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Test Fixture Compensation Techniques in Impedance Analysis

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Introduction

The complex impedance measurement is widely used electronics design for ultrasonic systems [1, 2], material properties investigation and condition monitoring [3]. Impedance spectroscopy is applied in medicine and biology [4], fuel cell characterization [5].

The impedance spectroscopy is complicated by acquisition system and test fixture errors. This paper is analyzing the compensation techniques performance for frequency range up to 20 MHz. The investigation has been based on automated impedance measurement system [2] developed by authors.

The measurement system

The automated impedance measurement system [2] is targeted for the impedance measurement application. The system structure is presented in Fig.1.
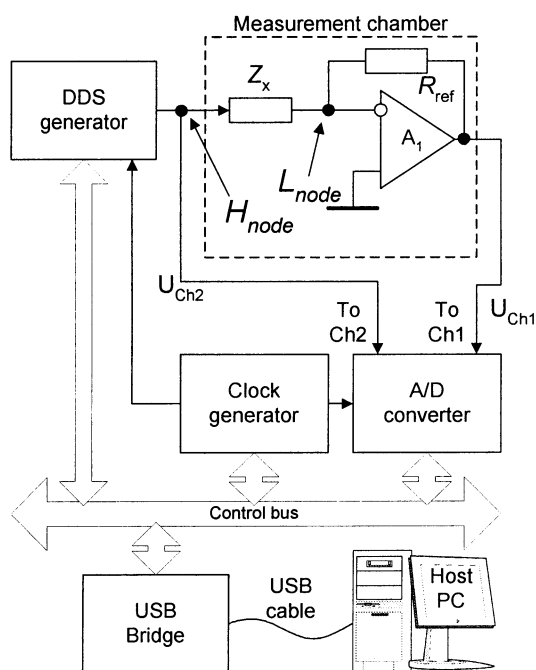

Fig. 1. System employing the auto-balancing bridge structure

System is using the auto-balancing bridge (ABB) technique for impedance measurement. It contains the direct-digital-synthesis (DDS) based excitation signal generator and two simultaneous 10 bit analog-to-digit converters (ADC) for resulting waveforms collection. The data sampling rate can be selected in 1 Ms/s to 100 Ms/s range. The ADC is using two 256 k samples deep memory banks. The system control and data collection is performed by the host PC via a high speed USB2 interface. The device under test (DUT) is connected to nodes H and L.

The amplitude and phase estimation is done by the sine wave correlation (SWC) technique [1]. The fitting function is:

$$u(t) = U_c \cos(2\pi f t) + U_s \sin(2\pi f t) + U_0, \quad (1)$$

where U_c and U_s are the in-quadrature amplitudes, U_0 is the DC component and f is the excitation frequency. This method does not require the frequency estimation if common clock source both for exciting signal generation and waveform acquisition is used. The measured impedance Z_x can be calculated using Ohm's law from the voltage and current values. The ABB technique employs the inverting topology operational amplifier (Fig. 1). The current flowing through Z_x is mirrored by the resistor R_{ref} current. The potential at the operational amplifier inverting pin is maintained at zero (sometimes called a "virtual ground"). Then the Z_x current can be calculated using the voltage at the operational amplifier output:

$$Z_x = \frac{\overline{U}_{Zx}}{\overline{I}_{Zx}} R_{ref} = \frac{\overline{U}_{Ch2}}{\overline{U}_{Ch1}} R_{ref}. \quad (2)$$

The ABB technique has a disadvantage in accuracy at high frequencies: the "virtual ground" voltage is not maintained to zero due to the operational amplifier performance limitation at higher frequencies.

Simulation using P-Spice

In order to evaluate the ABB performance at higher frequencies the simulation using P-SPICE has been done. Two low noise operational amplifiers: AD8099 and

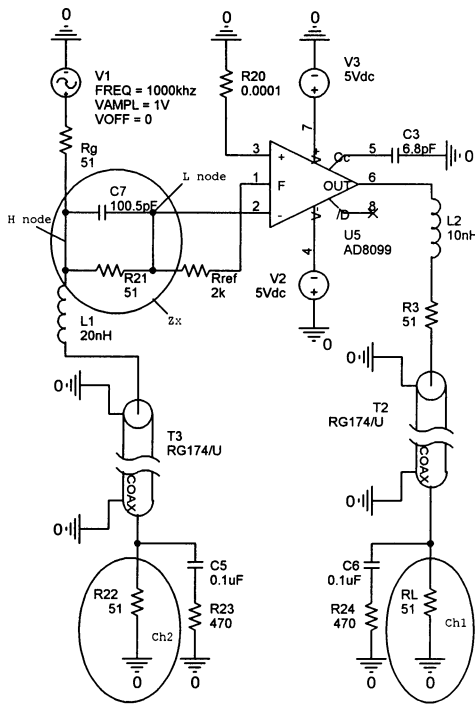LMH6624 have been used. The schematic diagram used in AD8099 modeling is presented in Fig. 2.

Fig. 2. Simulated circuit for AD8099 amplifier

Measurement channels Ch1 and Ch2 are connected to ADC using 0.5 meter long coaxial cables RG174/U. Inside the measurement chamber signal is routed using short piece of wire. These wires are simulated by additional inductance. The wire loss resistance is ignored since connection contains 51 ohm resistors and coaxial cable is modeled as lossy transmission line. The ADC input stage is simulated by R and C circuits (Fig. 2). The investigated circuit is the parallel connection of 51 ohm resistor and 100 pF capacitor. Additional 0.5 pF is used to simulate the test fixture parasitic capacitance.

The results obtained from P-SPICE simulation are presented in Fig. 3. Operational amplifier AD8099 has 3.8 GHz gain bandwidth product (GBWP) and LMH6624 has 1.5GHz GBWP. But due to limited open loop gain at high frequencies (only 40 dB at 20 MHz for LMH6624 and 50 dB for AD8099) the impedance of "virtual ground" is increasing, so is the voltage U_L.
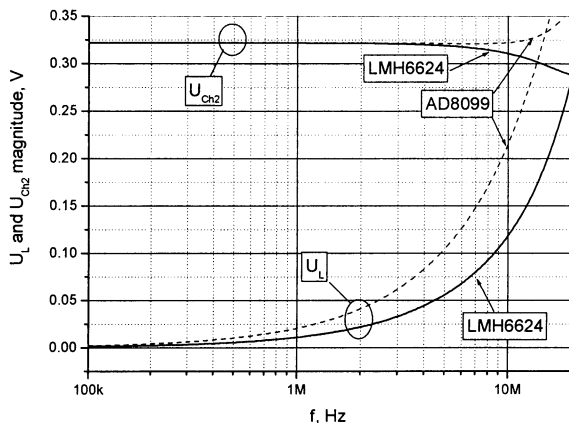

Fig. 3. Simulation results: voltage on nodes H (U_{Ch2}) and L (U_L)

Since the equation (2) assumes the voltage U_L to be zero, the obtained impedance is not correct (Fig. 4 and Fig. 5).
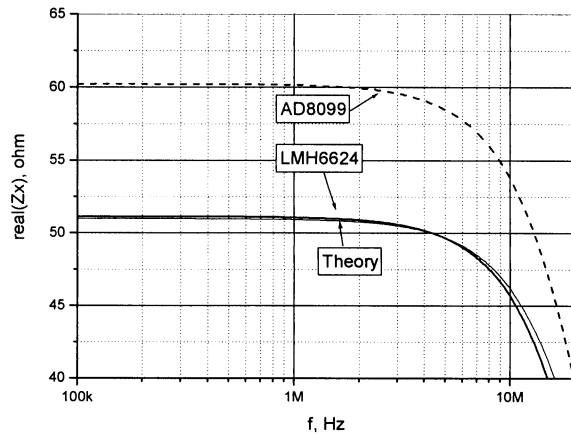

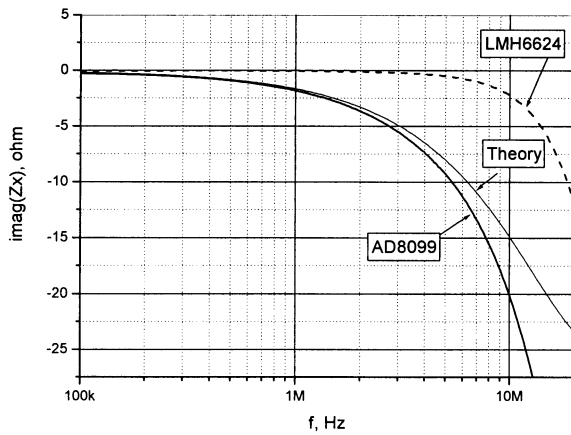**Fig. 4.** Real impedance part obtained from simulation

Fig. 5. Imaginary impedance part obtained from simulation

It can be seen from Fig. 3 that voltage U_{Ch2} is no longer equal to U_{Zx} at higher frequencies. Therefore the obtained impedance is deviating from theory. It is interesting to note that two aforementioned amplifiers have different influence: the LMH6624 has closer to theory results for real impedance part, while AD8099 has closer results for imaginary part.

Compensation and calibration techniques

The implementation of the remote measurements requires the cable application for shielding and signal routing. The imperfectness of the measurement circuit can be compensated in two ways:
-hardware compensation using additional electronics [3];
-the software compensation by using the additional Open/Short measurement results [6];
-the software compensation by using the results from Open/Short/Load measurement [7].

The hardware compensation should implement the additional instrumentation amplifiers to measure the U_{Zx} and U_{Rref} properly. The modification of the circuit presented in Fig.1 is suggested in Fig. 6. The software implementation requires additional measurements to be taken. It is can also be used in test fixture and acquisition electronics errors compensation. One measurement is taken when Z_x attachment nodes are shorted (Short measurement

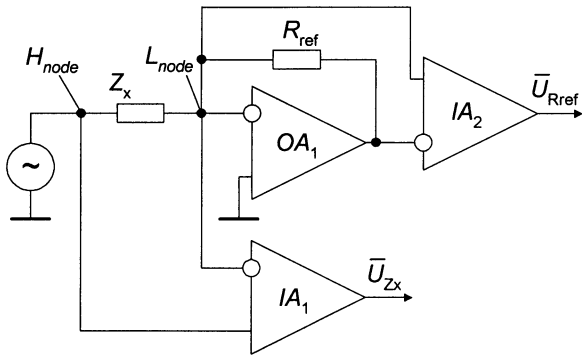- Z_s is obtained), while other is in Open condition (Z_o is obtained).

Fig. 6. Circuit diagram for node L compensation

Then the DUT measurement data Z_{xm} is compensated by using the stored Z_s and Z_o values to get the true DUT impedance value Z_{DUT}

$$Z_{DUT} = \frac{Z_{xm} - Z_s}{1 - \frac{(Z_{xm} - Z_s)}{Z_o}}. \qquad (3)$$

The Open/Short compensation only assumes that there is additional impedance placed in series and in parallel to DUT. The error sources introduced in the rest of circuitry and in acquisition part are impossible to compensate. The Open/Short/Load compensation allows for more exhaustive corrections. In addition to Open and Short measurements it is using the calibrated (known) load measurement. The measurement result Z_{stdm} of this standard device with a known impedance value in addition to the Open/Short measurement data is used to effectively solve the problems which cannot be corrected with the Open/Short compensation technique. Using the theoretical impedance Z_{std} of the calibrated load the true impedance value of DUT is calculated as:

$$Z_{DUT} = Z_{std} \frac{(Z_o - Z_{stdm}) \cdot (Z_{xm} - Z_s)}{(Z_{stdm} - Z_s) \cdot (Z_o - Z_{xm})}. \qquad (4)$$

While hardware implementation has the advantage of single measurement, the Open/Short/Load compensation seems the most attractive one since it is able to account for the imperfectness of the rest of the system.
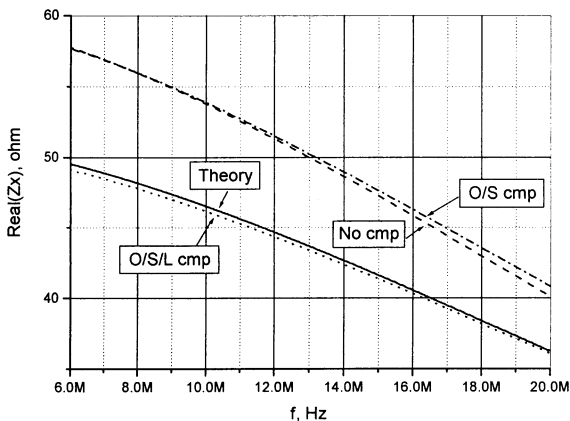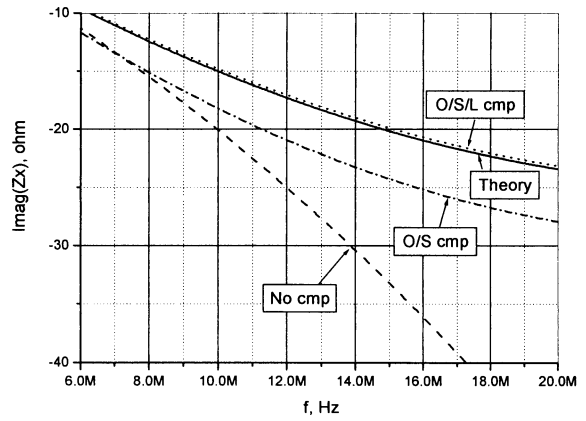

Fig. 8. Imaginary impedance compensation for simulated data

The hardware compensation is in full power when used in low frequency range. When compensation in high frequency range is needed the instrumentation amplifier availability (IA$_1$ and IA$_2$ in Fig. 6) is limited to a dozen of MHz. The analysis presented in [8] is analyzing the hardware introduced errors.

In order to evaluate the software compensation effectiveness, simulation using P-Spice have been done using the Open, Short and Load measurements. Open conditions measurement contained the 0.5 pF and 1 TΩ parallel elements connected to test nodes. The Short condition has been simulated by 0.5 pF and 0.001Ω elements. Load used 300.5 pF and 100 kΩ elements. The simulation results of same (Fig. 2) parallel connection of 51 Ω resistor and 100 pF capacitor as DUT impedance measurement are presented in Fig. 7 and Fig. 8.

The Open/Short only compensation is outperformed by Open/Short/Load compensation. Next chapter is presenting the experimental results of the software Open/Short/Load compensation technique.

Experimental results

Fig. 5 indicates AD8099 has better performance. The real world experiments and simulation have been carried out using this amplifier only. Same DUT and conditions for Open/Short/Load have been used. The obtained results then were used for software compensation. The experiment and modeling results of raw data and compensated results are compared against theory (Fig.9, Fig.10).
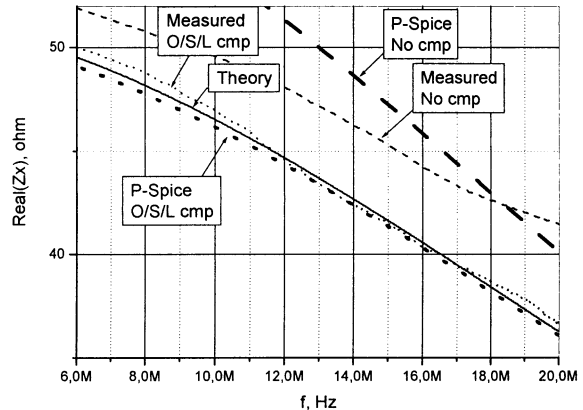

Fig. 7. Real impedance part compensation for simulated data

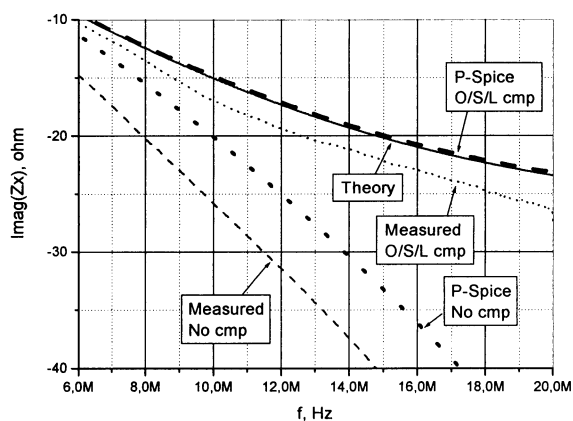**Fig. 9.** Real part of the measured impedance

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Fig. 10. Imaginary part of measured impedance

Figures indicate that software compensation is offering significant measurements results improvement. Results should be even better if combined with proper hardware compensation.

Conclusions

The test fixture compensation techniques for frequency range up to 20 MHz investigation indicates that software compensation is offering a powerful tool for impedance measurement quality improvement.

References

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L. Svilainis, V. Dumbrava. **Test Fixture Compensation Techniques in Impedance Analysis** // Electronics and Electrical Engineering. – Kaunas: Technologija, 2008. – No. 7(87). – P. 37–40.

The test fixture influence compensation techniques of the complex impedance measurement are analyzed. The auto-balancing bridge method has been selected for the measurements in 100 kHz to 20 MHz frequency range. The hardware and the software techniques for the test fixture influence compensation are briefly discussed. The complete simulation of the system using P-Spice has been done. The simulation results when using the OPA 8099 and the LMH 6694 operational amplifiers in the auto-balancing bridge method are presented. Three software compensation techniques for the test fixture influence have been analyzed and preliminary simulation and real world experiment results presented. The Open/Short measurement and Open/Short/Load software compensation techniques application results compared with theory both for P-spice simulation and experiment. Ill.10, bibl. 8 (in English; summaries in English, Russian and Lithuanian).

Л. Свилайнис, В. Думбрава. **Компенсация влияния устройств подключения к системе для измерения комплексного импеданса** // Электроника и электротехника. – Каунас: Технология, 2008. – № 7(87). – С. 37–40.

Проведен анализ компенсации влияния устройства подключения к системе для измерения комплексного импеданса. Исследован метод автоматического – балансового моста для измерения комплексного импеданса в диапазоне частот от 100 кГц до 20 МГц. Приведена короткая дискуссия аппаратных и программных средств компенсации влияния устройства подключения к измерительной системе. Произведено комплексное моделирование системы с помощью программы P-Spice. Представлены результаты моделирования при использовании двух типов операционных усилителей OPA 8099 и LMH 6694. Исследованы три метода компенсаций устройства подключения, представлены предварительные результаты измерений комплексного импеданса при использовании метода открытая цепь/закороченная цепь и метода открытая цепь/закороченная цепь/нагрузка. Приведены и сравнены результаты теоретического и экспериментального исследований. Ил.10, библ.8. (на английском языке; рефераты на английском, русском и литовском яз.).

L. Svilainis, V. Dumbrava. **Prijungimo įrenginio kompensacija impedanso matavimo sistemoje** // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2008 – Nr. 7(87). – P. 37–40.

Analizuojami kompleksinio impedanso matavimo sistemos prijungimo schemos įtakos kompensavimo būdai. Analizei buvo pasirinktas automatinio balansinio tiltelio metodas kompleksiniam impedansui matuoti dažnių diapazone nuo 100 kHz iki 20 MHz. Trumpai aptarti aparatiniai ir programiniai kompensavimo būdai. Atliktas kompleksinis sistemos modeliavimas programa P-Spice. Pateikti matavimo sistemos modeliavimo, naudojant operacinius stiprintuvus OPA 8099 ir LMH 6694, rezultatai. Išnagrinėti trys prijungimo schemos įtakos programinio kompensavimo būdai ir pateikti preliminarūs kompleksinio impedanso matavimo, naudojant atviros grandinės/trumpojo jungimo bei atviros grandinės/trumpojo jungimo/testinės apkrovos režimus, rezultatai. Tarpusavyje palyginti teorinių skaičiavimų, modeliavimo P-Spice ir realaus eksperimento rezultatai. Il.10, bibl.8. (anglų kalba; santraukos anglų, rusų ir lietuvių k.).