Chapter 11
Advanced Sensor Solutions for Automotive Applications

Paolo D'Abramo, Alberto Maccioni, Giuseppe Pasetti, and Francesco Tinfena

11.1 Introduction

A sensor is a device whose input is a physical phenomenon and whose output is a quantitative measurement of that physical phenomenon. In the world of electronics, sensors provide the interface between physical or chemical quantities and electrical signals. Direct or indirect measurements are provided depending on whether the output of the sensor is the interesting quantity or it acts as an information carrier for another quantity. Position, velocity, linear and angular displacement, electrical currents are examples of physical signals that can be indirectly measured.

Nowadays sensor signal-conditioning electronics, which performs the necessary analog and digital signal processing, is often provided by integrated circuits and in many cases the sensor itself is fabricated using IC technologies (either on the signal processing die itself or on a separate die). Sensors with integrated electronics are a powerful support in many applications over a broad range of mankind activities, particularly in the automotive environment [1].

The importance of electronics in automotive is constantly increasing and the growth of the number of electronic devices in modern cars is in large part due to the high quantity of sensors that are required for reliable vehicle operation and for achieving higher levels of efficiency, safety and comfort [2]. In fact, sensors with integrated electronics are involved in the engine control and contribute to improve performance, increase efficiency, reduce fuel consumption and cut harmful emissions to fulfill the stringent emissions limits set by environmental pollution standards. They are also used in almost all the safety systems of vehicles, whether

P. D'Abramo (✉)
ams AG, Tobelbader Strasse 30, 8141 Premstaetten, Austria
e-mail: paolo.dabramo@ams.com

A. Maccioni • G. Pasetti • F. Tinfena
ams Italy Srl, Via Giuntini 63, 56023 Navacchio (Pisa), Italy

A. Baschirotto et al. (eds.), *Wideband Continuous-time $\Sigma\Delta$ ADCs, Automotive Electronics, and Power Management*, DOI 10.1007/978-3-319-41670-0_11

the active ones, which help to avoid accidents, or the passive ones, which help to reduce the effects of accidents. Particularly the sensors play an essential role in all the active safety processes for crash avoidance (e.g. brake assistance, traction, steering and stability control), in all the active advanced driver assistance systems and also in some passive crashworthy devices (like airbags). Furthermore there are many essential comfort components and many desirable comfort features that operate sensing the environment and interacting with the passengers (e.g. seat occupancy detection, gesture sensing).

Whatever is their function, in the automotive applications the sensors have to operate in one of the harshest environment for electronic components and, at the same time, they have to ensure excellent reliability and durability levels. In terms of electrical constraints, the sensors have to fulfill especially more and more stringent requirements for Electro-Magnetic Compatibility (EMC): they have to operate correctly when exposed to strong electromagnetic fields caused by other equipment and also emit very low levels of radiated and conducted disturbances that may interfere with other electronic equipment on car. In order to guarantee this, all sensor solutions for vehicles have to undergo many severe EMC tests and fulfill the limits defined by automotive OEMs and international standards (CISPR25, IEC61967, ISO7637 and ISO11452 just to mention the main ones).

Examples of physical and chemical quantities that need to be monitored in automotive are: proximity, position, linear and rotational speed, linear and angular displacement, acceleration, torque, temperature, pressure, electrical current, humidity, airflow, fluid level, fluid concentration, selective gas concentration.

Many advanced sensor technologies are used to sense these quantities. One of the most interesting is based on the measurement of the capacitance variation between two electrodes, which is caused by the variation of the quantity to be indirectly sensed. The transducers that use this measurement principle are in general referred to as capacitive sensors and they are able to detect many of the physical and chemical quantities indicated above [3, 4].

A key advantage offered by capacitive sensors is that indirect measurements are performed without any contact between sensing device and mechanical system. This allows achieving high performance with a relatively easy, robust and cheap construction and for this reason they are widely used in automotive.

On the other hand, depending on the architecture, they could be very sensitive to electro-magnetic fields or they could be an efficient emitting source of disturbances. In particular there are capacitive sensors (e.g. for seat occupancy detection) where at least one of the electrodes needs to have a significant physical extension and act as an antenna, picking up the external electromagnetic fields and/or emitting disturbances.

This poses a huge challenge on the design of the signal conditioning electronics for those sensors: the read-out circuitry has to withstand and suppress the unwanted electromagnetic fields collected by the sensor electrodes while the drive circuitry needs to minimize the emission of unnecessary electromagnetic components. The next chapters describe several architectures for capacitive sensor interfaces and the design aspects to be considered for achieving excellent electromagnetic immunity and emission performance as required in automotive applications.

11.2 Architectures for Capacitive Sensor Interfaces

Different architectures are possible depending on the sensor configuration and the characteristics of the sensor capacitance.

Sensor can be (Fig. 11.1) "grounded" i.e. one of the two terminals is permanently grounded or "floating" i.e. both the terminals are accessible and can be controlled. This constraint has to be taken into account when choosing the sensor interface architecture.

Moreover sensors can have different characteristics in terms of capacitive range, offset value, resistive component (series or parallel), frequency response and so on. Based on these and the specific requirements of each application, the architecture of the sensor interface with the optimal trade-off has to be chosen.

The simplest method to measure the capacitance is to charge it with a constant current and measure the time to charge it until a reference voltage [5, 6]. Figure 11.2 shows the principle implementation.

The capacitance value C_{sense} can be obtained measuring the time delay between the falling edge of the "CLK" signal and the rising edge of the "Comp_out" signal:

$$C_{sense} = Ibias * Delay/V_{Ref} \tag{11.1}$$

The robustness of this architecture can be improved using a reference capacitor and a symmetrical circuit. In this way, errors due to the variation of components, like bias current and reference voltage, can be reduced drastically since the common mode errors do not impact the measurement result. Figure 11.3 shows the improved architecture. In this architecture, the value of the capacitance can be derived from the duty cycle of the "OUT" signal:

$$DutyCycle = C_{sense}/\left(C_{sense} + C_{Ref}\right) \tag{11.2}$$

Main advantages of the above mentioned approaches are the low complexity, a very low power consumption and fast measurement.

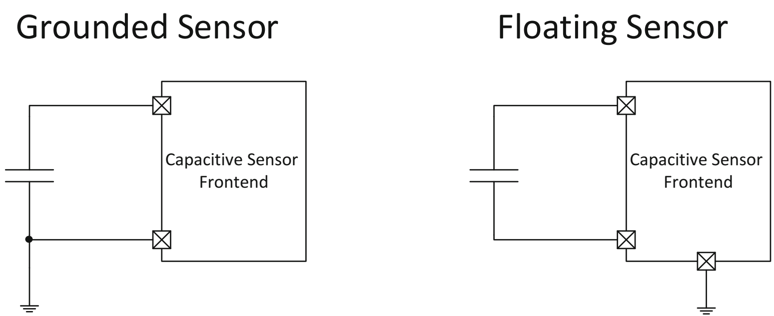

Fig. 11.1 Possible sensor configuration (grounded or floating)

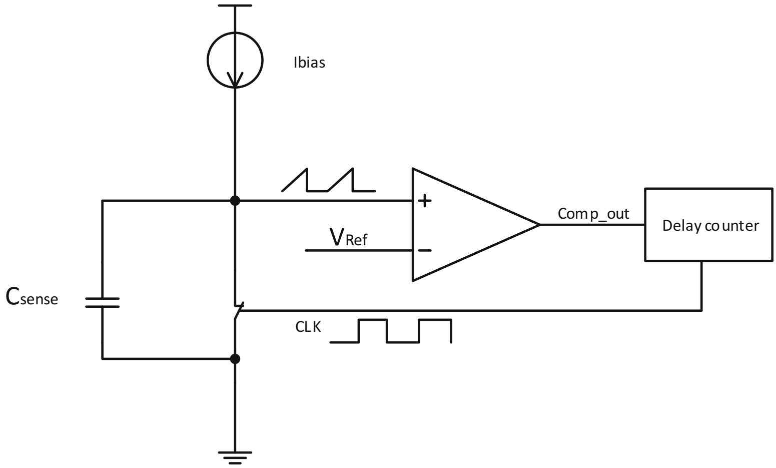

Fig. 11.2 Time measurement concept

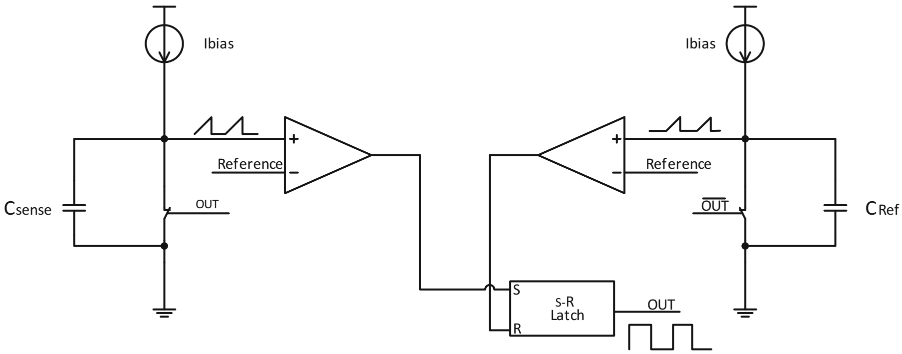

Fig. 11.3 Duty-cycle measurement concept

Unfortunately in terms of electromagnetic immunity, any disturbance on the electrodes affects the result of the measurement and it can only be minimized averaging multiple readings, with a negative impact on response time and power consumption.

In terms of electromagnetic emissions, the speed of the charge and discharge ramps should be as low as possible but this is constrained by the required response time; moreover, the lower the slope of the charging ramp, the more susceptible the front-end is to internal noise (high jitter) and external disturbers (low immunity). An additional constraint to the useful ranges of charge and discharge slopes are the parasitic resistive (series and parallel) and inductive components of the sensor.

A more sophisticated architecture makes use of a Sigma-Delta converter where the sensor capacitance acts as one of the modulator capacitor in the switched capacitor amplifier (Fig. 11.4) [7, 8].

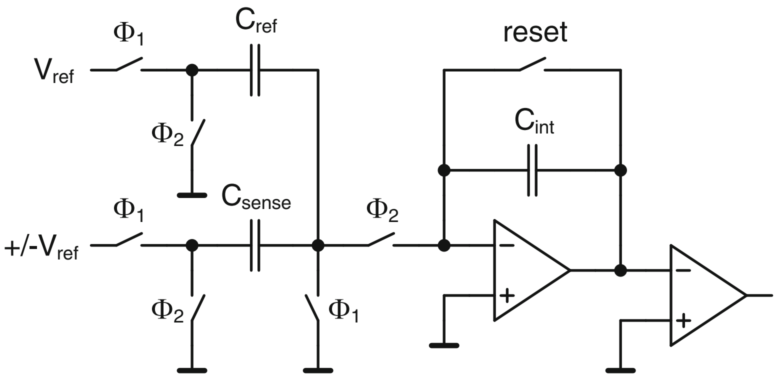

Fig. 11.4 Sigma-Delta switched-capacitor measurement concept

The sensor capacitance value can be calculated according to Eq. 11.3, where M is the mean value at output of the comparator and OSR is the oversampling ratio of the Sigma-Delta converter:

$$C_{sense} = \frac{M}{OSR} C_{ref} \tag{11.3}$$

Main advantages of this architecture are the low noise and the high dynamic range. The desired trade-off between accuracy, settling time and power consumption can be achieved choosing the appropriate oversampling ratio.

In terms of electromagnetic immunity the Sigma-Delta provides good filtering, while the fast commutations of C_{sense} terminals are still critical for the emissions.

The main disadvantage of this architecture is that it requires a floating sensor where both terminals of the capacitor can be driven. This is often not the case for many applications like proximity and gesture detection.

To achieve optimal EMC performance without the need of a floating sensor, the architecture shown in Fig. 11.5 can be used, where the capacitive component of the sensor impedance is measured forcing a known AC voltage and sensing with synchronous demodulation the quadrature current sourced by the driver.

The "drive path" provides the current required to drive the sensor electrode at the excitation frequency (chosen based on the application requirements and sensor characteristics) while keeping the spurious harmonic content at the minimum.

The quadrature component of the current sourced by the driver is sensed by the "pick-up path", which suppresses the potential interfering signals thanks to the synchronous demodulation and adequate filtering.

The next two chapters highlight the specific design aspects to be considered in this architecture in order to achieve optimal electromagnetic emissions and immunity performance respectively.

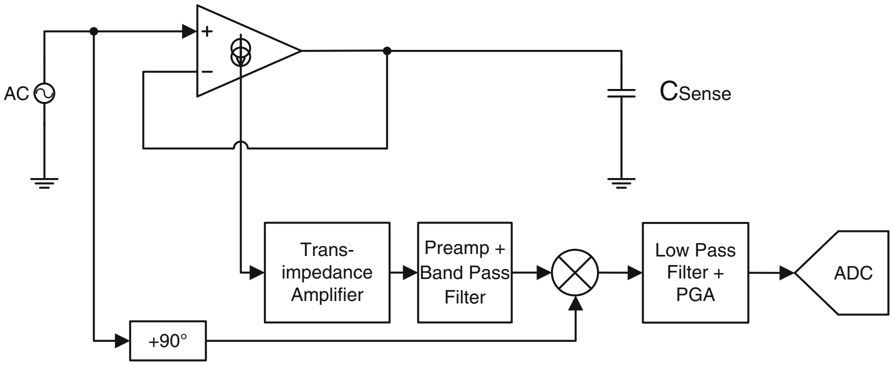

Fig. 11.5 Complex impedance measurement concept

11.3 Design Considerations for Electromagnetic Emissions

The critical part in terms of emissions is the drive path that generates the sinusoidal excitation of the electrode: on one hand the electromagnetic energy injected by the driver into the sensor is radiated by the electrode and on the other hand the AC current that the driver sinks from the supply may cause conducted emissions through the corresponding wire.

Ideally a pure sinusoidal excitation signal would limit the emission spectrum to a single tone at the selected operating frequency. This can be achieved quite well using an oscillator with high spectral purity as signal source. Unfortunately the application requires the programmability with very fine steps of the operating frequency over a wide range which would make such an implementation too large in area (multiple oscillators with large trimming structures are needed).

In order to fulfill those requirements within an acceptable silicon area, the excitation signal is generated by digital synthesis and a sinusoidal DAC.

The sinusoidal DAC gives a good approximation of the sinewave, but, because of non-idealities (e.g. quantization, mismatch of the levels, switching transients), the spectrum of the output signal contains harmonic components of the chosen operating frequency, which can be attenuated adding a low-pass filter between the output of the DAC and the input of the electrode driver.

For the particular application the best trade-off to achieve the required harmonic content while keeping current consumption and silicon area to an acceptable level needs a 16 phases DAC (Figs. 11.6 and 11.7). Special attention has to be taken care also in the DAC layout to minimize the sources of the above mentioned non-idealities.

The high frequency clock to generate the DAC phases is obtained using a multi-phase (16 in this case) PLL locked on the fundamental excitation frequency; using an oscillator at 16 times the sinewave frequency would require much higher current with a negative impact on the conducted emissions.

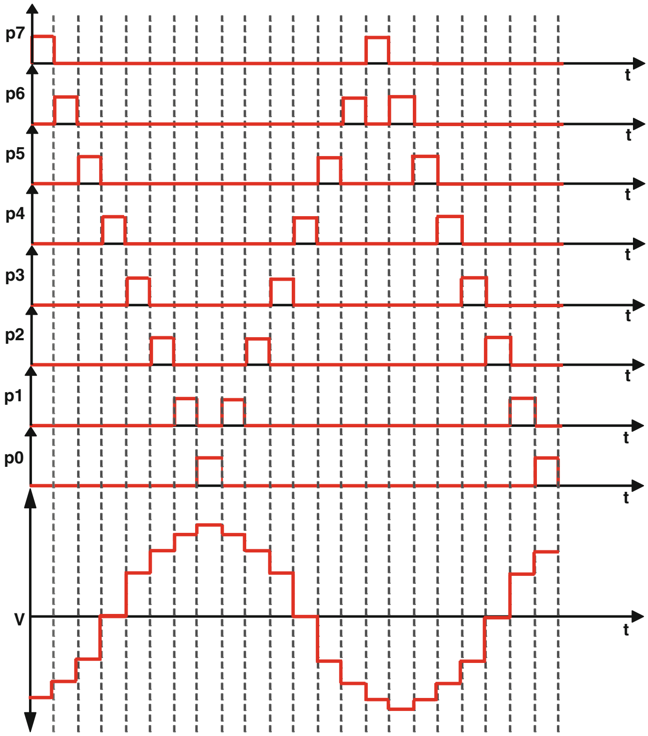

Fig. 11.6 Sinusoidal DAC operation in the time domain

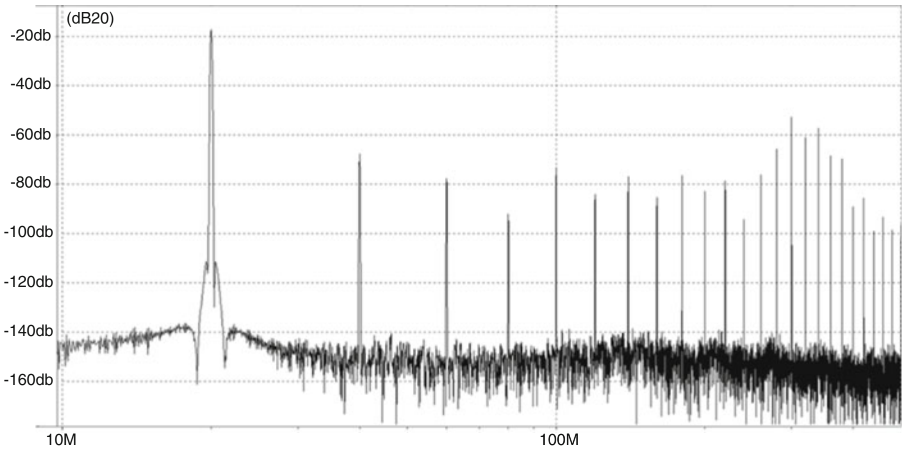

Fig. 11.7 Sinusoidal DAC output in the frequency domain

The sinusoidal DAC output is a low power signal which can't drive directly the electrode. An output driver is needed in order to provide the required current (5 mA for a 100 pF sensor driven with 400 mV at 20 MHz). In order to avoid introducing additional unwanted harmonic components, the design of the driver has to ensure that its linear operation region (avoiding saturation effects both at the input and the output stages) covers the dynamic range of the sinusoidal signal with a proper margin over process, supply voltage and temperature variations.

Last but not least, any parasitic couplings between blocks operating at different frequencies inside the IC have to be minimized. Those introduce crosstalk that can generate intermodulation products between two or more frequencies, leading to additional components in the emission spectrum: for example a parasitic coupling between the electrode excitation frequency and the fixed digital clock frequency will generate an unwanted component which is not a harmonic of the excitation signal itself.

It can be caused by many sources (e.g. parasitic resistance of the supply and ground connections, parasitic capacitive coupling via the substrate or the metal routing, parasitic coupling via common bias blocks) and appropriate measures have to be taken in both schematic and physical design: proper concept for the generation and distribution of reference voltages and bias currents, dedicated supply and ground routing from the pad to each sensitive block, shielding of sensitive signal routing.

The conducted emissions through the supply pins, generated by the drive path but also by other blocks like the digital part, are also a concern, which can be addressed using a LDO to generate the 5 V supply from the 12 V battery voltage with adequate load regulation to suppress all the high frequency components of the IC supply current.

Also the level of the excitation frequency itself may exceed the allowed emission limits. In this case a spread-spectrum scheme can be implemented to vary the operating frequency using a periodic function so that the signal energy is distributed over a wider band and the peak emission level is reduced. When using this, the pick-up path (especially the ADC sampling clock) needs to be synchronized to the periodic modulation signal, in order not to generate measurement ripples.

11.4 Design Considerations for Electromagnetic Immunity

The disturbances can reach the IC through either the sensing electrode or the power supply. The main function of the pick-up path is exactly to amplify and isolate the signal component (AC current in quadrature to the sensor excitation signal), which is then converted into the digital domain for further processing.

Regarding the disturbance collected directly by the sensing electrode, the inherent selectivity in the frequency domain of the architecture is used to reject unwanted input signals that are at different frequencies or not coherent with the excitation signal.

However, the previous sentence is true only if adequate measures are taken in the design to ensure that the all the blocks, for both the drive and the pick-up path, do not saturate even in presence of the worst external interferers.

In particular, the operating current of the electrode driver for a 100 pF sensor operated with 400 mV amplitude at 20 MHz is equal to:

$$Z_{sense} = 1/\left(2^*\pi^*f^*C\right) = 1/\left(2^*\pi^*20\ M^*100\ p\right) = 80\ \Omega \qquad (11.4)$$

$$I_{out} = V_{out}/Z_{sense} = 400\ m/80 = 5\ mA \qquad (11.5)$$

But in the given application experimental measurements show that during immunity tests up to 15 mA can be induced on the sensor electrode, three times higher than the operating current! This implies that, as first step to achieve optimal performance in terms of electromagnetic immunity, the driver has to be sized to handle up to 20 mA without saturating.

The same consideration applies to the whole pick-up path, which has to sense such a current still keeping a linear response. Only under these conditions, the high selectivity of the synchronous demodulator and related filters can guarantee an effective suppression of the interferers while extracting correctly the amplitude of the sensor excitation current.

The disturbances reaching the IC through the power supply are handled using a LDO with adequate PSRR over the relevant frequency range to generate the supply voltages of the different IC blocks, which need also to be optimized with respect to PSRR. Special care has also to be taken, as mentioned already, both in schematic and physical design to avoid crosstalk between blocks.

Of course the most appropriate trade-off between selectivity of the pick-up path and the other application requirements (e.g. response time, noise, temperature drift) has to be determined. In the specific application single digit fF measurement errors could be achieved with conversion times below 100 μs and current consumption below 100 μA (in low-power mode, required when the car is parked).

Last but not least, in case a strong but narrow-band disturber is within the pick-up receiving band, a frequency hopping scheme can be adopted switching dynamically the excitation frequency to a different one far enough from such an interfering signal.

11.5 Conclusions

Sensors are more and more widely used in many applications over a broad range of mankind activities, particularly in the automotive environment.

Among these, the capacitive sensors play a significant role because they can indirectly monitor many different physical quantities with the advantage of a contactless implementation.

In this work several architectures for capacitive sensor interfaces have been presented, with special focus on the design aspects to be considered for achieving excellent electromagnetic immunity and emission performance as required in automotive applications.

References

1. E. Marenzi, G.M. Bertolotti, F. Leporati, G. Danese, Capacitive sensors matrix for interface pressure measurement in clinical, ergonomic and automotive environments, in *Euromicro Conference on Digital System Design (DSD), 2013*, pp. 803–806, 4–6 Sept. 2013. doi:10.1109/DSD.2013.123
2. B. George, H. Zangl, T. Bretterklieber, G. Brasseur, Seat occupancy detection based on capacitive sensing. IEEE Trans. Instrum. Meas. **58**(5), 1487–1494 (2009). doi:10.1109/TIM.2009.2009411
3. R. Reichenbach, D. Schubert, G. Gerlach, Micromechanical triaxial acceleration sensor for automotive applications, in *12th International Conference on TRANSDUCERS, Solid-State Sensors, Actuators and Microsystems, 2003*, vol. 1, pp. 77–80, 8–12 June 2003. doi:10.1109/SENSOR.2003.1215257
4. Y. Hezarjaribi, M.N. Hamidon, A.R. Bahadorimehr, Pressure sensors based on MEMS, operating in harsh environments (touch-mode), in *Electronic Manufacturing Technology Symposium (IEMT), 2008 33rd IEEE/CPMT International*, pp. 1–5, 4–6 Nov 2008. doi:10.1109/IEMT.2008.5507791
5. J. Cho, S. Park, Capacitive sensor for automotive engine oil degradation using wireless network, in *International Symposium on Advanced Packaging Materials: Microtech, 2010. APM '10*, pp. 88–91, Feb 28, 2010–Mar 2, 2010. doi:10.1109/ISAPM.2010.5441375
6. F. Baronti, F. Lenzi, R. Roncella, R. Saletti, Distributed sensor for steering wheel rip force measurement in driver fatigue detection, in *Design, Automation & Test in Europe Conference & Exhibition, 2009. DATE '09*, pp. 894–897, 20–24 Apr 2009. doi:10.1109/DATE.2009.5090790
7. D.S. Lee, H.D. Tiwari, S.Y. Kim, J. Lee, H. Park, Y. Pu, M. Seo, K.Y. Lee, A highly linear, small-area analog front end with gain and offset compensation for automotive capacitive pressure sensors in 0.35-um CMOS. IEEE Sens. J. **15**(3), 1967–1976 (2015). doi:10.1109/JSEN.2014.2369471
8. L. Cardelli, L. Fanucci, V. Kempe, F. Mannozzi, D. Strle, Tunable bandpass sigma delta modulator using one input parameter. Electron. Lett. **39**(2), 187–189 (2003). doi:10.1049/el:20030146