Matching and Tuning RF Coils for NMR Tomograph

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Abstract: *The most used matching circuit for RF coils of NMR tomographs is analysed from the point of view of tuning. Elements of the circuit are calculated in generic form so that the resulting formulas could be used also on high frequencies where parasitic influences may not be neglected. The output impedance of the circuit is calculated and analysed aiming at phenomena occurring during tuning the circuit.*

1. Introduction

Matching circuit is an important part of RF coil. It has to match the impedance of the coil to the impedance of the receiver of NMR imager without added losses. The task can be the most successfully fulfilled by capacitive matching circuits. The paper [1] showed two types of capacitive matching circuits used in NMR tomographs. The second type of the both is more frequently used for it provides more easily realisable values of capacitors. Nevertheless during tuning capacitors of the matching circuit some phenomena occur inhibiting to match the coil properly. The purpose of this paper is to analyse the matching circuit for using at wide span of frequencies and for proper tuning i.e. for finding the proper resonance. The results of the study can be used in NMR practice.

2. Results

The most frequently used matching circuit with RF coil can be found in the Fig. 1. Its main advantages are easily realisable values of the matching capacitors. RF coil is represented by its real $R_c(\omega)$ and reactive $X_c(\omega)$ parts of the impedance. If the whole circuit is tuned to resonance $\omega = \omega_o$ the input impedance of the receiver $\mathbf{Z}_{in}(\omega_o) = R_{in}$ and the matching capacitors C_1 and C_2 can be calculated as

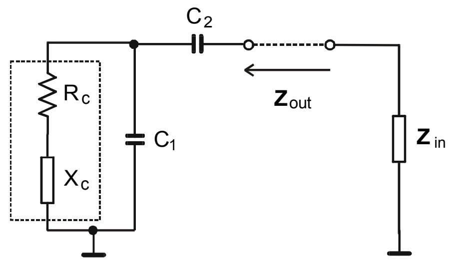


Fig. 1. RF coil with matching circuit.

$$C_1 = \frac{-R_c(\omega_o)^2\sqrt{R_c(\omega_o)} + R_c(\omega_o)R_{in}\sqrt{R_c(\omega_o)} - X_c(\omega_o)^2\sqrt{R_c(\omega_o)}}{\omega_o\left(R_c(\omega_o)^2 + X_c(\omega_o)^2\right)\sqrt{R_{in}\left(R_c(\omega_o)^2 - R_c(\omega_o)R_{in} + X_c(\omega_o)^2\right)}} +$$

$$+\frac{X_c(\omega_o)\sqrt{R_{in}\left(R_c(\omega_o)^2 - R_c(\omega_o)R_{in} + X_c(\omega_o)^2\right)}}{\omega_o\left(R_c(\omega_o)^2 + X_c(\omega_o)^2\right)\sqrt{R_{in}\left(R_c(\omega_o)^2 - R_c(\omega_o)R_{in} + X_c(\omega_o)^2\right)}}$$

and

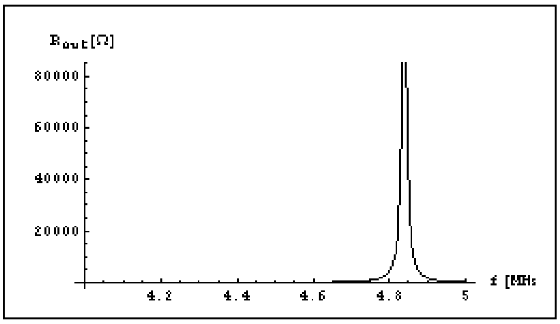
$$C_2 = \frac{1}{\omega_o}\sqrt{\frac{R_c(\omega_o)}{R_{in}\left(R_c(\omega_o)^2 + X_c(\omega_o)^2 - R_c(\omega_o)R_{in}\right)}}\ .$$

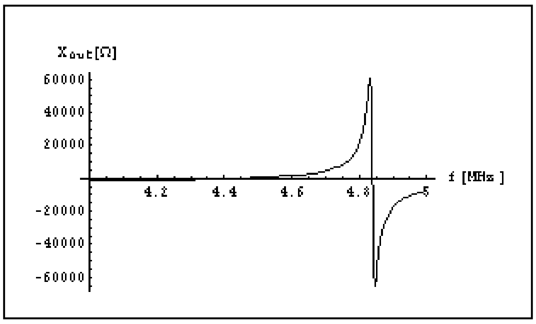
The output impedance of the RF coil with the matching capacitors $\mathbf{Z}_{out}(\omega)$ is expressed as

$$\mathbf{Z}_{out}(\omega) = R_{out}(\omega) + \mathbf{j}X_{out}(\omega) = Z_{out}(\omega)e^{\mathbf{j}\varphi_{out}} = \frac{R_c(\omega)}{(\omega C_1 R_c(\omega))^2 + (\omega C_1 X_c(\omega) - 1)^2} +$$

$$+\mathbf{j}\frac{\omega C_2 X_c(\omega)+2\omega C_1 X_c(\omega)-1-C_1C_2R_c(\omega)^2\omega^2-\omega^2C_1^2R_c(\omega)^2-C_1C_2\omega^2X_c(\omega)^2-\omega^2C_1^2X_c(\omega)^2}{\omega C_2((\omega C_1R_c(\omega))^2+(\omega C_1X_c(\omega)-1)^2)}.$$

A new coil is usually matched the first time by help capacitors C_1 and C_2 without any sample. On introducing the sample two couplings occur between the coil and the sample: the inductive and the capacitive. The inductive coupling is necessary for getting a signal from the experiment; the capacitive coupling is undesirable and causes losses. Therefore the parameters of the coil $R_c(\omega_o)$ and $X_c(\omega_o)$ can change unpredictably depending on parameters of the sample and $R_c(\omega_o)$ can be considered as a constant and $X_c(\omega_o)=L\omega_o$ only as a special case how it was described in [1]. At high frequencies moreover parasitic circuit elements influence the coil impedance and make it even more complex also without a sample. Fig. 2. a) and b) show real and reactive parts of the impedance $\mathbf{Z}_{out}(\omega)$ varying as frequency for a typical RF coil without parasitic influences and a sample matched at $f_o=4.45$ MHz to the receiver with $R_{in}=50\,\Omega$.





a) real part b) reactive part

Fig. 2. Output impedance of a typical RF coil matched to 50 Ω at 4.45 MHz.

Although the coil should be matched only at one frequency, $\mathbf{Z}_{out}(\omega)$ has two points of the resonance. They can be calculated for an unloaded coil far from its own resonance as

$$f_1=\frac{1}{2\pi\sqrt{2}}\sqrt{\frac{2}{(C_1+C_2)L}+\frac{C_2}{C_1(C_1+C_2)L}-\frac{R_c^2}{L^2}-\frac{\sqrt{-4C_1(C_1+C_2)L^2+(-2C_1L-C_2L+C_1^2R_c^2+C_1C_2R_c^2)^2}}{C_1(C_1+C_2)L^2}}$$

and

$$f_2=\frac{1}{2\pi\sqrt{2}}\sqrt{\frac{2}{(C_1+C_2)L}+\frac{C_2}{C_1(C_1+C_2)L}-\frac{R_c^2}{L^2}+\frac{\sqrt{-4C_1(C_1+C_2)L^2+(-2C_1L-C_2L+C_1^2R_c^2+C_1C_2R_c^2)^2}}{C_1(C_1+C_2)L^2}}$$

The formulas above were calculated considering that the impedance of the coil may be expressed as its inductance and resistance. It is possible only if the coil is far from its own resonance and if the coil impedance is not influenced with some couplings. Nevertheless such simplification was necessary because expressing the impedance of the coil in generic form as a function of the frequencies f_1 and f_2 would disable their calculation.

The dependence of the difference between the frequencies $\Delta f=f_2-f_1$ on the quality factor $Q=\frac{\omega_o L}{R_c}$, $X_c(\omega)=\omega\ L$ is depicted in Fig. 3. The higher Q the closer are the frequencies f_1 and f_2 to each other. Very interesting can be the course of tuning at the resonant frequency

$\omega = \omega_o$ as shown in Fig. 4. a) and b) for the module and the argument of the output impedance depending on capacitors C_1 and C_2. It is obvious that tuning by C_1 yields two items of resonance and only one of them is the proper. The capacitor C_2 on the other hand has main influence on the R_{out} value. The correct matching has to be set in co-operation of the both capacitors C_1 and C_2. The values of the capacitors in the figures are typical for a typical coil. They can be easily realised by typical variable capacitors. The resonance occurs at two values of C_1 capacitor and the distance between the both capacitance values varying as the quality factor Q is depicted in the figure Fig. 5., considering $Q = \frac{\omega_o L}{R_c}$ and $X_c = \omega_o L$. The higher the quality factor Q the smaller the value of $\Delta C_1 = C_{12} - C_{11}$.

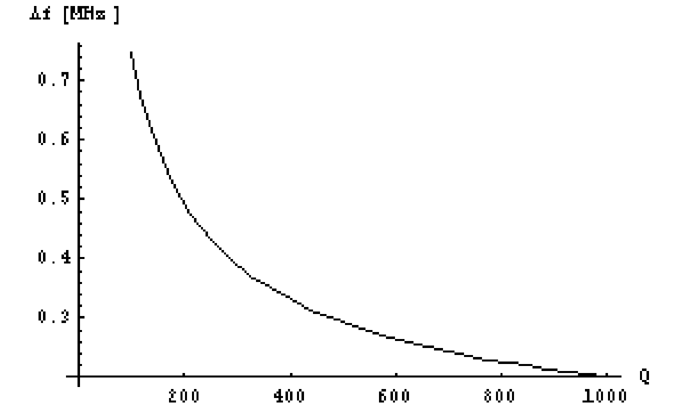
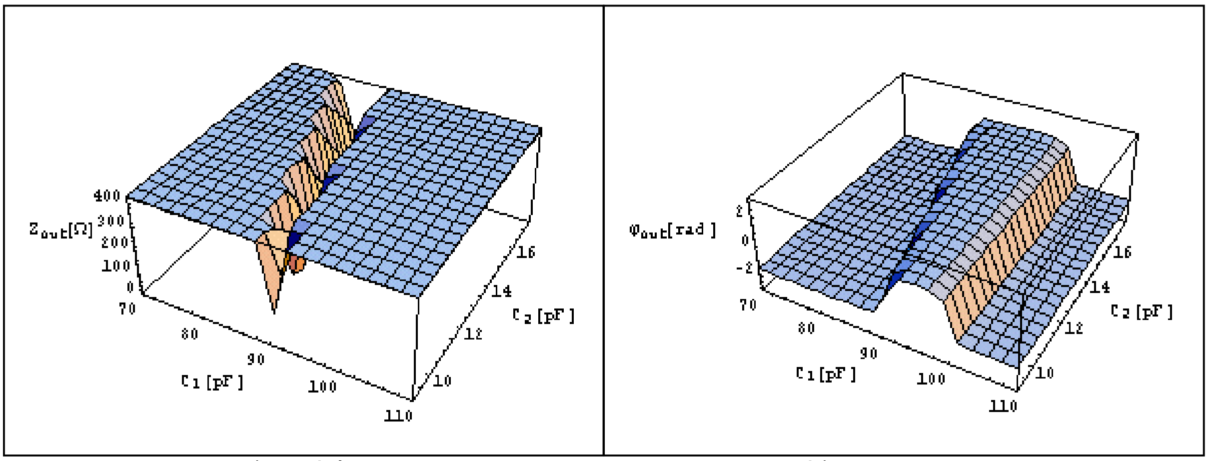


Fig. 3. Distance between the resonant frequencies, depending on quality factor of the coil.



a) module b) argument

Fig. 4. Output impedance of matched coil varying as tuning capacitors.

The values of the both items of resonance capacitance can be calculated as

$$C_{11} = \frac{1}{2(R_c(\omega_o)^2 + X_c(\omega_o)^2)\omega_o^2}(-\omega_o(-2X_c(\omega_o) + C_2 R_c(\omega_o)^2\omega_o + C_2 X_c(\omega_o)^2\omega_o) -$$
$$- \sqrt{(-4(R_c(\omega_o)^2 + X_c(\omega_o)^2)\omega_o^2(1 - C_2 X_c(\omega_o)\omega_o) + \omega_o^2(-2X_c(\omega_o) + C_2 R_c(\omega_o)^2\omega_o + C_2 X_c(\omega_o)^2\omega_o)^2)})$$

and

$$C_{12} = \frac{1}{2(R_c(\omega_o)^2 + X_c(\omega_o)^2)\omega_o^2}(-\omega_o(-2X_c(\omega_o) + C_2 R_c(\omega_o)^2\omega_o + C_2 X_c(\omega_o)^2\omega_o) +$$
$$+ \sqrt{(-4(R_c(\omega_o)^2 + X_c(\omega_o)^2)\omega_o^2(1 - C_2 X_c(\omega_o)\omega_o) + \omega_o^2(-2X_c(\omega_o) + C_2 R_c(\omega_o)^2\omega_o + C_2 X_c(\omega_o)^2\omega_o)^2)})$$

The quality factor is an important parameter of an unloaded RF coil. The designed coil is usually characterised by its Q and capacity necessary to its tuning to resonance. Basing on the two measured quantities, values of the capacitors C_1 and C_2 can be calculated and the coil can be matched completing the calculated values by experimental results.

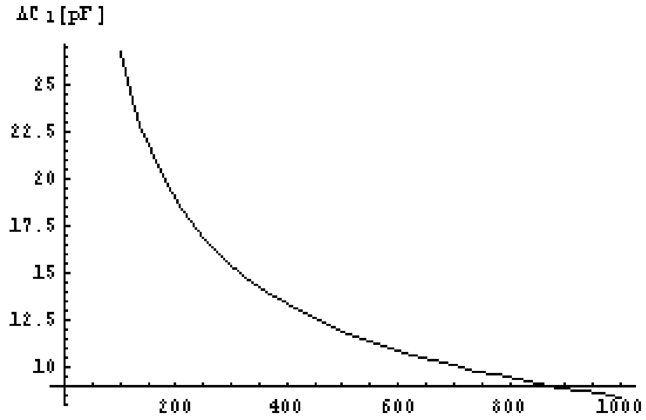
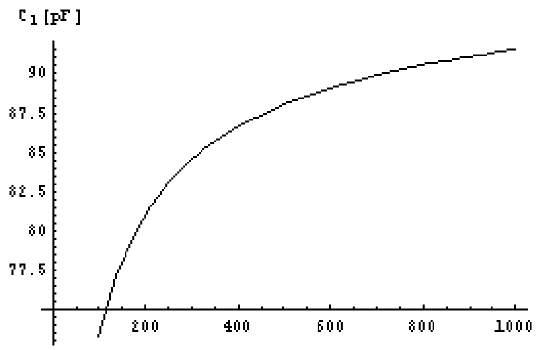
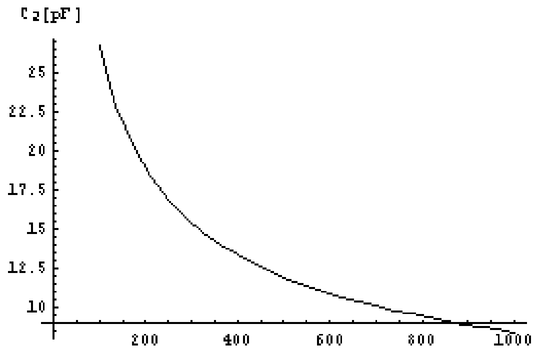


Fig. 5. Distance between the two capacitance values varying as the quality factor.

Introducing a sample into the coil causes different couplings creating and the both parts of the coil impedance the real and the reactive become complex functions of frequency. Despite of that it is often assumed that introducing a sample simply influences the quality factor of the coil. Investigating the Q changes can thus provide approximate information on variable capacitors span. The dependence of capacitance C_1 and C_2, varying as Q can be observed in Fig. 6. a) and b) for a typical coil with $R_{in} = 50\Omega$ and $f_o = 4.45MHz$.



a)



b)

Fig. 6. Values of matching capacitors varying as coil quality factor Q.

The figures provide a good picture on tuning and matching problems. They can also give information on sensitivity of the resulting capacity on changes of the coil quality factor.

3. Conclusion

Purpose of the paper was investigating phenomena occurring during tuning an RF coil for NMR tomograph. It is obvious that tuning a coil, mainly if new can bring some problems. The derived theory, depicted by many figures, can help solving such problems.

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References:

[1] Andris, P.: Matching RF Coils for NMR Tomograph. Journal of Electrical Engineering / Elektrotechnický časopis **50**, 1999, no. 5-6, pp. 147-150.
[2] Wolfram, S.: Mathematica. Wolfram Research, Inc., Champaign, 1993.