ERROR SOURCE IDENTIFICATION AND STABILITY TEST OF A PRECISION CAPACITANCE MEASUREMENT SYSTEM

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Abstract: An experimental study is reported for low-frequency noise behavior and identifying the error source of a capacitance measurement system. A test set-up and a special test strategy for this measurement were applied to differentiate between the kinds of external low-frequency interference. The set-up and strategy allowed accurate measurement of the low-frequency component of the intrinsic input noise of the capacitance measurement system. The capacitance measurement system reported was found in the study along with an extremely low value for the low-frequency (1/f) noise with a corner frequency of 2 mHz, and a very high thermal stability of 2 ppm/K, which confirm the design target of this capacitance measurement system.

Key words: Measuring capacitor, low-frequency noise, stability, drift, humidity dependency.

1. INTRODUCTION

Capacitive sensors are popular in industry for displacement measurement, acceleration measurement, pressure measurement, etc. Such a measurement concept can be realized in a simple way and it performs well. In [1] a fast measurement system for capacitance is reported which is intended to be used as interface for multi-channel capacitive sensors with a maximum capacitance of 1pF. The capacitor measurement system is designed to fit the requirements for the continuous measurement of capacitance with high accuracy, yet without the need for periodic calibration [1]. The requirements are namely a very high level of stability and extremely low drift in time and with environmental conditions. The system level design of the charge measurement system can be found in Figure 1.

The measurement is performed by applying an excitation voltage ΔU at the unknown capacitance C_{xi} and measuring the stored charge Q_x in the voltage. The unknown charge Q_x is amplified 50 times by an input charge amplifier and is summed with a reference charge Q_N with opposite polarity, which is generated in a reference charge generator. The sum ΔQ is fed to an integrator. The output voltage of the integrator U_{int} is monitored with a comparator. The state of the comparator controls the reference charge generator and holds the integrator output at 0V. This condition is achieved when the reference charge is equal to the amplified input charge. When the amount of the reference charge has been determined, the gain of the input amplifier and the excitation reference voltage are known, the value of the unknown capacitance is defined. The role of the clock is to accurately define the value of each charge quant which builds up the reference charge. The control logic modifies the contents of the charge-counter every time a charge quant is added or removed from the reference charge.

The measurement is executed in two cycles using both directions of the excitation voltage change. In this way, the input offset voltages and the low-frequency noise of the input amplifier and the integrator are cancelled. The excitation voltage generator and the reference charge generator use a common voltage reference. Therefore, slow variations in the reference voltage do not influence the accuracy of the measurement system [2].

With this principle of operation, the measurement system should have an excellent performance with regard to long-term stability. The reference components of the transfer function are time, the absolute value of one resistor, and the ratio between resistor pairs. All these components are very stable over both temperature and time [2].

However, previous applications of the capacitance measurement system showed drift of the output signal over time and out-of-spec 1/f noise, which should not be there. Thus, a systematic and experimental study of the capacitance measurement system was carried out in order to identify the errors source of such drift and 1/f noise. A new test set-up and test routine were created and applied to reduce the different kinds of interference from the environment to a minimum, which helps in identifying the possible cause of the intrinsic drift and 1/f noise.

For our measurement, the performance of our test set-up was first thoroughly investigated with respect to reference stability, EMI effects, temperature control, and vibration. Numerous tests with modifications of the set-up helped to identify and largely minimize the sources of drift mentioned above.

Next, we investigated the temperature behavior of the capacitance measurement system. A negative temperature coefficient was measured by applying a proper temperature swing.

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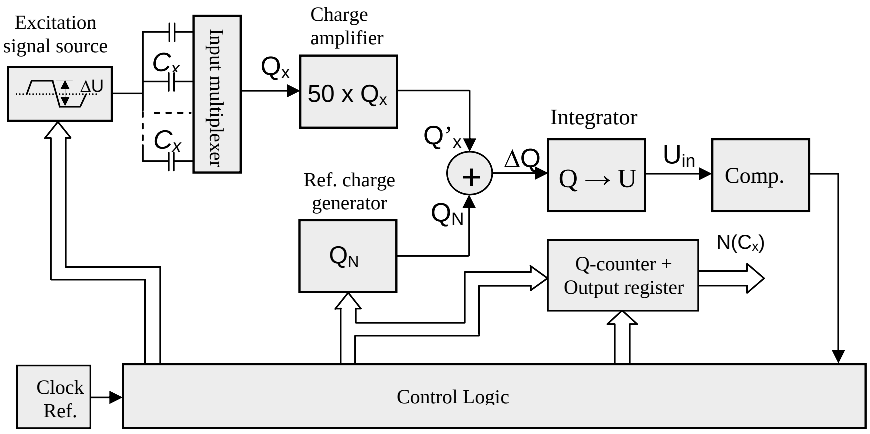


Figure 1. The capacitance measurement system.

This paper provides a demonstration of the test set-up and the most important test results related to the low-frequency noise and the stability. The test results confirm the excellent performance of the capacitance measurement system, which is in agreement with the design targets. A discussion of the test results is also given.

2. TEST STRATEGY AND METHODS

Since thermal stability and 1/f noise were the point of interest in this investigation, a long-term test and a test with temperature variation was required.

Usually when the intrinsic noise of an electronic circuit is measured, the input of the electronic circuit (which is most sensitive to interference) is short-circuited to avoid any external interference, after which the noise at the output of the circuit is measured. This approach is applicable in amplifiers using the so-called "chopping technique", which eliminates the low-frequency component of the input noise and the input drift [3,4]. The principle of operation for the capacitance measurement system also incorporates a kind of chopping technique. However, the realization of this chopping technique requires the use of an external capacitor plus an excitation signal, meaning that the input-noise cannot be measured simply by short-circuiting the input of the system. On the contrary: we have to cope with potentially significant sources of drift (the external capacitor) and a path for external interferences (the cables used to connect the external capacitor to the input of the capacitance measurement system). The main objective of the selected test strategy is therefore to reduce to minimum the effect of these external components on the measurement result.

Figure 2 presents the basic measurement set-up. The set-up includes the DUT (device under test, i.e. the measurement system being tested), an external reference capacitor, and a computer to process the output data. The reference capacitor consists of two parallel plates and is placed in an oven where the temperature and the humidity level can be either programmed or controlled manually (see Figure 3). The value of the reference capacitor is 0.5 pF, which is in the middle of the measurement range of the DUT. In order to make the reference capacitor insensitive to the variation of the temperature in the oven around its set value, aluminum blocks with a large thermal capacitance are placed around it. The capacitor is connected to the measurement system using twisted and shielded wires in order to avoid external interference. Finally, with the help of Pt-100 sensor, the temperature of the capacitive sensor is measured.

The capacitance measurement system is placed in another oven, where the temperature can also be monitored and controlled by computer (see Figure 4). The analog front-end of the system (charge amplifier) is most sensitive to temperature variations, which is why another aluminum block is attached to the charge amplifier in order to increase the thermal constant and to stabilize the temperature. At the same time, this aluminum block improves the immunity of the analog component to electromagnetic interference. Temperature sensors are mounted on the board being tested to monitor the temperature change during the tests.

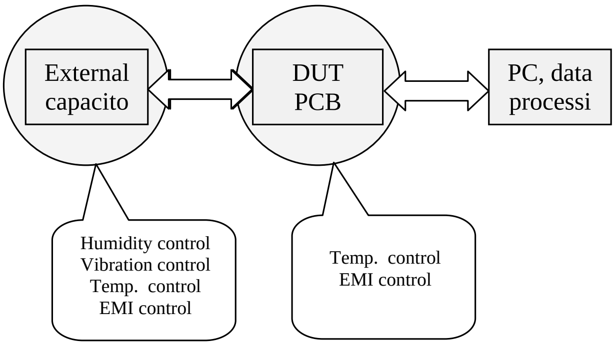


Figure 2. Basic measurement set-up.

Figure 3. The external reference capacitor in an oven encapsulating an Al block with vibration dumping.

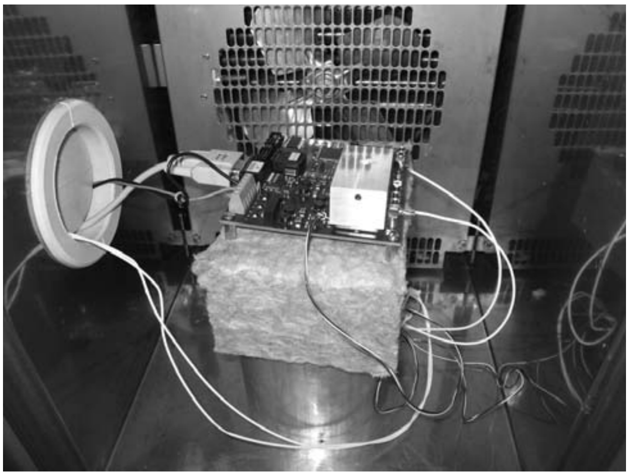


Figure 4. Photo of the capacitance measurement system PCB board in a second oven. An Al block additionally stabilizes the temperature of the input stage.

The measurement system (DUT) is connected to a computer, where control, data acquisition and data processing are performed. For the noise test, the power spectrum density of the measurement data is extracted to see whether it meets the specifications; for the long-term stability test, a moving average of 10,000 samples is applied, which increases the resolution and allows monitoring of the temperature behavior of the capacitance measurement system.

Two types of experimental studies of the DUT were performed: (1) a study of the 1/f noise and (2) a study of the long-term stability. For the study of the noise behavior, special attention was paid to the mechanical vibration of the set-up, since extremely small capacitance values are measured. Any vibration in the set-up may cause relative displacement of the two plates of the reference capacitor, and consequently generate noise at low frequencies, which is exactly the frequency band of our interest. Therefore, a vibration absorption structure was added to the set-up which mainly focuses on the reference capacitor. To test the dumping effect of the anti-vibration structure, experiments with and without vibration absorption were performed, and the results are presented in the next section.

Another issue with regard to the low-frequency noise experiment is the temperature control of the DUT. Since the effect of self-heating cannot be ignored, the DUT has to be placed in a temperature-stable environment to achieve accurate results.

During the experimental study of the long-term stability and the temperature coefficient of the DUT, attention was paid to the control of the humidity of the environment for both the board and the reference capacitor. The relative humidity was maintained at a constant low level throughout the test, since an increase in the humidity level can affect the value of the reference capacitor and the DUT itself.

Electromagnetic interference (EMI) can also be a source of noise. To prevent this from happening, the two Pt-100 temperature sensors, which were placed in the reference sensor and on the DUT, were electrically shielded. Additionally, the oven acted as a shield for the DUT.

3. EXPERIMENTAL RESULTS

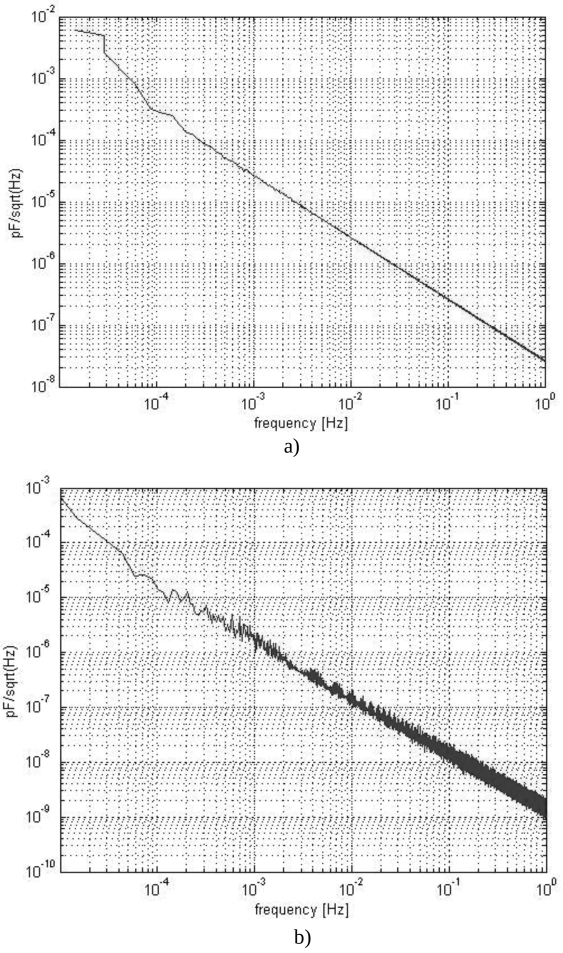
3.1 Preliminary tests

A number of preliminary tests were performed to identify and consequently eliminate or control the effect of external disturbing factors like mechanical vibration, humidity, and temperature variation in the noise performance of the DUT.

Mechanical vibration: One of the ‘prime suspects’ for the external contribution to the 1/f noise of the DUT was the susceptibility of the external reference capacitor to mechanical vibrations. To check the efficiency of the applied vibration dumping, two measurements were performed: one measurement with mechanical vibration suppression of the oven and the other without. A comparison of the results with and without mechanical vibration suppression is shown in Figure 5. The plot in Figure 5a is the power spectrum density (PSD) of the output noise without vibration control in the test set-up, while the plot in Figure 5b is the output PSD with vibration control in the test set-up. From this comparison it can be concluded that the small vibration of the oven does contribute to the low-frequency noise, since the plot on the left has a PSD noise level that is one order of magnitude higher in the low-frequency range. Since the focus is only on the low-frequency (i.e., 1/f) behavior resulting from the moving averaging of 10,000 samples at the output, the “noise floor” in Figure 5 cannot be seen.

Thermal effect and thermal stability: The next experiment focused on the thermal stability of the DUT. The temperature behavior of the DUT was tested by applying a temperature swing to the board and recording the output data. The result is presented in Figure 6.

The plot in Figure 6a shows the temperature swing in the oven, while the plot in Figure 6b shows the respective temperature of the DUT recorded by the Pt-100 temperature sensor. Since an aluminum block was added to the board, a thermal filtering effect was demonstrated. The time constant of the thermal filter is clearly larger than the period of the temperature swing applied, which results in a smoothing of the temperature swing. The plot in Figure 6c shows the output signal of the DUT during the temperature swing. There is a clear correlation between the temperature change and the variation of the output signal. From the experimental results presented above, a temperature coefficient of less than -2 ppm/K was calculated by dividing the relative variation of the output signal of the DUT by the value of the thermal swing. The obtained result demonstrates very good thermal stability of the board.

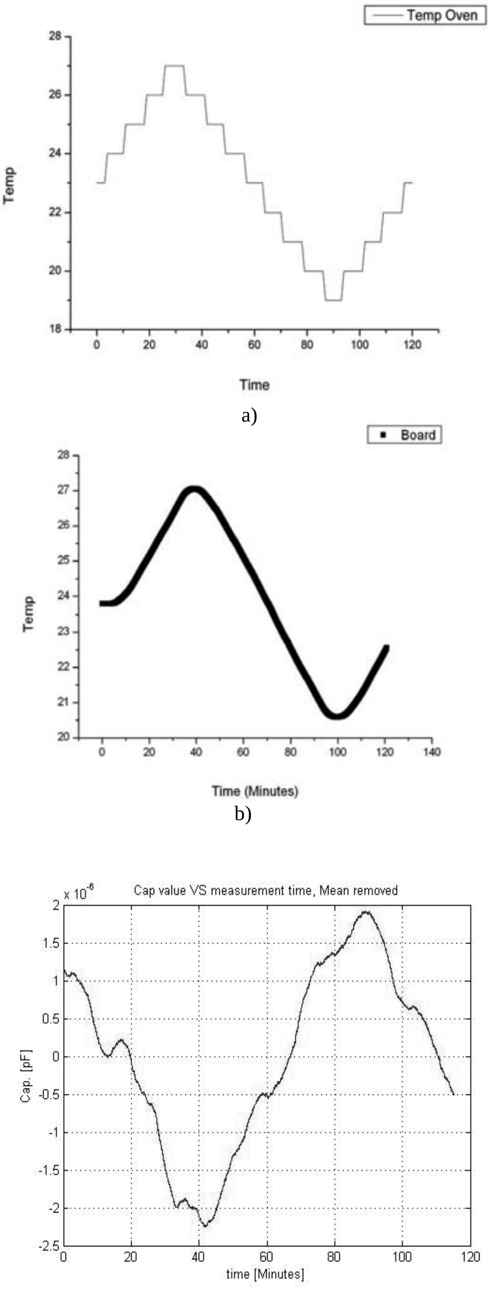


a)

b)

Figure 5. PSD of the measured output noise (a) with and (b) without vibration suppression of the set-up.

We conducted a similar temperature-variation test with the reference capacitor. The measured thermal coefficient of the capacitor was 0.7aF/K.



a)

b)

c)

Figure 6. Thermal behaviour of the DUT: (a) temperature swing in the oven; (b) respective temperature swing of the DUT; (c) output signal of the DUT during the temperature swing.

Humidity effect: Relative humidity (RH) variation of the measurement environment may have an effect on both the external reference capacitor and the DUT, even when the temperature is constant. Two experiments were performed at a fixed temperature for both the reference capacitor and the DUT. In one experiment, the relative humidity was varied from 30% to 50% and back to 30% in the oven where the reference capacitor was conditioned (see Figure 7). In the second experiment, the relative humidity in the oven of the DUT was varied from 30% to 40%, and again back to 30% (Figure 8).

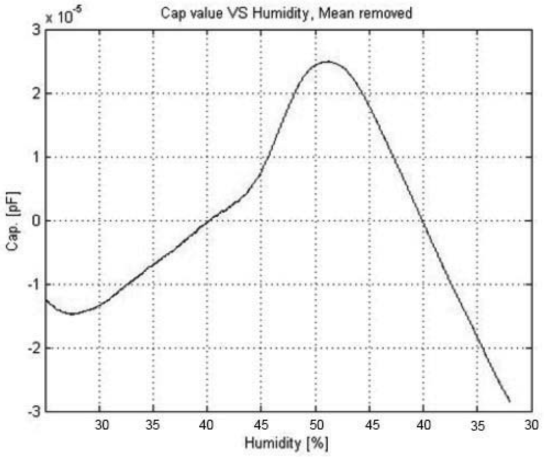


Figure 7. Corresponding change of the measured capacitance with the relative humidity swing of the reference capacitor from 30% to 50% and back to 30%.

There is a clear correlation between the relative change in humidity and the change in the measured capacitance value. The sensitivity to humidity variation of the reference capacitance extracted from Figure 7 is 3aF/1%RH.

In this second experiment, we could not identify a correlation between the relative humidity change and the change of the measured capacitance value (see Figure 8). First, when the humidity increased, the output signal of the DUT also increased. However, it did not decrease when the humidity returned to its original level. Considering the extremely low variation of the measured capacitance during this experiment and the lack of correlation between the input signal (humidity) and the measured capacitance variation, we can assume that what we measured in this case was just a noise. The conclusion we can make is that the sensitivity of the PCB to humidity variation of the reference capacitance is less than 0.2aF/1%RH.

Measurement of 1/f noise: For this last experiment, all measures were taken to stabilize the test environment and to avoid external interferences.

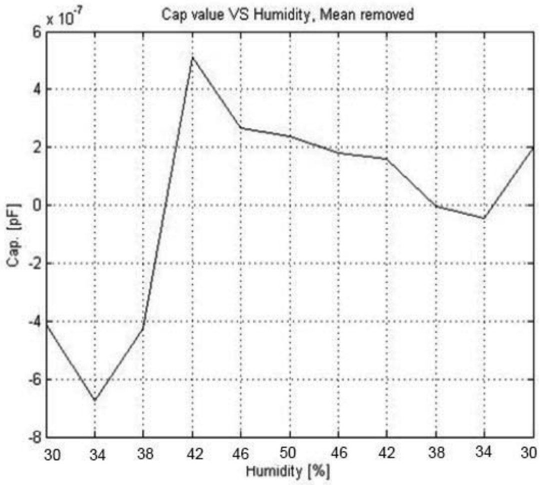


Figure 8. Measured capacitance during changing the relative humidity in the oven of the DUT, from 30% to 50%, and then back to 30%.

A long-term test was performed to measure the low-frequency input noise of the DUT. All the techniques mentioned above – vibration control, temperature control, EMI control, and humidity control – were used to avoid any effects of environment instability on the noise measurement result. The duration of the tests was 100 hours. The variation of the temperature during this test of both the DUT and the reference capacitor was 0.2 K. The generated noise due to the temperature variation of the PCB, keeping in mind the result in Figure 6, was less than 0.1aF. The noise contribution of the temperature variation of the reference capacitor was less than 0.2 aF. As can be seen from Figure 9, both values are well below the white-noise floor of the measured noise.

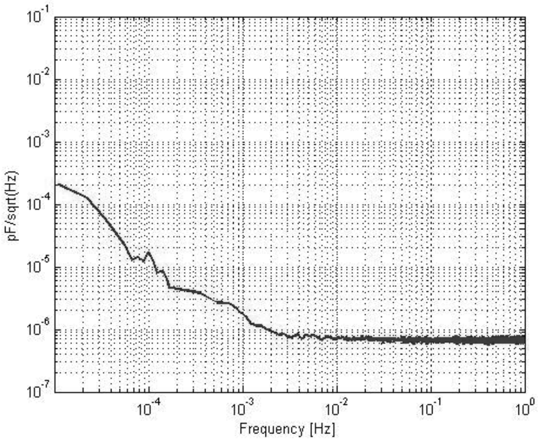


Figure 9. Long-term measurement result, where all technique of reducing external interference are applied**.**

During the last test, the variation of the humidity of the reference capacitor was less than 0.2%. With the help of the result presented in Figure 7, we calculated the noise contribution of the humidity variation, which was 0.6 aF, which is also below the value of the measured white-noise. The humidity variation of the DUT during the 1/f noise tests was within 0.5%. The contribution of this noise source was only 0.1 aF.

The power spectral density (PSD) of the measured data is presented in Figure 9. The measured noise floor was in the range of 1aF. The corner frequency of the 1/f noise was about 2 mHz, which is a very good result.

4. CONCLUSION AND DISCUSSION

In this paper a systematic test strategy for a capacitance measurement system was presented together with the test results. From the entire test procedure we can conclude that the DUT performs much better than what was concluded from previous tests results.

Any small variations in the environment, such as temperature, humidity, or vibration, will affect the measurement result mainly caused by the external reference capacitor instability.

By reducing the level of instability caused by external factors below the white-noise floor, a 2mHz 1/f-noise corner frequency was measured.

With regard to the thermal stability of the DUT, the tests showed a thermal coefficient of less than 2 ppm/degree, which is a very good achievement.

A valid question is: where, after all, is the residual 1/f noise coming from, after the chopping technique has been applied? In our opinion, there are three possible sources:

1) The presence of 1/f noise in the excitation signal of the DUT, which cannot be reduced by the chopping technique;
2) Parasitic signal paths on the PCB board of the capacitance measurement system;
3) The reference capacitor. Environmental dependence of the capacitance value is expected to have at least three contributions: a) relative dielectric permittivity b) mechanical effects and c) surface layers on the capacitor electrodes. Given the small frequency dependence of the dielectric constant of air, and the small mechanical effect as mentioned above, we thus relate this to surface effects, i.e., the adsorption and desorption of water on the surface. In [5], it is found that this layer will result in a strong frequency dependency of the capacitor, and will lead to a different humidity co-efficient at different frequencies. This frequency dependence is an important error source and should not be included in the 1/f noise contribution of the DUT.

This performance of the capacitance measurement system allows it to be used in applications where long-term measurements need to be performed without intermediate calibrations. For example, one such application is in space to measure very slowly changing displacements caused by fundamental universal phenomena.

More experiments will be conducted in the future to try to locate the main sources of the remaining low-frequency noise and to further improve the performance of the DUT.

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