Macromodel of Intelligent Sensor Structure with Accelerometer

M,Husak, J. Jakovenko, P. Kulha, J. Novak, V. Janicek,

Department of Microelectronics
Faculty of Electrical Engineering, Czech Technical University in Prague
Technicka 2, CZ – 166 27 Prague 6, CZECH REPUBLIC
husak@feld.cvut.cz, tel. +420 224 352 267, fax: +420 224 310 792

ABSTRACT

The paper describes conceptual approach to the design of a tilt structure determined for integration on a chip. An accelerometer for measurement of inclination in x and y axes is used as a sensor. There is described approach to the development of functional and system model of the structure. A hardware model has been developed for verification of properties. Model properties have been simulated using simulators of electronic circuits. Basic parts of the hardware model are: accelerometer, microprocessor, interface.
The system is temperature-compensated. The values of referential position are set automatically.

Keywords: accelerometer, tiltmeter, microsystem, interface, microprocessor

1 INTRODUCTION

During the process of sensor system or microsystem design determined for integration, it is necessary to use modern design approaches. Models on different levels represent an inseparable part of this process. The models enable to develop the system starting from logical functions up to layout design. It is necessary to use a complex approach based on system engineering [1].

Development of the integrated tiltmeter using accelerometer as a sensitive sensor element has been divided into several parts. The topic of this paper is description of the model development of the whole system and verification of its properties using electronic hardware model. For simulation of the properties, there have been used tools for simulation of electronic circuits. Simulation and modeling have been focused on optimization of circuit layout of the system. There has been performed, for example, sensitivity analysis for identification of properties of transmission chain. At the system input there is an analogue quantity – tilt. At the system output there is an electric quantity in digital form.

2 CONCEPTUAL MODEL OF THE SENSOR SYSTEM

When designing the model we start from basic blocks. These blocks ensure basic functions of signal processing. The blocks are characterized by input and output quantities. The models of individual blocks and the whole system comprise basic algorithms for signal processing according to designed functions. The aim is to optimize mutual interconnection of signals between individual blocks and guarantee of mutual compatibility of signals between these blocks – see figure 1.

Figure 1: Complex model of tiltmeter system.

2.1 Mathematical model of the system

The mathematical model starts from the description of vector division of forces and acceleration of deflected mathematical weight.

From the model of mathematical pendulum it is possible to derive the relation between tilt and static acceleration.

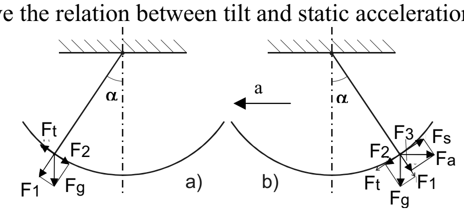

Figure 2: Principle of a) Static, b) Dynamic acceleration

If the hinge attachment of the mathematical pendulum moves with a certain acceleration a, the hinge deflects to the opposite side with certain angle α, see figure. 2a). Value of this angle depends on weight of the bob and value of the acceleration. In tilted state three forces influence the bob: force F_2 caused by gravitational force F_g that returns the bob to original equilibrium state, force F_s caused by inertial force F_a, deflecting the bob in the opposite direction and friction force F_t acting against force F_s. Values of these forces are given by following equations:

$$F_2 = F_g \cdot \sin(\alpha),\;\; F_S = F_a \cdot \cos(\alpha),\;\; F_t = k \cdot F_S \qquad (1)$$

where k is coefficient of friction that corresponds to beam stiffness in the accelerometer construction, $F_g = mg$ and $F_a = ma$. At each point equality of forces must hold, according to the equation (2).

$$F_S = F_2 + F_t \quad (2)$$

Equivalent expression is

$$ma \cdot \cos(\alpha) = mg \cdot \sin(\alpha) + k \cdot ma \cdot \cos(\alpha) \quad (3)$$

After modifications - dividing the equation by mass *m* and merging members containing expression cos(α) - we get expression for the value of deviation in dependence on dynamic acceleration:

$$\alpha = arctg\left[\frac{a}{g}(1-k)\right] \quad (4)$$

We do not consider moving of hinge attachment but only its tilt by angle *α*. Thanks to gravitational force, the hinge returns to vertical position. This situation is illustrated in figure 2b) where the whole system is only turned back by angle *α*.

This time only two forces influence the tilted ball: force F_2 caused by gravitational force F_g, returning the ball to its equilibrium state and friction force F_t in the opposite direction, but having the same value. This equality follows from the equality of forces in each point of the trajectory of the ball. If we compare figure 2a) and figure 2b) we arrive at conclusion that the tilt angle of the hinge at tilt of the hinge plane is caused by imaginary (fictitious) acceleration. Acceleration value is proportional to the value of force F_t. Considering the fact that we have turned the whole system at the beginning by angle *α*, we find out that this acceleration is proportional directly to the value of force F_t and not to its product with the function cos(α). Thus we can write the equation:

$$F_t = F_2 = mg \cdot \sin(\alpha) = ma \quad (5)$$

From (4) the relation between static acceleration and tilt value can be acquired:

$$\alpha = \arcsin\left(\frac{a}{g}\right) \quad (6)$$

Using accelerometer as a sensor of static acceleration or tilt, it is necessary to consider this non-linear dependence of acceleration on tilt angle and correct it in an appropriate way.

2.2 Model of the accelerometer for tilt measurement in both axes x and y

Design of the system with accelerometer comes from the equation (6). Mathematical expression calculates the tilt angle from the measured acceleration in axis x and axis y.

The calculations of tilt angle α_x in axis x and α_y in axis y are realized in mathematical unit. According to requirements laid on accuracy and complexity of the system, the mathematical unit can be realized either in analog or digital version. Analog version is simpler but it offers fewer possibilities for signal processing. Digital version of the mathematical unit is significantly more complex for the design but it offers more possibilities for signal processing and realization of functions. In our model we have proposed communication between individual blocks using digital signals. Digital signals are not prone to interference.

2.3 Model of mathematical unit

In mathematical unit the calculation of tilt is realized. The input data are signals from accelerometer in a suitable form. The output signal from mathematical unit gives the information on tilt in x axis and y axis. These signals are led to information unit for final display, recording or further processing.

3 REALIZATION OF THE HARDWARE MODEL

For verification of basic functions of the designed model there has been chosen a hardware model of the system. For realization of the model commercially available parts have been used. Individual blocks realize designed functions. The signal shape between individual system parts has been modified according to properties of used parts.

For mathematical processing of information from the accelerometer, there has been used a microprocessor and PC as an information unit. The hardware model has been completed with communication circuits that ensure correct data transfer between individual parts of the system. Another block ensures thermal compensation. Correct operation of the system is controlled by control software. Hardware model concept is shown in figure. 3.

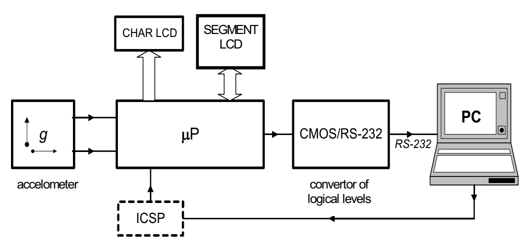

Figure 3: Hardware model of sensor system for measurement of tilt in X and Y axis

3.1 Accelerometer

There has been used a sensitive two-axes accelerometer with analog and digital output with PWM modulation with adjustable period length. It enables direct connection to evaluating microprocessor without A/D convertor. The sensor with range of ±2g can be used for sensing static acceleration – gravitational effect.

Digital outputs have nominal sensitivity value of 12.5 (±2.5) %/g for both axes. Internal convertor realizing both outputs has discrimination of 14 bits, which exceeds discrimination of accelerometer itself. Connected microprocessor must be able to measure mark-space ratio of modulated signal in the range 35-65% with sufficient accuracy for acquisition of information about tilt. It is ideal to use a microprocessor with integrated 16-bit counter/timer and double capture system as its peripheral accessory for this purpose. It is not necessary to measure with high accuracy because discrimination is limited especially by the noise of sensor itself (up to 1 $\mathrm{mg}/\sqrt{Hz}$). Not used analog outputs have given sensitivity value of 312 mV/g and with respect to interference they are blocked with capacitors to ground (GND) [2], [3].

3.2 Microprocessor as mathematical unit

Since it is necessary to measure mark-space ratio of output signals of used accelerometers and send measured data via serial link, a microprocessor with integrated 16-bit counter/timer and double capture system, circuit for synchronous and asynchronous transmission and sufficient number of INPUT/OUTPUT (I/O) outlets have been chosen. There has been chosen a microcontroller. The processor is of hardware type, i.e. it has separate memory for data and program (8 kB, word length 14 bits). Timing can be done by external signal of frequency up to 20 MHz. It can reach 5 MIPS (5.10^6 instructions/sec).

On the chip there are peripheral circuits [4], [5]: Two 8bit and one 16bit counter/timer with programmable predivider, two capture, comparing and PWM output modules, 10bit A/D convertor with fivefold multiplex input, synchronous serial port (SSP) supporting SPI™ and I^2C™ transfer protocols in both Master and Slave modes, universal synchronous/asynchronous receiver-transmitter (USART/SCI) with 9-bit address discrimination, Brown-out Reset for monitoring decrease of supply voltage.

3.2.1 ICSP™ - option to program in application

PIC microcontrollers of medium performance class, are nowadays equipped with ICSP™ function (In-Circuit Serial Programming) as standard. This function enables microcontroller programming in finished application in the following way: at first the application with microcontroller (hardware) is designed and then it is programmed (software); in case of FLASH program memory it can be programmed repeatedly. This property brings substantial advantage in design and compilation of application execution because it is not necessary, for example, to take the microcontroller out of precise socket and put into programmer socket for re-programming and back. Instead of continuous strain of its outlets, the adjusted application can be directly connected with the programmer by five-wire cable. If needed it is possible to update the program saved in FLASH memory, add new functions and properties.

3.2.2 Hardware model of temperature compensation

For precise setting of temperature compensation connection with a concrete circuit, there has been chosen a way of precise measurement of temperature dependence of output signal, i.e. mark-space ratio of the given accelerometer sample in the temperature range –15 °C to +80 °C. The mark-space ratio has been measured for X and Y axes in 4 boundary positions. Measured data have been placed to EEPROM memory of the microprocessor. The temperature compensation has been realized in software in the microprocessor using data acquired from measurement of temperature dependence of tilt of X and Y axes. Calibration is performed automatically using data on measured surrounding temperature.

3.3 Software control of the system

The model includes system autocalibration. The autocalibration enables to define initial setup of the inclination of the tiltmeter as referential position before measurement. The calibration cycle saves the information into memory and further measurements are related to these values. The algorithm for control of measurements with autocalibration functions is illustrated in figure 5.

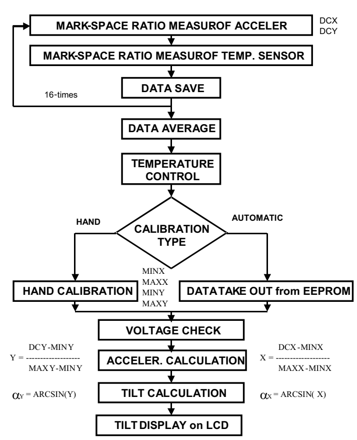

Figure 4: Algorithm for control of measurement, tilt calculation and calibration

4 RESULTS

Hardware model of the tiltmeter system has been realized. The circuit functions have been simulated and modeled using SPICE program. Possible errors in tilt are caused by numerical errors of calculation and storing of measured data, and by temperature variations that represent parasitic parameter of the whole system. Using temperature model, sensitivity of feedback and the whole system to temperature has been simulated.

Hardware model of the system has been tested for tilt in both axes and for tilt in the range of ±90° for each axis.

The measurements have been performed for "manual" and "automatic" calibration of initial positional setup of the system. The measured data have been compared with simulated ones. The deviations between measured and real values are presented in figure 5.

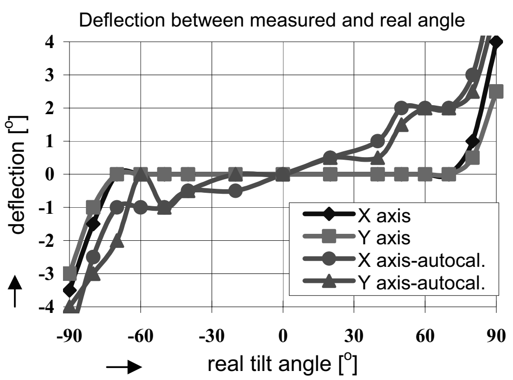

Figure 5: Measurement error in dependence on tilt angle (manual or autocalibration)

The dependence is shown for environment temperature of 24 °C. Greater error of automatic calibration is caused both by error of temperature measurement and by error done by inaccuracy calibration value stored in EEPROM.

It is obvious from the curve of conversion function arcsin that in the areas around the values ±90° there are so-called dead zones, namely zones with zero sensitivity. This fact is reflected in measurement accuracy in the highest ranges. There have been measured temperature dependences as well. Since the sensor itself is temperature dependent, then the whole sensor system is temperature dependent. When testing stability of the measuring system at constant measuring temperature there have not been detected practically any time changes in measured data. Due to intrinsic sensor noise the mark-space ratio of output signals varies in certain interval that can be decreased by averaging, however choosing discrimination value of 0.5° the measured value is sufficiently stable.

There has been measured deviation between measured and real adjusted tilt value In the range of temperature -10 °C to +80 °C at 5 tilt values (0°, ±45° and ±80°). Deviations for tilt values of 0°, 45° and 80° for X and Y axes are shown in figure 6. Absolute accuracy value of the devices is practically temperature independent, it is given by precision of measurement of tilt angles.

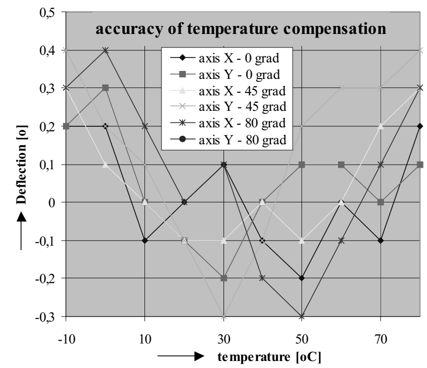

Figure 6: Accuracy of temperature compensation

5 CONCLUSION

There has been developed a system model of tiltmeter system using accelerometer as a tilt sensor. In the model there have been defined signals and their processing in individual blocks of the system. There have been performed functional and logical simulations. For verification of simulated results, there has been designed and realized a hardware model using commercial parts. Circuit and functional simulations using SPICE program have been performed. The model includes temperature compensation and automatic calibration of the referential position of the system as well.

Local display or PC connected via RS 232 can be used for evaluation of information about measured tilt. PC serves for measured data storage and processing. If the system is well calibrated, then it can be used for tilt measurement in both axes in the rage of ±80°, tilt angle 90° represents "dead" point of measurement. Measurement accuracy value in the given range has been ±0.5° at the laboratory sample; hysteresis has been negligible. Setting of the sensor system for measurement at given location is enabled thanks to fast and simple calibration (the system itself evaluates data).

At present design, modeling and simulation for the system realization in integrated version are being performed using ConvetorWare and CADENCE tools.

Acknowledgements

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