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Modelling of Read Channel of Biomedical Sensors

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Abstract: ***This paper presents a methodology for modelling a read channel of biomedical sensors by providing a platform for sub-block level analysis of complete read out channel. As a result, concepts can be proved along with circuit schematics. This paper focuses on modelling an intermediate stage between output of sensor value and input to monitoring system. As outputs of typical biomedical sensors are either capacitive or resistive value, we convert this capacitance/resistance value into equivalent voltage value and amplify them further to digital equivalent level of any processors. This model uses Matlab coding for channel modelling. The model is designed taking into consideration the parameters like offset voltage, temperature variations and change in transistor dimension (aspect ratio). A satisfactory result is obtained and tabulated comparing output voltages produced by change in different nonlinear parameters. The results are tabulated for comparison with circuit schematic results.***

Keywords: C to V conversion, op-amp modelling, analog to digital conversion, Matlab

1. Introduction

There are a lot of terms which are often used for sensors including transducer, meter, detector, and gauge. Sensors are devices that can transform non-electrical signals into electrical signals. Sensor or transducer is a device which can respond to a measured object and transform it into signals which can be detected. They are usually composed of a sensitive component which directly responds to a measured object, a conversion component and related electronic circuits. Biomedical sensors are classified into physical sensor, chemical sensor and biosensor [1]. Physical sensor could be employed to measure blood pressure, body temperature, blood flux, blood viscosity, biological magnetic field etc. Chemical sensor is utilized to detect the ingredient and concentration of body liquid such as Ph value, Ca^{+} concentration, glucose concentration etc.

In nature, biosensor is a kind of chemical sensor, which is mainly used to detect biological signals. The material used in the construction of sensor's outer body must be biocompatible because they play a crucial role in determining an overall performance and longevity of implantable biomedical sensor. The sensors are best if they are wearable that is it can be incorporated in the patient's clothes or implanted under the skin or stuck onto the skin. The patient can be eventually monitored round the clock every day of the week (24 x 7) with wearable or implantable sensors. To measure physiological values like blood flow, glucose level and to detect injections with high accuracy is enhanced when the sensor is in direct physical contact with the body. The reason behind the development and deployment of wearable medical sensors are to allow better follow-up and eventually better diagnosis outside the hospital, while allowing the patient to carry on with the normal life and also engaging in everyday activities.

This paper focuses on biomedical sensors whose output is either capacitive or resistive. The capacitance range considered here is 0.1-3 pico farad. The major blocks of consideration are C to V conversion, amplification and analog to digital conversion. These blocks are complex analog blocks and therefore circuit simulation and performance is hectic. Instead, if these blocks are represented in terms of models then it is easier to debug and characterize readout channel block by block. Therefore, mathematical sub-block level modelling is utilized here.

2. Capacitance to voltage conversion

To begin with, the first major block of implementation is capacitance to voltage conversion. Various methods are available for C to V conversion. The design used here for capacitance to voltage conversion for capacitive sensor will reduce the size and supply voltage of circuit. This paper focuses on input capacitance value ranging from 0.1 to 3 pico farad. This range of capacitance is divided into low, mid and high-range respectively. Low-range varies from 0.1 to 0.9 pico farad, mid-range varies from 1 to 1.9 pico farad and high range varies from 2 to 3 pico farad. The equation used for capacitance to voltage conversion is [2].

$$V0 = \left(\frac{Cx-Cr}{Cf}\right)(Vr2 - Vr1) \quad (1)$$

Where Cx is the capacitance value to be converted into Equivalent voltage.

Cf and Cr are designed capacitors.
V0 is the output of C to V block.
Vr1 is the common mode voltage.
Vr2 is the reference voltage.

Here we assume $Vr2$ and $Vr1$ to be 500milli and 100milli volt respectively.

Equation 1 shows linear relation between capacitance and voltage. Values of Cf and Cr varies for each range of capacitance. This is done to make the output of C to V block to vary between 0 and 400milli volt for each range of capacitance respectively. Accordingly $Cr = 0.1$ pico farad and $Cf = 0.8$ pico farad for low-range capacitance, Cr=1pico farad and $Cf = 0.9$ pico farad for mid-range and $Cr = 2$ pico farad and $Cf = 1$ pico farad for high-range of capacitance respectively.

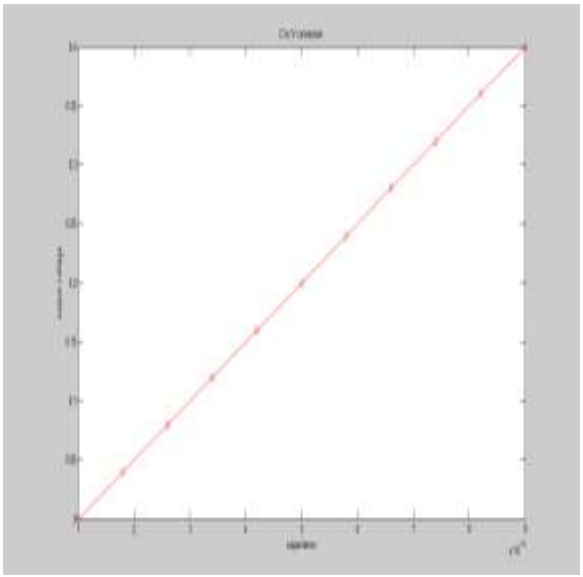

Figure 1: Input capacitance v/s equivalent voltage

3. Amplification

Since biomedical signals are weak, we amplify these signals to a defined value which is decided by gain (A) of the amplifier stage. We use MOS op-amp in the amplification stage whose gain is given by $gm * rds$ [3], where gm is the transconductance and rds is drain to source resistance. The purpose of using MOSFET op-amp over a regular BJT transistor is that it requires very little current to turn on (less than 1mA), while delivering a much higher current to a load. Gm is defined as the ratio of current through the output of a device to the voltage across the input of a device. For MOSFETs in particular, transconductance is the Change in the drain current divided by the small change in the gate/source voltage with a constant drain/source voltage.

Typical values of gm for a small-signal field effect transistor are from 1 to 30 milli Siemens. The value of gm depends on offset voltage, change in aspect ratio (W/L) and temperature. We discuss these 4 cases one by one.

3.1 Case 1

Change in W/L where W and L is width and length of transistor channel respectively. Here the change in W/L is assumed to be 10% of W/L, where W/L is user defined value. Typical value of W is 650nm and L is 200nm. In case 1 gm is determined is given by equation [3]

$$gm = \sqrt{(2kn\ id\ \left(\frac{\Delta w}{l} + \frac{w}{l}\right)}) \quad (2)$$

Where$\frac{\Delta w}{L}$ = change in transistor dimension.

Id = drain current.

$$kn = \mu n\ Cox \quad (3)$$

Where μn = mobility of electrons.

Cox = thickness of oxide layer.

Id is a programmable value and typical value assumed here is 12µ ampere. Here rds is assumed 316 kilo ohm and kn is assumed to be 71.2μ.

3.2 Case 2

Change in temperature.

In case 2 standard temperature is assumed to be 27 degree Celsius. Here gm is given by [3]

$$gm = kn \frac{\mathrm{W}}{\mathrm{L}} (Vgs - Vth) \quad (4)$$

The equation below gives the variation in temperature [5]

$$\frac{\partial Vth}{\partial T} = -\frac{1mV}{C} \quad (5)$$

Here Vth is the threshold voltage determined by change in temperature. For every 1ºC rise in temperature, the threshold voltage V_{TH} reduces by one milli volt and Vgs is gate to source voltage. Any change in temperature with respect to the standard value effects gm value which in turn effects the gain.

3.3 Case 3

Offset voltage.

In case 3 offset voltage is assumed to be 5% of the input voltage given to amplification block and gm is given by [3]

$$gm = \sqrt{(2\ kn\ Id\ \frac{W}{L})} \quad (6)$$

3.4 Case 4

Change in all 3 parameters simultaneously.

Here gm is given by

$$gm = kn\left(\frac{\Delta w}{l} + \frac{w}{l}\right)(Vgs - Vth) \quad (7)$$

The user is given an option to select 1 of the cases i.e. change in W/L or offset voltage or temperature or all the 3 parameters at once. And hence the gm value differs in all cases and also the gain of op-amp. Once the value of gain (A) is known, the output of amplification stage is given by equation [4]

$$VO = A(V1 - V2) \quad (8)$$

Where V1= output of c to v block and V2 is zero volt.

The supply voltage varies from system to system, therefore in this model the supply voltage vdd is a programmable value. The user can give any typical value and in this paper vdd is taken as 5 volts. If the output of amplifier stage crosses vdd value then that output value is limited to vdd else the output is unaltered and sent to amplification block.

4. Analog to digital conversion

Analog to digital converters are required to convert real world signals produced by sensors to a digital pattern used by a

computer. Processing, storing and transmission of Digital data is easy. Hence digital format is preferred over Analog. In real implementation, parameters such as temperature, pressure, humidity and so on are first converted by a sensor to an electrical quantity and by using an appropriate analog circuitry the signal is processed before being applied to an A/D converter. The analog to digital conversion process is at times also known as quantization, implying the individual discrete steps that the output assumes.

For dealing with the different system requirements different techniques have been evolved. Some of the techniques are modified for highest accuracy and for fastest possible conversion speed. The various types of A/D converters include flash, successive approximation, staircase, and delta sigma forms. This paper focuses on flash ADC for analog to digital conversion. Flash convertor consists of a series of comparators, each one comparing the input signal and a unique reference voltage [6].

Effectively, for each quantization step there is one comparator. The output of amplification stage is applied simultaneously to all the comparators. If this input voltage is greater than reference voltage then output of that comparator is logic high else logic low. Here the reference voltage is programmable value. The value assumed here is 5 volt.

Hence output of string of comparators is a 16 bit value which is in turn given to 16:4 priority encoder that will turn this simple unweighted sequence into a binary value, which is the final digital output. The logic propagation delay is the only time delay involved in this conversion .Therefore, for rapidly changing signals this conversion technique is very useful. The only disadvantage associated with this type of ADC is that, it requires a huge number of comparators compared to other ADCs, especially as the precision increases. A flash converter requires 2^n-1 comparators for an n-bit conversion. For a 16-bit flash converter 65, 536 comparators are needed, whereas for an 8-bit conversion it requires 255 comparators. For precision much greater than 8 bits the flash converters are impractical because of their power consumption, size and cost. This paper focuses on 4-bit A/D converter which will require 15 comparators. Since analog to digital conversion involves quantization process, the output does not exactly represent a given input value; rather, it corresponds to an approximation. The error resulting from the approximation is known as quantization uncertainty. With greater resolution, the magnitude of the quantization uncertainty is less. Therefore, we must increase the number of bits in the output, if we need less quantization error .We normally expect that steadily increasing values of input to produce equally spaced digital values in the output, when the input signal is converted to digital output. Sometimes, however, the output may skip one or more steps or digital numbers. Similarly, the output may remain on a given step throughout a range that ideally includes two or more steps. This type of performance is generally caused by linearity errors.

Through the entire range of operation, the amount of input change to produce a change in the output will be consistent, if the converter has no linearity problems.

With an increasing input signal we expect a series of digital numbers in the output that are progressively larger. It is possible, however for a particular output step to be smaller than the preceding step. That is, the magnitude of the digital output decreases rather than increasing for a particular step. This type of output response is called non- monotonic.

Figure 2 Shows relationship between input capacitance value and digital output.

This graph is for different range of capacitance i.e. for low, mid and high range .The first staircase is for low range (0.1 to 0.9 pico farad) of capacitance .Similarly second and third staircase represents the mid(1 to 1.9 pico farad) and high range (2 to 3 pico farad) of capacitance values. For each range of capacitance the variation in digital output is from binary value 0000 to 1111.

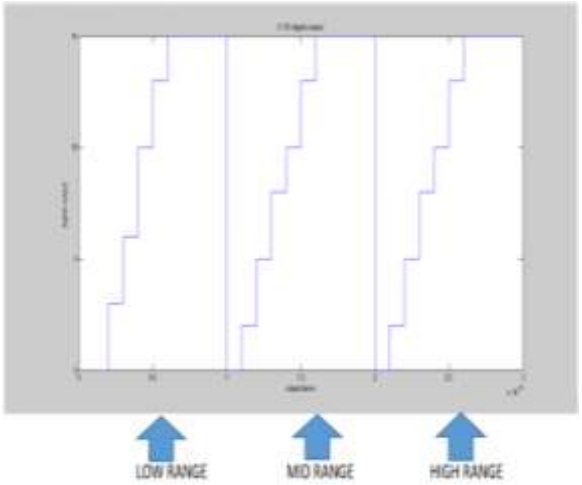

Figure 2: Input capacitance v/s and digital output.

5. Simulation Results

As we know, the value of capacitance varies from 0.1-3 pico farad, the user is provided with an option to enter any value in this range. If the user enters a value out of this range, a message is displayed as capacitance value out of range. For example, assume the entered capacitance value is 1.6 pico farad, it is converted to equivalent voltage of 0.24 volt. This voltage is given to amplifier stage. As mentioned before there are 4 different cases in amplifier stage. The user is given an option to select 1 of these cases. In the table 1 shown below values for all 4 cases are tabulated for comparison purpose. The tabulated results are for $Id = 12\mu$ ampere, $W/L = 2.4$ temperature=30° Celsius and vdd=5 volts. In each case gm is calculated and multiplied with rds value to obtain gain (A). Now this is the gain of amplifier stage and output of amplification stage is given to ADC. ADC generates the corresponding digital output.

Table 1: Digital output for different nonlinear Parameters

Parameters	Gain (A)	Output voltage (Vo)	Digital output
Delta W/L	21.2244	1.6979	1010
Delta temperature	20.3986	1.6319	0101
Delta offset	20.2366	1.6999	0101
All parameters	22.4385	1.8848	0110

6. Future Scope

As mentioned before, this paper focuses on C to V conversion. The similar algorithm can also be implemented on biomedical sensors whose output value is resistive i.e. R to V conversion can be performed and same model can be followed from amplification stage.

7. Conclusion

Biomedical sensors provide newborn methods of diagnostics, minimal surgery and drug discharge. These methods are used to meet the ever growing demand for superior quality medical care. Highly miniaturized systems are being formulated that can be injected in patients through a syringe needle for monitoring health of patients and taking appropriate actions whenever necessary.

This paper focuses on intermediate stage between output of biomedical sensor and input to monitoring system. Capacitive sensing is used for low power applications due to zero static current requirements for signal readout. A complete readout channel is modelled using Matlab and the simulation results are shown using GUI (Graphical user interface). Output of biomedical sensor is provided as input to capacitance to voltage conversion block. The variation in capacitance is linear with respect to the variation in output voltage within a wide range. The output voltage of C to V block is given to an amplification block. After amplifying the signal it is given to ADC. The ADC quantizes the input voltage and then converts it into digital (binary code) output. The results are tabulated and the output is compared for different nonlinear parameters.

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