A System for Testing the Sterility of Food Products with Impedance Measurement

Georgi Panayotov Shterev*, Stoyan Nihtianov Nihtianov, Nikolay Nedyalkov Petrov* and Gerard C. M. Meijer
Faculty of Information Technology and Systems, Delft University of Technology, Mekelweg 4, 2628CD Delft, The Netherlands, E-mail: S.Nihtianov@ITS.TUDelft.NL
* Electronics and Automatics Department, Technical University - Sofia, Branch Plovdiv,

Abstract

A System for Testing the Sterility of Food Products with Impedance Measurement *consists of an interface circuit for impedance measurement based on a second-order harmonic oscillator; a microcontroller calculating the values of both impedance components R_X and C_X; a personal computer for data processing and visualization. The resistive component is defining for the condition of the tested object; from the capacitive component we can judge how tightly the electrodes are pressed as well as for the quality of the container of the tested object.*

The measurement range for C_x is from 50 pF to 200 pF; for R_x is from 10 Ω to 150 Ω The relative error for C_x and R_x is less than 0,3%. The measurement frequency range is up to 10 MHz.

I. Introduction

Due to the modern high-technological and cheap components, units and blocks – integrated circuits with high degree of integration and microprocessors, personal computers and appropriate software for them, the prime cost of these systems continuously decreases while the accuracy and the qualitative indices improve. The basic requirements to these components are the low prime cost, the high reliability in operation and the easy usage in real conditions.

Figure 1 shows a simplified block diagram of the system. As an input converter (1) are used two tips (electrodes) that tightly press the food container such as a plastic bottle for testing the sterility of fresh milk.

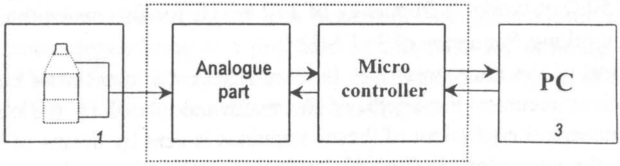

Fig. 1 Block diagram of the system

From this converter the signal is amplified and processed in interface circuit (2) including an analogue part and a microcontroller.

The analogue part represents an oscillator circuit of a second order for measuring of the impedance by means of the auto-balanced bridge technique also called "vector-voltage-current- ratio technique method" [1,2]. This principle is mainly used in impedance analyzers and RLC-meters [3]. It has a complicated functional circuit and working range up to 100 kHz. The requirements to the impedance measuring gauge for testing the sterility are to a great extent different from those of common use. The most principal difference consists in the preliminary known narrow field of changing of the resistive component which changes up to several percentages of its rated value. Taking into account the equivalent substituting circuit, shown on Fig. 2, by increasing the working frequency we achieve better results.

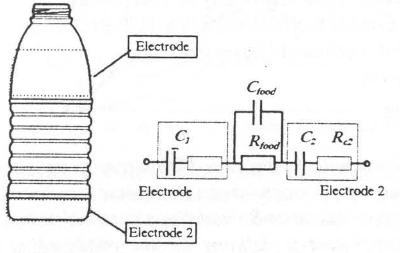

Fig.2 Plastic bottle with two external electrodes for non-destructive sterility testing and the equivalent electric circuit of the measured impedance.

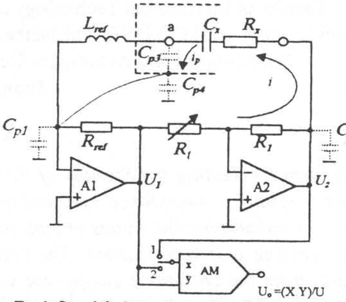

Fig.3. Simplified impedance interface circuit.

Now we shall consider a specialized technique for measuring of the impedance which operates in the frequency range up to 10 MHz. This technique uses a second-order harmonic oscillator and is developed for the needs of non-destructive testing of sterility [4, 5, 6]. As a whole the technique is based on the change of the conductivity of the food product which is caused by the growth of a large number of bacterial species.

For the testing of great quantities of products we are interested mainly in the accurate and fast measurement of the resistive component of the impedance. The capacitive component (the wall of the package) is connected consecutively with the resistive one and gives information about the quality of the food container. The values C_1, C_2, R_{C1} and R_{C2} depend on the surface of the testing electrodes and the quality of the polymer out of which the food containers are made. The values of R_{food} and C_{food} depend on the state of the tested product. For sterile UHT-milk the typical values are: $C_1+C_2 \approx$ 250 pF, R_{food} is about 50 Ω at working frequency of 1÷2 MHz; for fish sauce the R_{food} is approximately 20 Ω at working frequency of 3÷5 MHz.

The basic function of the microcontroller is to configure the measuring converter and to take with sufficient accuracy the length of the width modulated by the converter output impulses. The numerical equivalent of theses impulses is sent by means of RS 232 communication port to the computer (3) (Fig. 1) for further processing and visualization of the measuring process. The decisions for switching over of the working conditions, the range of the system and for optimizing of the measuring time are taken using the data stored in the microcontroller.

Section II discusses the principle of operation of the interface circuit. In section III the measurement setup is presented. In section IV the experimental results are presented and discussed. Finally, the conclusions are in section V.

II Principle of operation

The main blocks of the interface system for testing of sterility are: a second-order harmonic oscillator, an analogue multiplier and a controller.

A natural choice of a resonator is a serial RLC group in which R_x and C_x are the components of the unknown impedance and L_{ref} is known reference inductance. It is assumed that the operational amplifiers (Fig.3) are ideal - $A_1+A_2=\infty$ and their frequency band is unlimited. The circuit will start oscillating at a frequency which is equal to that of the series resonance:

$$\omega_o = 1/\sqrt{C_x L_{ref}} \quad (1)$$

if the condition is fulfilled

$$(R_{ref} R_1)/(R_x R_t) = 1 \quad (2)$$

The amplitude of the oscillations is defined by (2). If it is necessary to have oscillations for the different values of R_x we have to change the value of one of the rest three resistors, so that the condition (2) should always be valid. For this purpose the variable resistor R_t is used. When we know its value, it is easy to calculate the value of R_x. If the frequency of the oscillating signal is measured, we can also calculate the value of the unknown capacitive component C_x (1). The advantages of this solution are that there is no need of an external oscillator and detector. On the other hand there is always maximum sensibility for the unknown resistive component R_x because the frequency of the generations is always equal to the frequency of the generated oscillating circle.

A practical realization of such an oscillator is shown on Fig. 4. The potentiometer R_t (Fig. 3) is replaced by a MOSFET transistor. Its gate voltage may be used for calculating the value of R_x. If it is necessary, its characteristic may be made linear. Its temperature dependence is a problem. In this case for defining of R_x is used the ratio U_1/U_2. The both voltages are measured in two steps by means of an analogue multiplier – AD835 (Fig. 4). First, we measure their multiple:

$$U_{o1} = \frac{U_1 U_2}{U} \quad (3)$$

and then the square of the first voltage:

$$U_{o2} = \frac{U_1^2}{U} \quad (4)$$

The voltages U_{01} and U_{02} are constant, measured at the output of the multiplier and U_e is a reference voltage which is fed to the integrated circuit. By dividing (3) by (4) we receive the ratio

$$\frac{U_{o1}}{U_{o2}} = \frac{U_2}{U_1} = \frac{R_x}{R_{ref}} \qquad (5)$$

From (5) we can calculate the resistive component R_x

$$R_x = R_{ref} \frac{U_{o1}}{U_{o2}} \qquad (6)$$

The value of the capacitive component C_x may be defined if we know the frequency of the oscillated signal

$$C_x = \frac{1}{L_{ref} . \omega_0^{\ 2}} \qquad (7)$$

The applied method has three basic advantages. First of all, by using the ratio of the two output voltages of the multiplier we eliminate its multiplication error, which at high frequencies could be significant. Secondly, the harmonic distortions at the output of A_2 caused by the variable resistor R_t, are reduced. The distortions of the signal U_2 are the highest when the potentiometer is at the highest value. At the same time the oscillator acts as a filter for the high-level harmonics. When U_1 is multiplied by U_2 only the first harmonic of U_2 really exists in the measured constant voltage at the output of the multiplier.

Another advantage is related to a partial compensation of the error due to the phase shift:

$$\varphi_A = \varphi_{A1} + \varphi_{A2} \qquad (8)$$

caused by both amplifiers. This phase shift forces the oscillator to operate at frequency ω_g, which differs from the resonance frequency ω_o of the oscillating circle.

$$\omega_g \approx \omega_o \left(1 + \frac{\varphi_A}{2Q}\right) \qquad (9)$$

where Q is the quality factor of the oscillating circle. Taking into account the phase error caused by the amplifiers we can notice that the equation (5) will undergo changes

$$U_{o1} = \frac{U_1 U_2 \cos(\varphi_{A2})}{U} \qquad (10)$$

From the last equation it is realized that the full compensation of the error is achieved when

$$\varphi_{A1} << \varphi_{A2} \tag{11}$$

The value of R_x has a direct effect on the quality factor Q. In order to preserve the oscillating frequency ω_g independent of the value of Rx, from which we calculate C_x, we have to use an amplifier introducing small phase shift in the range of the oscillating frequency (see 9).

The use of a controller reduces the time for measuring. It is divided into three intervals. The first one - for measuring of the period and during that time we count the incoming impulses at the input F (Fig. 4) of the controller. The received periodogram has relative error

$$\varepsilon_{max} = \frac{1}{N} \tag{12}$$

where N represents the number of the counted impulses.

It is foreseen the time for counting of the impulses to be adjusted from 1 up to 250 ms depending on the needs of the customer. The second interval of time is used for measuring the voltages at the output of the analogue multiplier AD 835 in both working conditions. The total time for measuring plus the time provided for adjusting of the output voltage is 4,8 ms. The third interval of time is used for the transfer of information between the controller and the personal computer. It is neglectfully small in comparison with the other intervals.

The calculations of the above worked out equations, when the initial values of L_{ref}, R_{ref}, U_{ref} etc. are introduced, are performed in real time by the software programme of the personal computer.

III. Measurement setup

The experiments were carried out with the circuit shown in Fig.4. For a reference inductance L_{ref} we used molded inductors IM-6-38 (Dale Electronics, Inc.) with features: small package, epoxy molded construction with superior moisture protection, high Q and self-resonant frequency, low DC resistance, and an insulation resistance higher than 1000 MΩ.

The undumping circuit is realized with two wide frequency bandwidth ($f_{-3dB} \approx 850$ MHz) current-feedback operational amplifiers OPA 660 (Burr Brown). A current-feedback operational amplifier (CFOA) is the best choice in our application for two reasons. Firstly, it has a high-frequency performance that is superior to the performance of the voltage-feedback amplifiers (a higher cut-off frequency; f_{-3dB}). This means we have a lower phase shift φ_A in our measurement frequency range. Secondly, the cut-off frequency and the phase shift φ_A change only slightly for different values of R_x. In this way, although a multiplicative error is introduced, the transfer characteristic stays linear and the phase-shift error in (10) can be cancelled by using the multi-signal measurement technique. The relatively high input noise current of CFOA (a few tens of pA/√Hz) is not a serious problem in this application, because the loop current we use is in the mA-range and besides, the output noise of A2 is filtered by the resonance circuit.

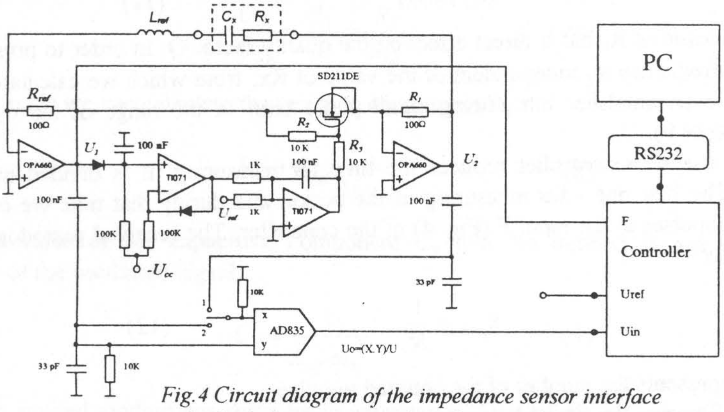

Fig.4 Circuit diagram of the impedance sensor interface with which the experimental results were obtained.

The automatic gain-control circuit (AGC) is realized with two OpAmps TL071 (TI), and the MOSFET SD211DE (Siliconix) is used as a voltage-controlled resistor. By keeping the amplitude of U_1 constant the AGC circuit fixes the loop current $i \approx U_1/R_{ref}$, so it is independent of the value of R_x. With resistor R_2 and R_3 the linear operating region of the MOSFET has been extended [7].

For the AC-to-DC conversion we use the four-quadrant voltage-output multiplier AD835 (Analog Devices). It has an internal reference voltage U with a nominal value of 1.05 V and –3 dB output bandwidth of 250 MHz. The inputs of the analog multiplier are capacitively coupled to the outputs of the amplifiers A1 and A2. For the biasing of AD835 two resistors of 10k are used in parallel with capacitors of 33 pF, which produces an output offset voltage of about 52 mV. The capacitors are to prevent that the circuit oscillates at frequencies higher than 10 MHz.

For switching over of the separate working conditions, measuring of the oscillated frequencies and sending of the result of this measurement to the personal computer is used a microprocessor PIC16F876 (Microchip). The relatively high frequencies which have to be measured by the processor enforce the using of an external 8 bit counter 74HCT4520 which is cascade connected with the internal for the processor 16 bit Timer. The timer operates in counting mode. As a result we have a 24 bit counter. In this way the usage of the interruption, generated by the Timer in case of its overfilling, is eliminated too. The measuring time for one frequency may be changed in the range from 1 to 250 ms.

The connection with the personal computer is accomplished by means of the RS232 communication protocol. The exchange is realized at speed of 19200 bytes per second.

Results, sent to the personal computer are visualized by an interface programme. By using it the customer has the opportunity to change the time for measuring; to average the results of the measurements and to record them in a file; to include a service working mode. The service working mode is foreseen for testing of the hardware. This means that it is possible to switch over to one of the working modes of the oscillator and this state is preserved till giving a new command.

IV. Experimental results

With a spectrum analyzer the harmonic distortion levels of U_1 and U_2 (see Fig.4) were measured for two values of R_x: - 50Ω and 100Ω, and for an amplitude of U_1 of 0.75 V. Table 1 presents the results for the measured relative power of the second and the third harmonic of U_1 and U_2 with respect to the power of the first harmonic. As one can see, the distortion level of U_2 is quite low and it is further reduced by the filtering effect of the resonator. Figure 4 shows the relative error of the measured resistive component R_x of the impedance versus its value for two frequencies: – 1032 kHz and 1871 kHz. The measurement range of the resistive component was from 30Ω to 170Ω.

F, MHz	Rx, Ω	Harmonics of U_1		Harmonics of U_2	
		2^nd^, dBm	3^rd^, dBm	2^nd^, dBm	3^rd^, dBm
2	50	-42	-39	-26	-30
	100	-44	-45	-30	-40
6	50	-32	-43	-19	-30
	100	-35	-49	-30	-46
9	50	-30	-42	-20	-38
	100	-31	-47	-27	-45

Table 1

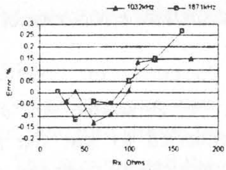

Fig.5. Relative error of the measured resistive component for lower frequencies.

As a reference the Impedance Analyzer HP4194A was used, whose error for this frequency range does not exceed 0.125%. The measurement results showed a maximum error of ±0.15% for frequency 1032 kHz and a maximum error of + 0.3% and –0.2% for frequency 1871 kHz.

For higher frequencies the Impedance Analyzer was not suitable as a reference measurement instrument as its error increases rapidly with frequency; at 10 MHz it is already above 1%. For this reason we took as reference our result for R_x=100Ω and by changing the DC value of R_x with 10Ω we covered the range from 30Ω to 200Ω. Figure 5 shows the error with which we measured the relative changes of R_x. For values of R_x below 100Ω, which is the range that is most interesting for us, the error is within ± 0.2%. Above 100Ω the error starts to grow. The highest value is 1.1% for frequency 9.9 MHz and R_x=180Ω. The errors displayed in Fig.5 and Fig.6 have a clear systematic component,

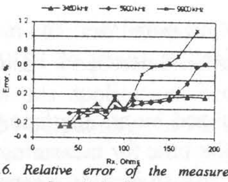

Fig.6. Relative error of the measured resistive component Rx at higher frequencies.

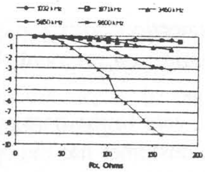

Fig.7. Dependence of the oscillating frequency on the value of Rx.

which can be explained with expression (10). For higher values of R_x and lower values of Rt, the phase shift φ_{A1} of A2 is slightly growing and the phase shift φ_{A2} of A1 is decreasing, which ensures better frequency compensation. The systematic error, especially for values of R_x above 100Ω, can be further reduced by using, for example, an appropriate read-out table.

Figure 7 shows the dependence of the oscillating frequency on the value of the resistive component R_x. This dependence means that the value of C_x is a function of R_x. For frequencies up to 2 MHz, the frequency changes only with ± 0.25% for R_x from 30Ω to 170Ω. With an increase in frequency the same small variation of the frequency is achieved for a reduced range of R_x. In other words, if the value of R_x is higher the measurement frequency must be lower in order to keep the error for C_x small. This is, of course, a natural choice for many applications, including the one presented in this article. An alternative solution is to compensate the error of C_x by applying a multi-signal or statistical error-correction measurement technique.

IV. Conclusions

A simple self-oscillating circuit for impedance measurement is presented. It is intended to test the sterility of aseptically packed food products by measuring the conductivity changes of the packaged food in a non-destructive way. The oscillator has been built with fast current-feedback OpAmps. To measure the resistive component of the impedance, we used an AC-to-DC converter with a wide frequency range analogue multiplier.

The advantages of this interface circuit are – (i) an external oscillator is not needed, (ii) synchronous detection is not necessary, (iii) at resonance frequency the reactive components compensate each other to ensure the highest possible sensitivity for the resistive component.

The presented experimental results prove that with this system, an accurate measurement of the impedance components can be achieved in a frequency range up to 10 MHz.

References

[1] D. Marioli, E. Sardini and A. Taroni, High-Accuracy Measurement Techniques for Capacitance Transducers, *Measurement Science and Technology,* Vol. 4, pp. 337-343, 1993.