Lab session: acoustic device spectral characterization

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Objective

The objective of this preliminary analysis is to understand the meaning of quantities measured by a network analyzer during the spectral characterization of an unknown device: impedance, admittance, scattering coefficient, real/imaginary part or angle/magnitude. The initial steps aim at becoming familiar with these general concepts, while the **last three questions** will use this prior knowledge to analyze the electric characteristics of surface acoustic wave devices. These last three questions **are the most important part of the lab session** and must be answered.

Background

We have discussed how any resonant circuit can be modelled as a RLC electrical circuit with R the motional resistance, C the motional capacitance and L the motional inductance. When characterizing an unknown circuit, we wish to estimate the values of these parameters. Their dependence with frequency will allow us to separate each contribution, with the inductor acting as a short circuit at low frequency and an open circuit at high frequency, as opposed to the capacitor acting as a short at high frequency and an open at low frequency. At resonance, the inductor and capacitor phase shift compensate and only the resistor remains.

A network analyzer measures the (vectorial) ratio of the output to the input voltage. This ratio defines the scattering coefficient S. This scattering coefficient can be characterized in reflection (S_{11}) or in transmission (S_{21} when powering port 1 and reading port 2).

The scattering coefficient is an electrical matching coefficient that does not relate to the physical parameters of the RLC circuit. The electrical behavior of the circuit is determined by its **admittance** (or its inverse, the impedance), while the scattering parameters define the matching condition between input and output (i.e. the power transfer efficiency). Because the S-parameters are a ratio of voltages, conversion to dB requires computing $20\log_{10}(S)$, the factor 20 taking care of squaring the voltage to compute a power (normalized to the reference impedance 50 Ω).

Numerical simulation

Using a numerical simulation software (GNU/Octave, Matlab, Scilab, numpy ...), we wish to compute the impedance, admittance and scattering coefficients of a RLC circuit.
Consider a circuit with $L = 1.5$ mH, $C = 0.5$ pF and $R = 50\ \Omega$.

1. What is the theoretical resonance frequency of this circuit ? [1]
2. What is the theoretical quality factor of this circuit ? [1]
3. Plot the impedance (real and imaginary part) of this circuit in a range from 0.9 to 1.1 times the resonance frequency.
4. Plot the admittance (real and imaginary part) of this circuit in a range from 0.9 to 1.1 times the resonance frequency.
5. What is the physical meaning of the imaginary part of the admittance in the low frequency region ?
6. What is the meaning of the magnitude of the impedance at resonance frequency ?
7. What is the imaginary part of the impedance at resonance frequency ?
8. Plot the magnitude of the scattering coefficient of this circuit. The admittance and scattering coefficient are related by

$$S = \frac{1 - Z_0 \times Y}{1 + Z_0 \times Y}$$

   with $Z_0 = 50\ \Omega$ the reference impedance.
9. Plot the magnitude of the scattering coefficient of this circuit, replacing $R = 50\ \Omega$ with $R = 150\ \Omega$. Compare with the previous chart and interpret.
10. A common mistake is to compute the quality factor as the width of the scattering coefficient. The definition of the quality factor is the width at half height of the real part of the admittance. Compare these two quantities with the theoretical quality factor computed in the second question.
11. A practical acoustic transducer is fabricated by patterning electrodes on a piezoelectric substrate. This structure creates a capacitance in parallel to the RLC circuit: the resulting circuit is called the Buttworth-Van Dyke model, with a static capacitance C_0 in parallel to RLC. Repeat the numerical simulations (3, 4) with $C_0 = 200$ pF.

12. How does the angle of the admittance compare between RLC and Butterworth-Van Dyke ?

13. How does the piezoelectric electromechanical coupling coefficient relate to C_0 and C ? [1]

14. Two measurements of SEAS10 resonators sold by SENSeOR as temperature sensors have been collected on a network analyzer and are available at `http://jmfriedt.org/seas10w2.s1p` and `http://jmfriedt.org/seas10z2.s1p`. The standard format for such datasets is the Touchstone format with `snp` extension (`s1p` for a measurement in reflection, `s2p` for a measurement in transmission).
    - Find the format of this file, and by reading the header analyze its content.
    - Plot the magnitude of the reflection coefficient from each file. Reading Touchstone files in GNU/Octave is easily achieved using `dlmread()` and skipping the five first lines, or with `gnuplot` whose imaginary part notation is `{0,1}` so that a complex number is written as `re*{1,0}+im*{0,1}`.
    - What is the difference between the W and Z files ? Which one is most appropriate to characterize the sensor properties ?

15. From the data collected, what is the quality factor of the resonance ? The sensor is made of two resonances in parallel, so that two quality factors must be provided for each sensor.

16. The operator has mistakenly forgotten to calibrate the instrument before characterizing the instrument, and provides the datasets at `http://jmfriedt.org/seas10w2uncal.s1p` and `http://jmfriedt.org/seas10z2uncal.s1p`. Repeat the previous analysis and comment.

References

[1] J. Vig, *Quartz crystal resonators and oscillators – A tutorial*, 2000 at `https://www.am1.us/wp-content/uploads/Documents/U11625_VIG-TUTORIAL.pdf`