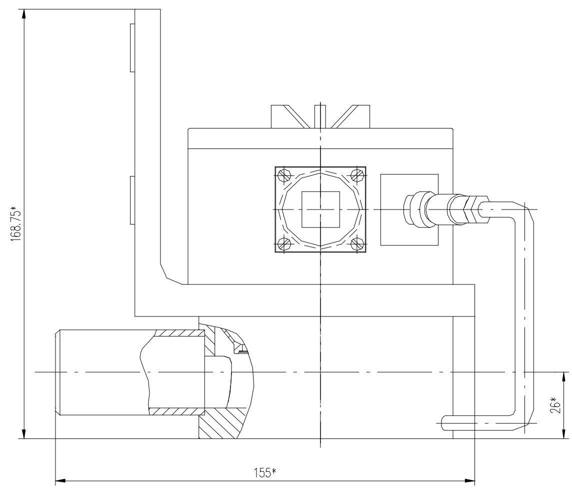

Figure 2: The general view of the SASE.

SASE consists of two independent parts: upper one with electronics inside and lower one (usually named as vessel) filled with water. The general view of the sensor is shown at the Fig. 2 (all dimensions are given in mm). All the body parts are done with stainless steel. On the top there is a special nest for a 1.5 inch ball to provide alignment survey.

SASE electronics

The electronics of SASE is mounted on two printed circuit boards. The board 1 includes Lantronix XPort [3], Power supply controller, DC-DC converter and transformer. The board 2 includes **C=>F** converter and flash microcontroller. On the Fig.3 view of the SASE electronics is presented. The board 1 is at the right side, the board 2 is at the left one.

Figure 3: View of the SASE electronics

The functional circuit diagram of the SASE electronics placed on the board 1 is presented on the Fig. 4. The electronics on this board forms Ethernet interface and power supply voltage. The XPort is used as server for 10BASE-T/100BASE-TX Ethernet connection. Really it is a bridge between Ethernet local area network and the microcontroller's UART (universal asynchronous receiver/transmitter) port. Power Supply controller and DC-DC converter provide for safe power supplying of the sensor electronics. Input voltage is as high as 48V and output voltage is +3.3V. The transformer is used for galvanic insulation between external electric circuits and the sensor electronics.

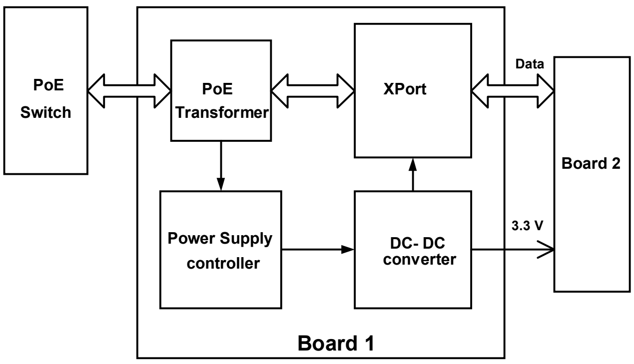

Figure 4: Functional circuit diagram of the SASE electronic board 1.

The functional circuit diagram of the SASE electronics placed on the board 2 is presented on the Fig. 5. All the electronics is operated under the microcontroller. The last is controlled by the commands of Operator Board computer via microcontroller's UART port and Power over Ethernet interface. The microcontroller's algorithm of autonomous operation is distributed inside its internal flash memory. **C=>F** converter for conversion of water level depending capacitance into frequency F, as we had described earlier, is a self-exciting relaxation oscillator. Its frequency of oscillations depends on value of monitored capacity C. The resulting pulse repetition frequencies are counted by the microcontroller via its I/O port inputs. The clock of counting depends on the system clock quartz oscillator. It takes about 1.3 s to measure oscillating periods that are essential for calculating of water level. AD22100 type monolithic silicon temperature sensor of Analog Device corp. is used for water temperature measurements. The ADC, used at the SASE electronics for temperature measurements, is built to the microcontroller. Temperature resolution is 0.1^{o}C.

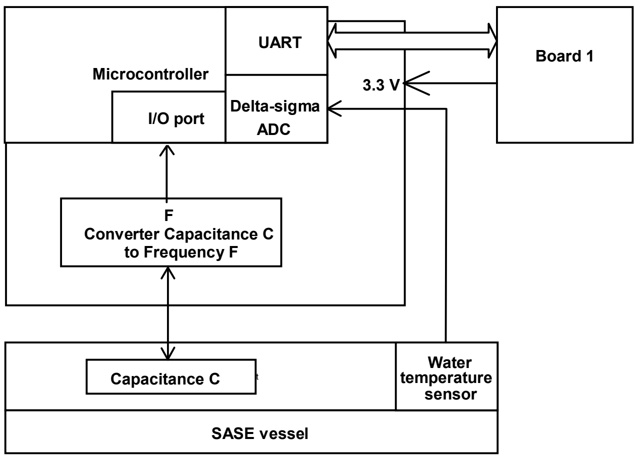

Figure 5: Functional circuit diagram of the SASE electronic board 2.

ULTRASONIC LEVEL SENSOR

General Description

Ultrasonic Level Sensor (ULSE) just as SASE sensor is designed to work into the Hydrostatic Levelling System for monitoring of the undulator's vertical position. The water level working range is +/- 2.5 mm relative to the middle of the water communication pipe. The resolution of the ULSE is 0.2 µm and the accuracy is 5 µm in measurement range of 5 mm.

A pulse-echo method is used in ULSE for water level measurements. The ultrasonic hydro-location is well known and widely distributed method of distance measurements for many applications. One of precise methods was described by Markus Schlösser and Andreas Herty at their report presented at the 7th International Workshop on Accelerator Alignment [4]. Their idea is to locate not only the water surface in a vessel, but also two addition surfaces with calibrated distance between them (D1) and at the calibrated distance to alignment reference target (D2), see Fig. 6. This idea had pushed us to develop the electronics and, as a result, all the Ultrasonic Level Sensors module for the same purposes – to be a part of Hydrostatic Level Measurement System for precise measurement of the vertical displacements of some accelerator structures.

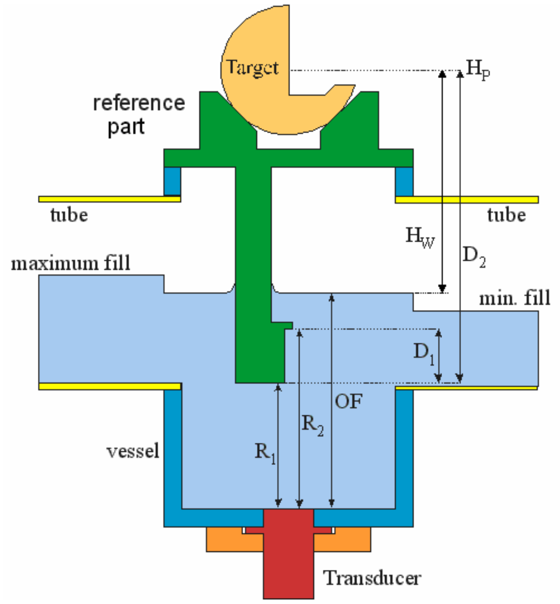

Figure 6: Principle of organizing the reference surfaces at the ultrasonic sensor.

The pulse-echo ultrasonic measurements can determine the location of free water surface in a vessel or location of reflective surface into water by accurately measuring the time required for a short ultrasonic pulse generated by a transducer to travel through a thickness of water, reflect from the free water surface or from the reflective surface, and be returned to the transducer. The two-way transit time measured is divided by two to account for the down-and-back travel path and multiplied by the velocity of sound in the test material. The result is expressed in the well-known relationship:

$$d = v \cdot t / 2 \quad (1)$$

Here d is the distance from the surface of transducer to the reflective surface or to free water surface, v is the velocity of sound waves in water, and t is the measured round-trip transit time.

Usually it is necessary to determine vertical distance between the free water surface and centre of alignment ball (Hw). It is easy to do by next formula:

$$H_W = D_2 - D_1 * \frac{t_{OF} - t_{R_1}}{t_{R_2} - t_{R_1}} \quad (2)$$

Here D_1 and D_2 are linear dimensions of the reference part. They can be measured with high accuracy after their fabrication. So ULSE has self-calibrating capability and as result there is a possibility to make measurements of absolute water level position with high accuracy. Because of self-calibrating capability one can eliminate electronics drifts of various origin.

Fig.7 presents general view of the ULSE. All the body parts were done with stainless steel with the lowest of part. It was done with plastic material. ULSE consists of ultrasonic transducer, vessel with tube outlet, reference part, temperature sensor. The reference part has two reference surfaces to calibrate the measurements and special nest for a 1.5 inch ball to provide alignment survey. There are no any electronics inside the body of ULSE. The electronics is placed into separate box, which can be located on some distance (up to 2 meters) from the mechanical body of ULSE.

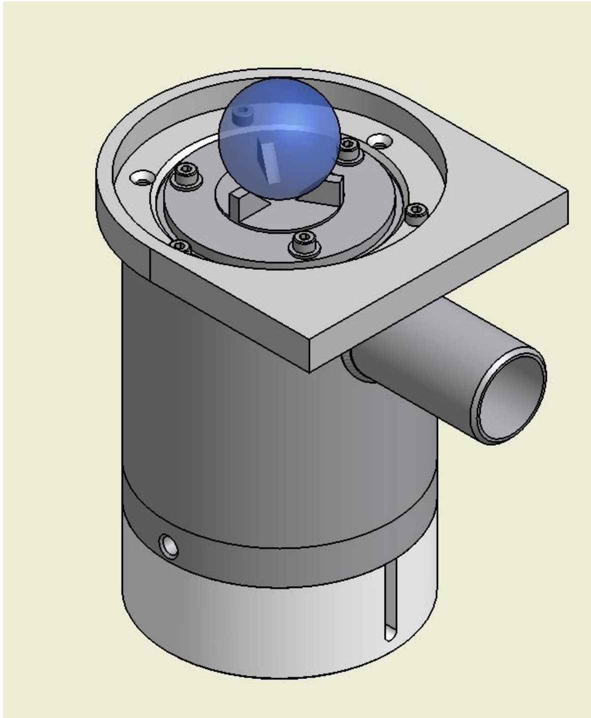

Figure 7: The general view of the ULSE.

For the ultrasonic measurements into water there are special transducers – immersion transducers. These transducers are designed to operate in a liquid environment. They usually have an impedance matching layer that helps to get more sound energy into the water. For the ULSE was chosen miniature transducer for immersion technique H10KB3 of Krautkramer production. The transducer is special designed to work during long time in submerged position. Detailed description of the transducer's choice for the ULSE presented at our report on IWAA06 [5].

ULSE electronics

As we can see from the sketch of Fig.6, main idea of organizing the precise water level variation measurements is to use the reference distances: one of them is the distance **D1** between two surfaces inside water of monitor; another one – the distance **D2** between one of this surfaces and geodesic reference probe positioned on the top of reference part outside of the vessel. These distances are well known due to possibility of special mechanical measurements at the stand outside the system and due to stable length of the reference part.

For this configuration of the reference part the transducer is placed at the bottom of the vessel. It transmits into liquid media (water) the pulse. Three reflected signals arrives the transducer with the delays, corresponding to the distances $\mathbf{R_1}$, $\mathbf{R_2}$ and **OF** from the transducer to each surface (Fig.8). Transducer, being in a role of receiving ultrasonic antenna, accepts all these signals and transmits them to the amplifier and to the electronics scheme for signal processing. The goal of the ULSE electronics is to measure time intervals with the accuracy as fine as possible and to calculate the resulting values.

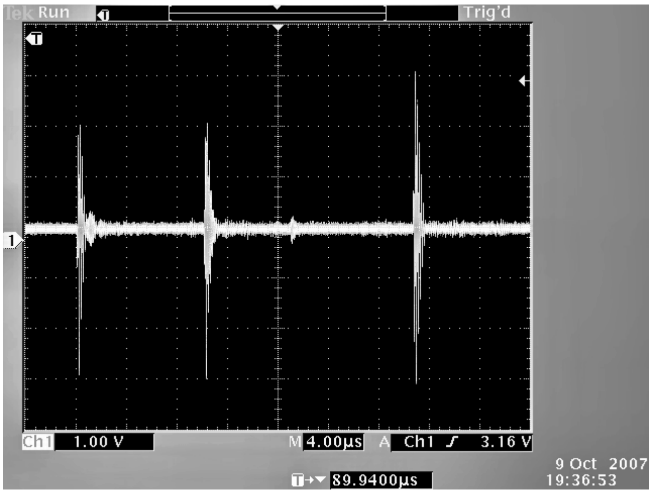

Fig.8 The oscillogram of the reflected signals.

The ULSE electronics is located in separate box. One box encloses electronics for one ULSE sensor. The general view of the box is shown on Fig.9. The box has four different connectors. Three of them are used for connection of the transducer, temperature probe, data acquisition system and power. The fourth connector is used for control of the reflected signals.

Fig.9 View the ULSE electronics box.

The functional circuit diagram of ULSE electronics is presented on the Fig.9. The electronics includes Transmitter/Receiver, Comparator, TDC (Time Digital Converter), Flash microcontroller, System clock oscillator, XPort, Power controller, DC/DC converters and Transformer. All the electronics is operated under the microcontroller. The latter is controlled by the commands of Operator Board computer via Power over Ethernet interface. The microcontroller's algorithm of autonomous operation is distributed inside its internal flash memory.

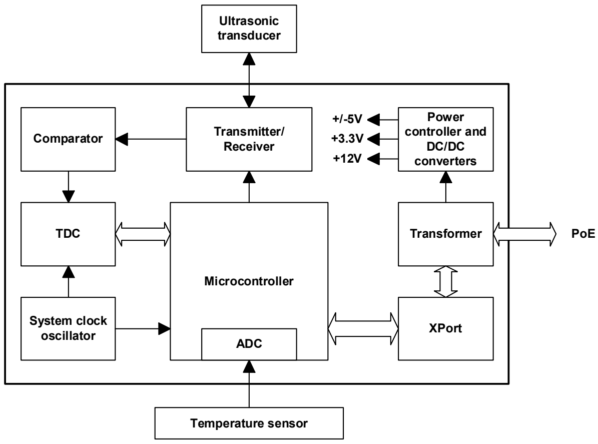

Fig. 10: The functional circuit diagram of ULSE electronics.

After power "ON" the microcontroller makes a measurement's cycle every 10 ms. It forms start pulse for the Transmitter and TDC. The Transmitter generates electrical pulse for transducer. The Receiver takes the reflected signals and sends them to the Comparator. The Comparator converts analogous signal of reflected oscillations into the digital "ON/OFF" form. To avoid the dependence of time measurements from reflected pulse amplitude we had applied the "zero level" comparator. It's time diagram is presented at Fig.11.

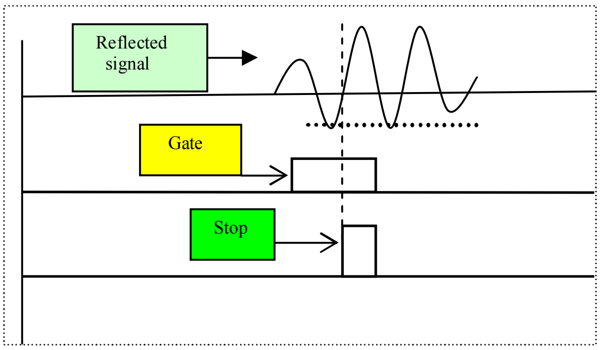

Figure 11: Time diagram of "zero level" comparator operation.

In the Comparator the reflected analogous signal, looking like a short bunch of oscillations, enters to the gate. Gate has predicted time position, duration and raw comparator. All of this allows selecting, for example, "first positive pulse after first negative pulse with sufficiently large amplitude". This signal enters to comparator having zero reference level and sufficiently high gain. The comparator's output produces the STOP signal for TDC.

TDC measures time intervals between the start pulse and the pulses coming from the Comparator. The microcontroller gets digital codes of the measured time intervals from TDC and transforms them to the distance digital codes for the next transmission to PC computer. The microcontroller also can measure temperature of ULSE vessel and accordingly temperature of water inside the vessel with help of temperature sensor and inboard ADC. AD22100 type monolithic silicon temperature sensor of Analog Device corp. is used for water temperature measurements. Temperature resolution is 0.1 ^{o}C. The work of the microcontroller and TDC is synchronized by System clock quartz oscillator. The XPort is used for 10BASE-T/100BASE-TX Ethernet connection. Power supply controller and DC-DC converters solve for safe power supplying of the sensor electronics. The input voltage of the converters is as high as 48V. The output voltages are +12V, ±5V and +3.3V. The transformer is used for galvanic insulation between external electric circuits and the sensor electronics.

DATA ACQUISITION SYSTEM

Data acquisition of the level measurements can be organized with the help of Local Area Network based on Power over Ethernet interface and standard system of commands "Field Point F1001", National Instruments Corp [6].

Power over Ethernet or PoE interface is a system to transmit electrical power, along with data, to remote devices over standard twisted pair cable in an Ethernet network. PoE interface operates under IEEE 802.3af specification. The specification provides 48 V DC over two out of four available pairs on a Cat3./Cat5. cable with a maximum current of 400 mA for a maximum load power of 15.4 W.

Functional diagram of HLS Data acquisition system is presented on Fig. 11.

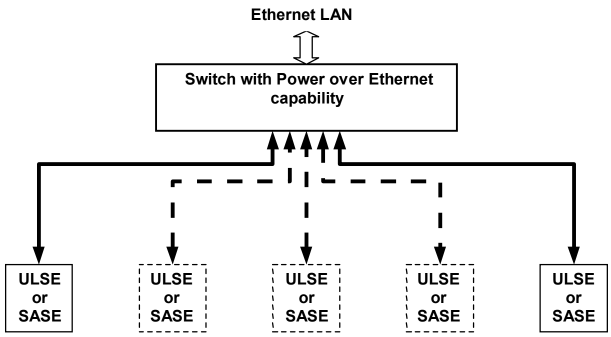

Figure 11: Functional diagram of HLS Data acquisition system.

All sensors (ULSE or SASE type) are connected up to standard switches with Power over Ethernet capability. The switches are connected to local area network based on Ethernet. Necessary total number of switches depends on their number of channels. Length of the connecting cables between the sensors and the Switch can be as long as 100 meters.

COMPASION OF TWO KINDS OF THE SENSORS.

During last 7 years more then 200 sensors of both type were fabricated and delivered to FNAL and SLAC. 80 SASE and 40 ULSE sensors were fabricated last year and delivered to SLAC in January 2008.

Ultrasonic sensor has a lot of benefits in comparison with capacitive one:

- More high absolute accuracy.
- More sensitivity at more high sample rate.
- Measuring data don't depend on electronics drifts (temperature and time) because of calibration capability during each measuring cycle.
- No dependence on a relation "signal/noise" from measuring level
- High linearity of transfer coefficient (output signal => level)
- No need in precise calibration – only accurate measurement of two linear sizes for reference part.

Accuracy of level measurements of ULSE sensor depends on the accuracy of the reference part. It has self-calibrating capability. But for accurate level measurements with help of SASE sensors it takes precise calibration, because transfer coefficient of the sensor is not linear. The calibrations of the SASE sensors were made in measurement range of 5 mm with step of 500 µm. On Fig.12 nonlinearity curves of transfer coefficient for 80 SASE sensors are presented. Curves of the nonlinearity are approximated with help of calibration data. In Table 1 there are statistical data for the nonlinearity.

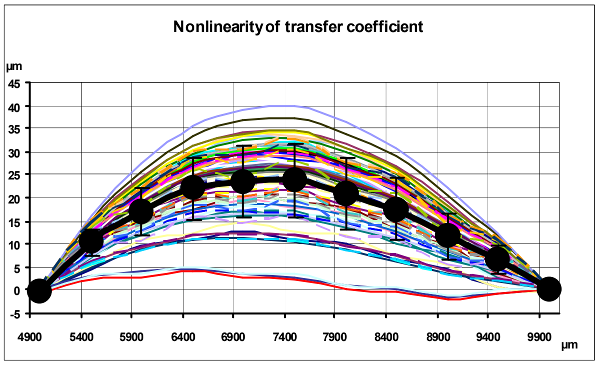

Figure 12: Nonlinearity of the SASE transfer coefficient.

On Fig.13 nonlinearity curves of transfer coefficient after interpolation by the 3rd order polynomial for the SASE sensors are presented. In Table 2 statistical data for the nonlinearity after interpolation are shown.

Table 1: Statistical data for the nonlinearity of 80 SASE sensors.

Real level, µm	Average difference, µm	Dispersion, µm
5000	-0.16	0.19
5500	10.32	2.99
6000	17.00	5.12
6500	22.09	6.71
7000	23.53	7.63
7500	23.78	7.94
8000	20.84	7.62
8500	17.46	6.65
9000	11.68	5.05
9500	6.56	2.99
10000	-0.03	0.20

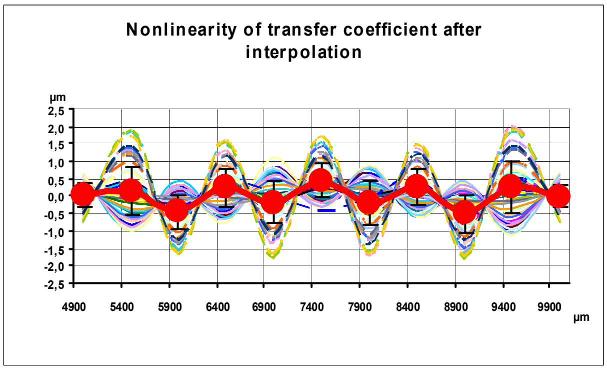

Figure 13: Nonlinearity of the SASE transfer coefficient after interpolation.

Table 2: Statistical data of the nonlinearity after interpolation for 80 SASE sensors.

Real level, µm	Average difference, µm	Dispersion, µm
5000	0.04	0.33
5500	0.14	0.69
6000	-0.45	0.50
6500	0.24	0.53
7000	-0.18	0.62
7500	0.44	0.48
8000	-0.21	0.63
8500	0.24	0.52
9000	-0.50	0.54
9500	0.25	0.74
10000	0.00	0.34

One can see the accuracy of the SASE sensors after precise calibration meet required value 5 µm in measurement range of 5 mm.

Capacitive level sensors have now only two benefits:

- Capacitive sensors are more inexpensive. For ultrasonic sensor price of transducer forms considerable part of costs.
- Capacitive sensors are working during many years. There is a big experience of work with them. Ultrasonic level sensors have not such experience.

So very important questions are:

- What is reliability of the ultrasonic transducers?
- How long they can work without essential worsening of their characteristics?

The ahead installation of HLS system at LCLS Undulator magnet line promises getting of very interesting experience. It will be the first HLS system consists of two different kinds of level sensors.

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