

Let us make a metal detector using a PC computer and a sound card

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Phase relations in resonant circuit

A resonant circuit is composed of a capacitor C and an inductor L . The inductor is made of wire, and wire exhibits a resistance; this is commonly presented as a resistor R_L connected in series with the inductor. Such resonant circuit can be excited by a sinusoidal signal R_0 using a resistor R connected in series with the resonant circuit as shown in Fig. 1.

The output signal X of the circuit is given by:

$$X = R_0 \frac{R_L + i\omega L}{R_L + R + i\omega(RR_L C + L) - RLC\omega^2}$$

The amplitude $|z|$ and phase φ of the output signal X are:

$$|X| = |R_0| \sqrt{\frac{\omega^2 L^2 + R_L^2}{\omega^2 R^2 C^2 (\omega^2 L^2 + R_L^2) - 2\omega^2 R^2 LC + \omega^2 L + R^2 + 2RR_L + R_L^2}}$$

$$\tan \varphi = \frac{\omega R (L - C(L^2 \omega^2 + R_L^2))}{\omega^2 L^2 + R_L (R + R_{LL})}$$

Both are shown in diagrams in Fig. 2 for selected values of components. The frequency where the phase angle between the output signal and the excitation signal is zero is called the resonant frequency ω_R :

$$\omega_R = \sqrt{\frac{1}{LC} - \frac{R_L^2}{L^2}}$$

From former equations (and experience) we know that the resonant frequency depends on inductance L and capacitance C in the circuit from Fig. 1. Increasing either the capacitance or inductance shifts resonant curve towards lower frequencies, and reducing either shifts the curve towards higher frequencies, Fig. 3.

Additionally, the equations (and experience) tell us that the value of the resistor R_L defines the width of the resonant curve and simultaneously the steepness of the phase change, when the capacitance and the inductance are kept constant, see Fig. 4.

Suppose we select the frequency of the excitation signal R_0 to be the resonant frequency and keep this frequency for the rest of the experiment. Any increase in the inductance will also decrease the phase angle to negative values. In other words: if one puts a ferromagnetic material inside the inductor, the phase angle between the output signal X and the excitation signal R_0 will become negative. This effect can be used to detect ferromagnetic materials inserted into the inductor.

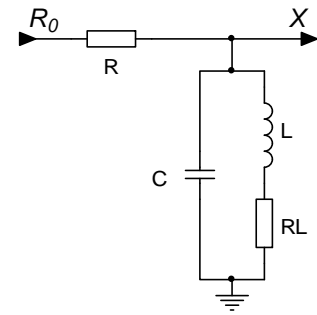


Figure 1: The resonant circuit used in a voltage divider

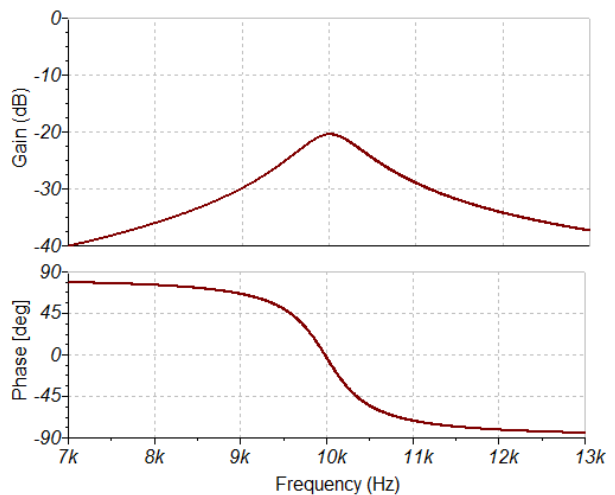


Figure 2: The amplitude and the phase of the output signal from the circuit in Fig. 1

Similarly, when a conductive material is placed inside the inductor, the AC magnetic field inside the inductor induces voltage in a conductive material, and due to this a current flows inside the conductive material. The current causes its own magnetic field which opposes to the field of the inductor, and thus reduces its strength. This effectively reduces the inductance, and results in positive phase angle between the excitation signal x and the output signal z .

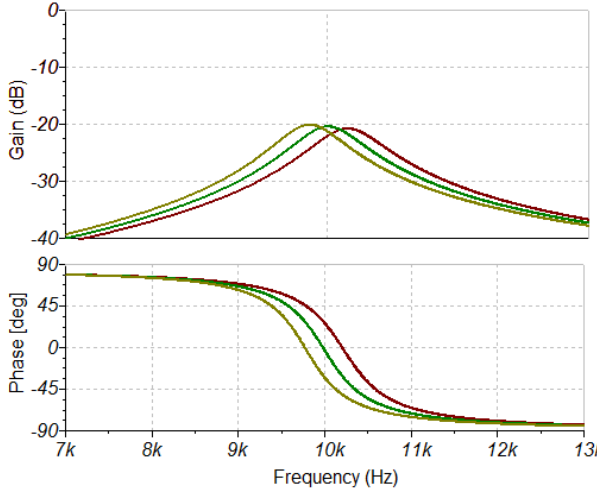


Figure 3: Changing the inductance shifts the resonant frequency (120uH, 115uH, 110uH)

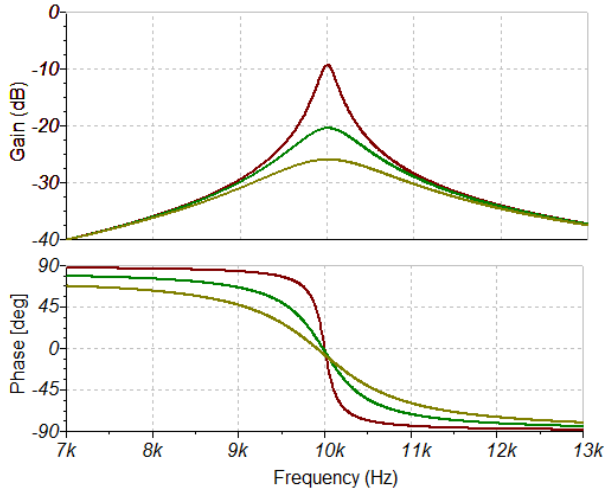


Figure 4: The resistance R_l defines the width of the resonance (100mΩ, 500mΩ, 1Ω)

Such effects can be used for detecting metal and ferromagnetic objects, like coins. A simple coin detector will be built for the experiment to demonstrate the usefulness of resonant circuit and mathematics to determine the phase angle between two sinusoidal signals.

One can also change the capacitance in the circuit. Suppose the plates of the capacitor are large, and a non-conductive object made of material with a dielectric constant different from the dielectric constant of the air is placed half-way between the capacitor plates. Then the frequency of the excitation signal is selected to get the phase angle of zero between the excitation signal and the output signal. Any subsequent movement of the object will change the capacitance in the circuit, and change the phase as well. Again, the measurement of the phase can be used to determine the position of the object within the capacitor.

The sensitivity of the circuit can be defined as the amount of phase change versus the amount of the change in inductance (or capacitance). From Fig. 4 one can see that resonant circuits with lower R_l are more sensitive, since the phase curve is steeper at the resonant frequency. It is therefore essential to build an inductor with low R_l to make circuit more sensitive.

Phase angle measurements - two sinusoidal signals - background

The phase angle φ between two sinusoidal signals X and R_0 can be determined using the procedure depicted in the block diagram in Fig. 5.

Input signals are given by:

$$X = A_X \sin (\omega t + \varphi) \qquad R_0 = A_{R0} \sin \omega t$$

Note that both input signals have the same frequency ω , and signal X is phase shifted towards reference signal R_0 for angle φ . Amplitudes of both signals are A_X and A_{R_0} respectively.

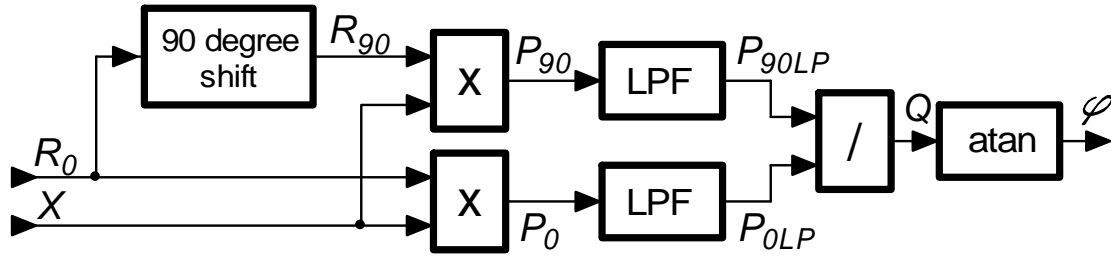


Figure 5: The block diagram for calculating the phase angle between two sinusoidal signals

The reference signal R_0 is first phase shifted for 90° to obtain:

$$R_{90} = A_{R_0} \cos \omega t$$

Signal X is multiplied with both versions of the reference signal R_0 and R_{90} to obtain:

$$P_0 = X \cdot R_0 = \frac{A_X A_{R_0}}{2} (\cos \varphi - \cos (2\omega t + \varphi))$$

$$P_{90} = X \cdot R_{90} = \frac{A_X A_{R_0}}{2} (\sin (2\omega t + \varphi) + \sin \varphi)$$

Signals P_0 and P_{90} are both composed of a DC component and a harmonic component with frequency equal to twice the frequency of the input signals. Harmonic components from both signals can be filtered out using two low-pass filters LPF on the block diagram. The corner frequency of both filters is the same and must be low enough to completely reject harmonic components from signals P_0 and P_{90} . The remaining DC components P_{0LP} and P_{90LP} divided to obtain quotient Q :

$$Q = \frac{P_{90LP}}{P_{0LP}} = \frac{\sin \varphi}{\cos \varphi} = \tan \varphi$$

From here the phase angle φ is derived using the inverse tangent function: $\varphi = \tan^{-1} Q$.

If the expected angle is small the calculation can be simplified by omitting the calculation of the numerically aggressive and time consuming inverse tangent function, since the inverse tangent of an angle is approximately the angle itself for small angles ($\varphi = Q$). The error is less than 1% for angles smaller than 10° and less than 1‰ for angles less than 3.5° .

Experimental Setup

As an experiment a resonant circuit from Fig. 1 will be used to detect metal objects. The inductor should be rather large to allow for the insertion of metal objects. A table-tennis racket size inductor should be sufficient, so an inductor with a circumference of 150mm and having 20 turns of wire with a diameter of 0.8mm was prepared. The inductance of such an inductor is about 100uH, and the resistance about 400m Ω .

The sound card of a personal computer was used to excite the resonant circuit and to measure both the excitation signal and the output signal from the resonant circuit. A sound card can sample and generate signals with frequency up-to 20kHz; it was decided to work below the middle of this range,

therefore the resonant frequency f_R should be about 10kHz. Based on this selection and the knowledge that:

$$f_R \cong \frac{1}{2\pi\sqrt{LC}}$$

a capacitor value was selected as 2.7uF.

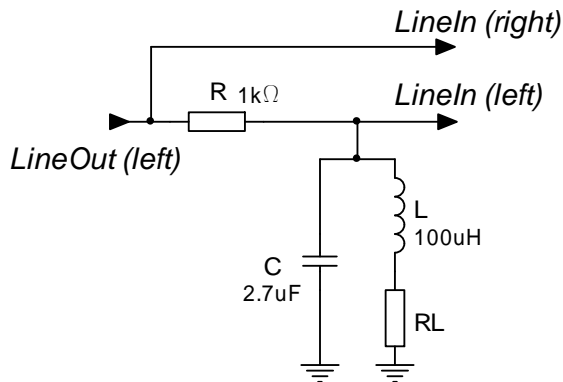


Figure 6: The connection of the resonant circuit to the sound card

Next the circuit was prepared on a breadboard having cables connected to line-out and line-in jacks on the computer sound card. Most desktop computers have stereo line-in jacks, and those can be used for the purpose. Most portable computers only have monaural input jack for microphone, those computers cannot be used for this experiment.



Figure 7: The photo of the resonant circuit used in the experiment

The complete connection is given in Fig. 6, and the photo of the setup in Fig. 7.

Implementation of the phase measurement algorithm in LabView

A Labview environment was used to perform the measurement. The complete program is shown in Fig. 8. The skeleton for simultaneous sampling and generating was used (see elsewhere on my pages for description and details of the skeleton).

The signal processing consists of two parts:

- The lower portion of the program within the “while” loop takes care for the generation of a sinusoidal excitation signal. Its frequency and amplitude can be adjusted in the user interface window (Fig. 9). The frequency should be adjusted to the exact resonance of the resonant circuit (phase is zero) to make the system most sensitive, and amplitude is adjusted to the largest value producing un-clipped signal at the output of the sound card.
- The upper portion of the program within the “while” loop takes care of the data processing and calculating the phase angle following the block diagram from Fig. 5.

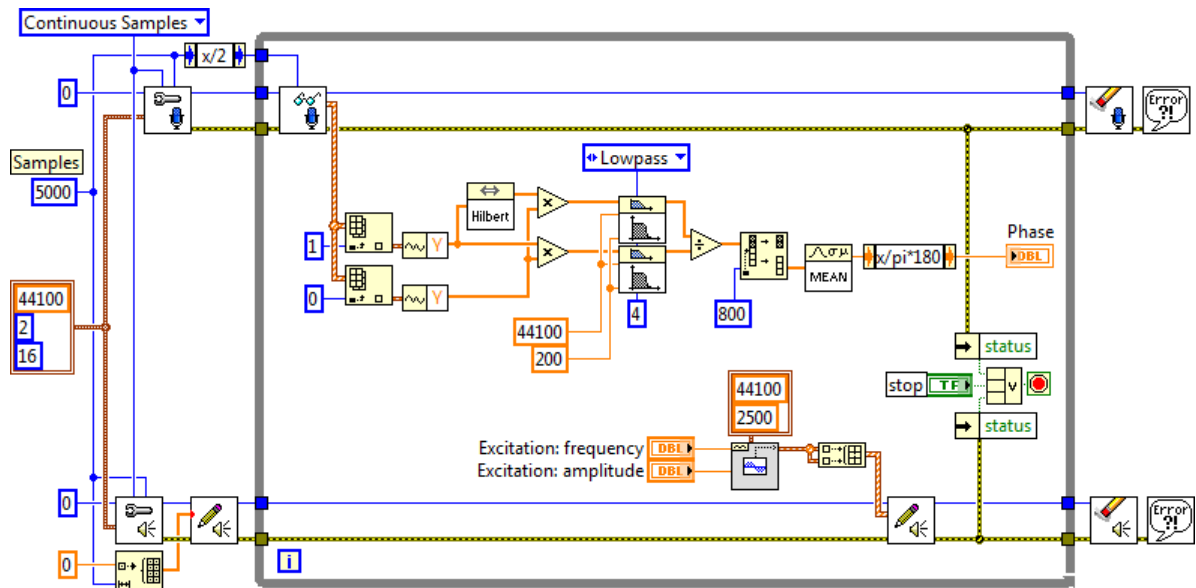


Figure 8: The complete LabView program

Figure 10 gives the excerpt of program used for measuring the phase angle. The Labview “Read SoundCard” block returns an array of waveforms, as presented in the upper left corner of the excerpt with a wide striped vertical line. The waveforms for left and right channel are extracted from the array using two modules on the left, the upper extracts first channel (left), and the lower extracts the zero-th channel (right). Both waveforms are then stripped of the excess data to obtain two arrays of plain samples for right and left channel, namely for the reference signal R_0 and the output signal X . Each array is 2500 element in length, as defined by constant “Samples”, Fig. 8. The reference signal R_0 is immediately shifted for 90 degrees to obtain R_{90} using a block “Hilbert”, which implements a Hilbert transformation algorithm.

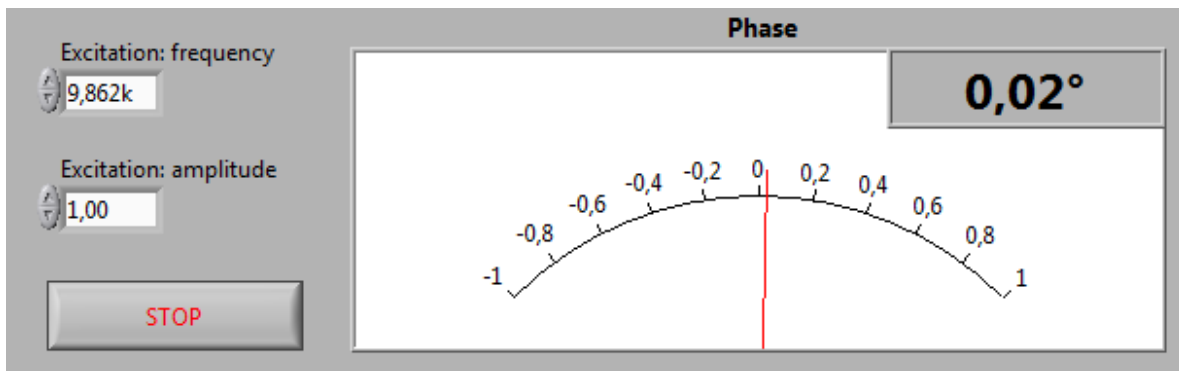


Figure 9: LabView: User interface window

Next signal X is multiplied with both versions of the reference signal R_0 and R_{90} to obtain P_0 and P_{90} . These signals contain unwanted sinusoidal components with frequency of about 20kHz, and those are removed by two low pass filters. Filters are IIR (Infinite Impulse Response) type, and coefficients for filters are calculated following the Butterworth pole placement, each has four poles and a corner frequency of 200Hz. The actual type, number of poles and corner frequency are not important as long as both filters are equal and successfully reject the unwanted component. The resulting DC signals are P_{0LP} and P_{90LP} , which are fed to next block for division to finally obtain signal Q .

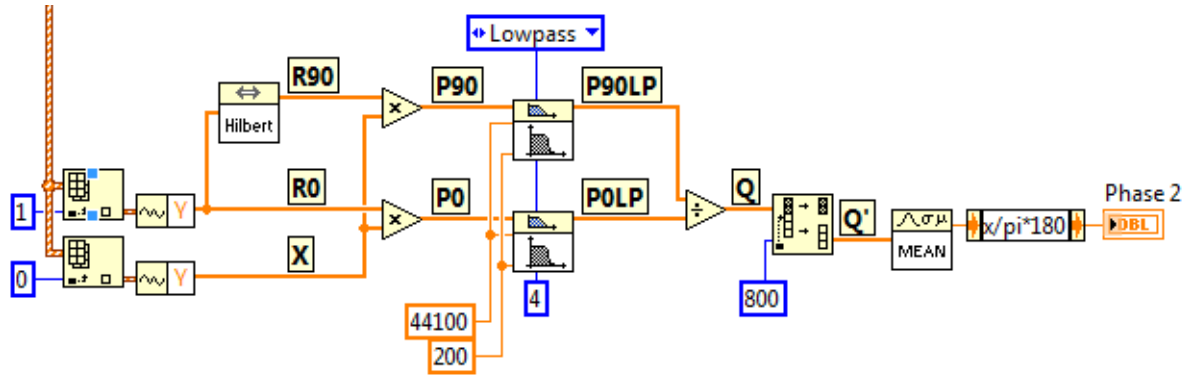


Figure 10: The procedure to calculate the phase angle

The signal Q is still an array of samples, and first part of the array contains bad values. The reason for bad values is the low pass filtering. Filters need some time to get to the correct result of filtering, and in the case presented first 800 elements of the array are bad and are stripped away and discarded. The rest of the array, 1700 elements, are averaged to get more reliable result, converted from radians to degrees and shown in the instruments "Phase 2" at the user interface window.

Results – random noise / resolution

The setup was tested by adding a "chart" to the user interface and charting consequent results within 100s. During a time of 100s a 1€ coin was moved three times into and out of the inductor. The corresponding chart is shown in Fig. 11. From this the phase change for a coin inserted into the inductor is less than 0.2 degrees, and this can be read without any problems since it produces two distinctive values. Actually the random noise when the inductor is left undisturbed is less than 0.05 degrees!

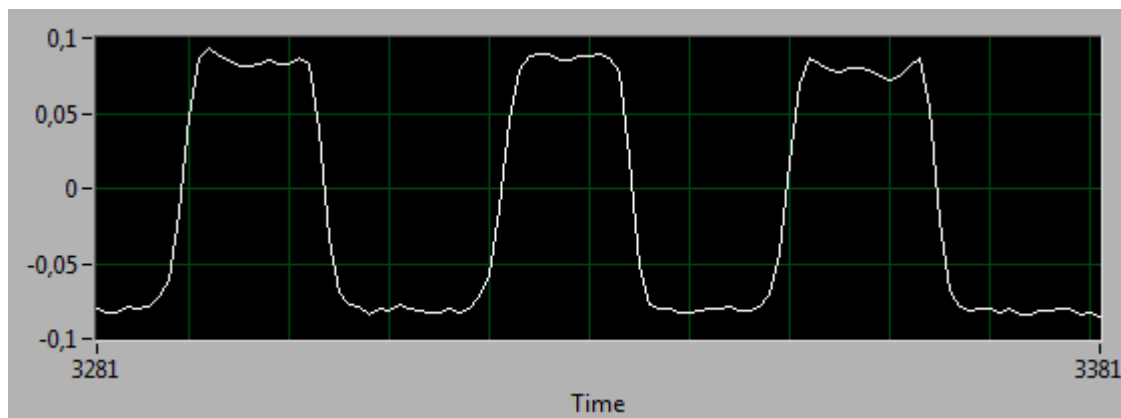


Figure 11: The detection of 1 EURO cent coin, vertical scale is in degrees, horizontal is in seconds.