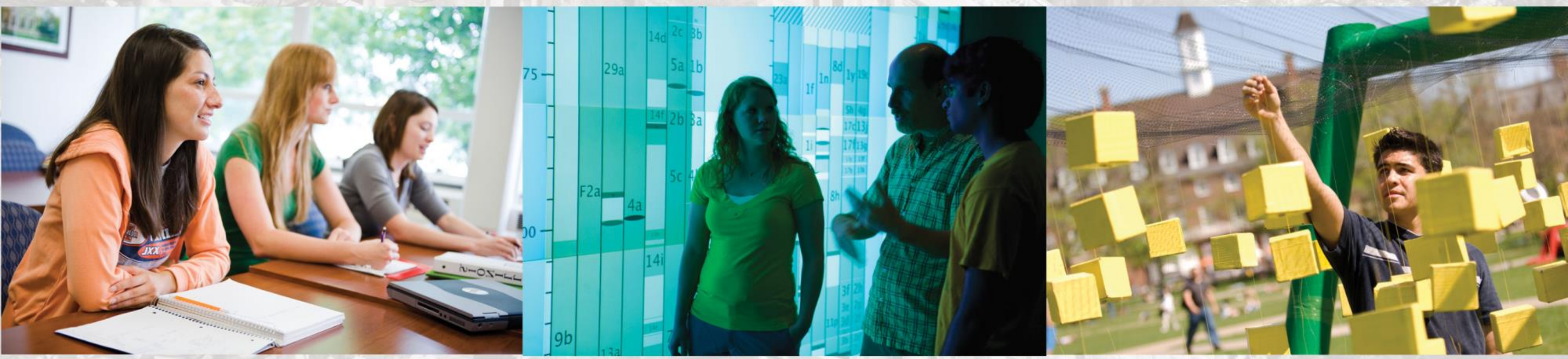
UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN

Investigation of the Properties of RLC Circuits

Physics 401, Fall 2015.

Eugene V. Colla



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This Lecture Covers Two Labs:

1. Transients and Oscillations in RLC Circuits.
2. Frequency Domain Analysis of Linear Circuits Using Synchronous Detection

This week:

1. Transients. Definition.
2. Transients in RLC
3. Resonance in RLC
4. Data analysis. Origin. Fitting.

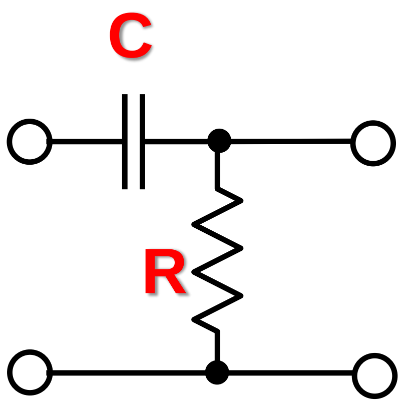
This Lecture Covers Two Labs:

1. **Transients and Oscillations in RLC Circuits.**
2. **Frequency Domain Analysis of Linear Circuits Using Synchronous Detection**

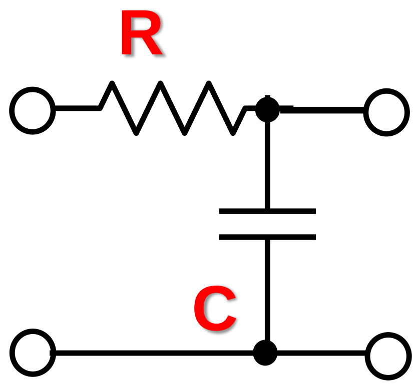
Next week:

1. **Time domain and Frequency domain representation of the data.**
2. **Frequency domain spectroscopy (FDS)**
3. **Lock-in amplifiers**
4. **Practical application of lock-in's in FDS**
5. **Taking data and simple data analysis using OriginPro**

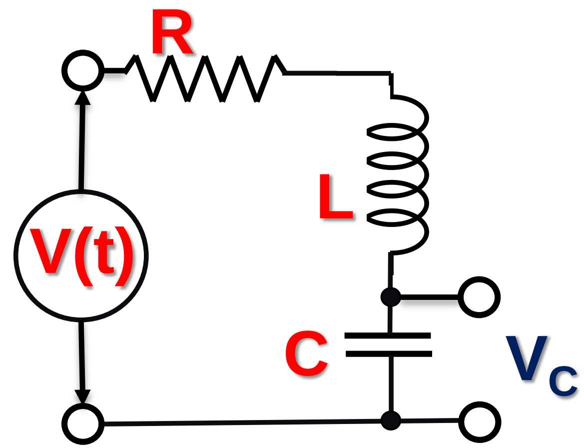
RLC Circuits:



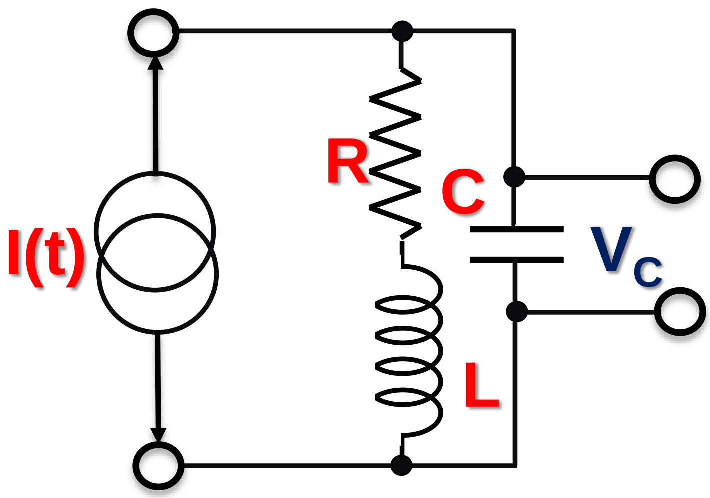
Hi-pass filter



Low-pass filter



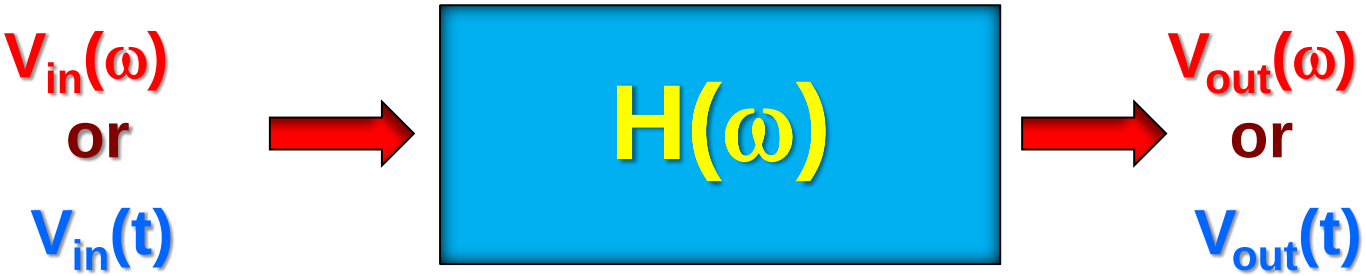
Series resonance circuit



Parallel resonance circuit

Investigation of the Properties of the RLC Circuits. General Idea.

Tested RLC network



$$\breve{H}(\omega) = \frac{\breve{V}_{out}(\omega)}{\breve{V}_{in}(\omega)}$$

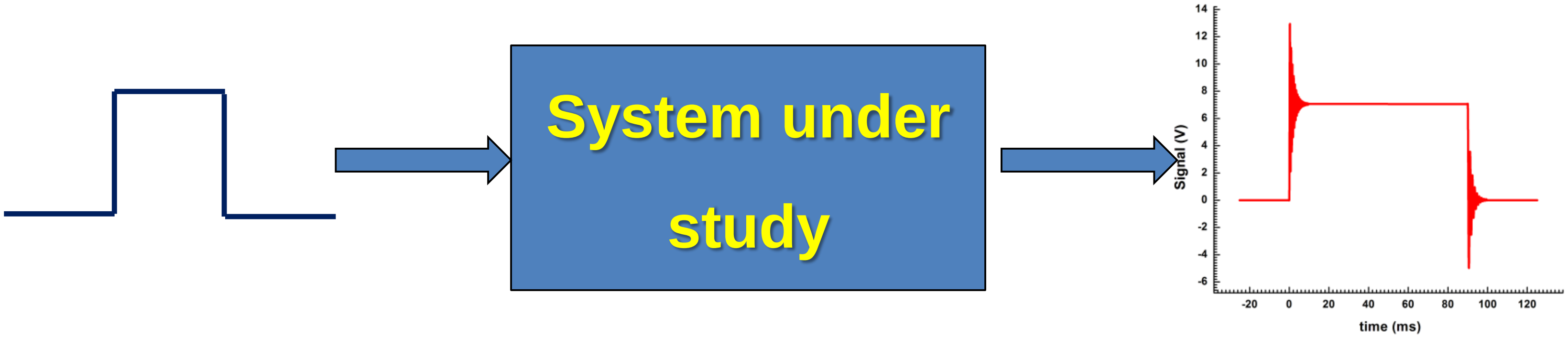
Frequency domain technique

Time domain technique

Time Domain Technique. Transients. Definition.

transient (physics) a short-lived oscillation in a system caused by a sudden change of voltage or current or load

a transient response or natural response is the response of a system to a change from equilibrium.

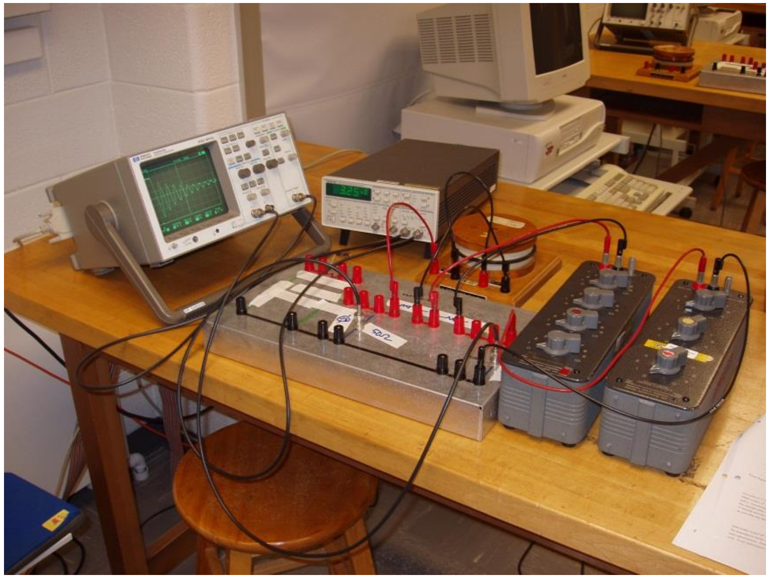


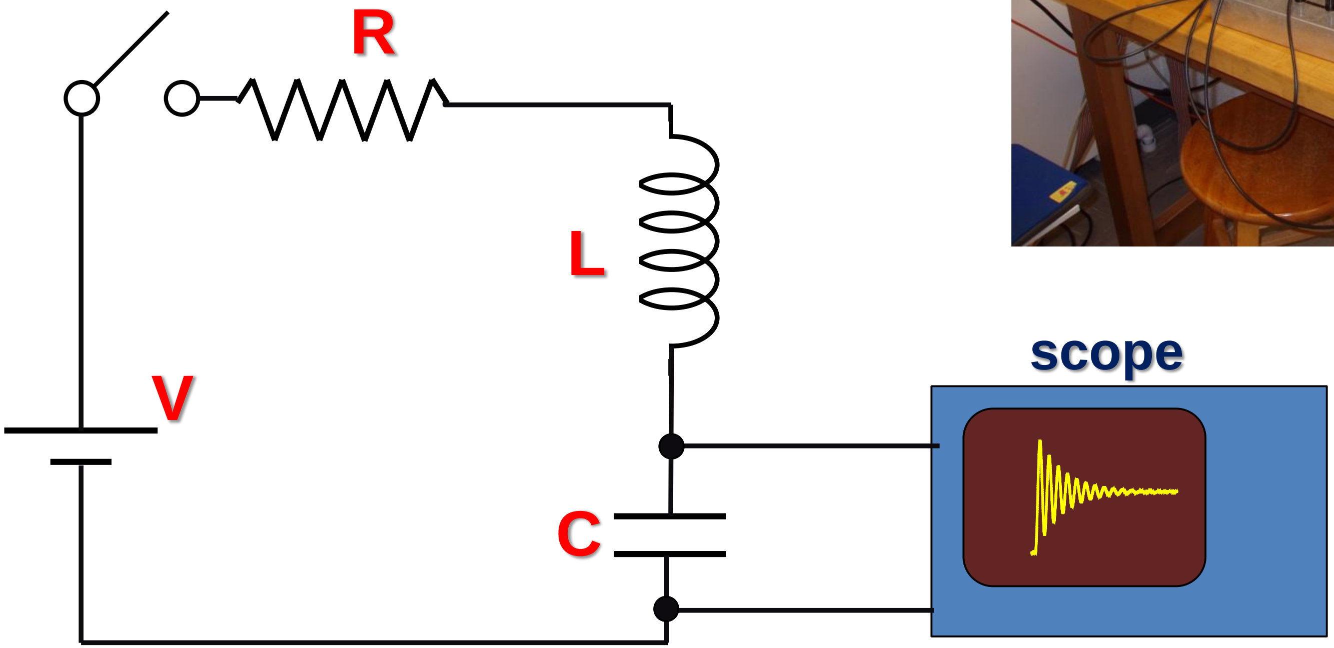
Transients in RLC Circuit.

Resistance ***R [Ohm]***

Capacitance ***C [μF] (10^{-6}F)***

Inductance ***L [mH] (10^{-3}H)***





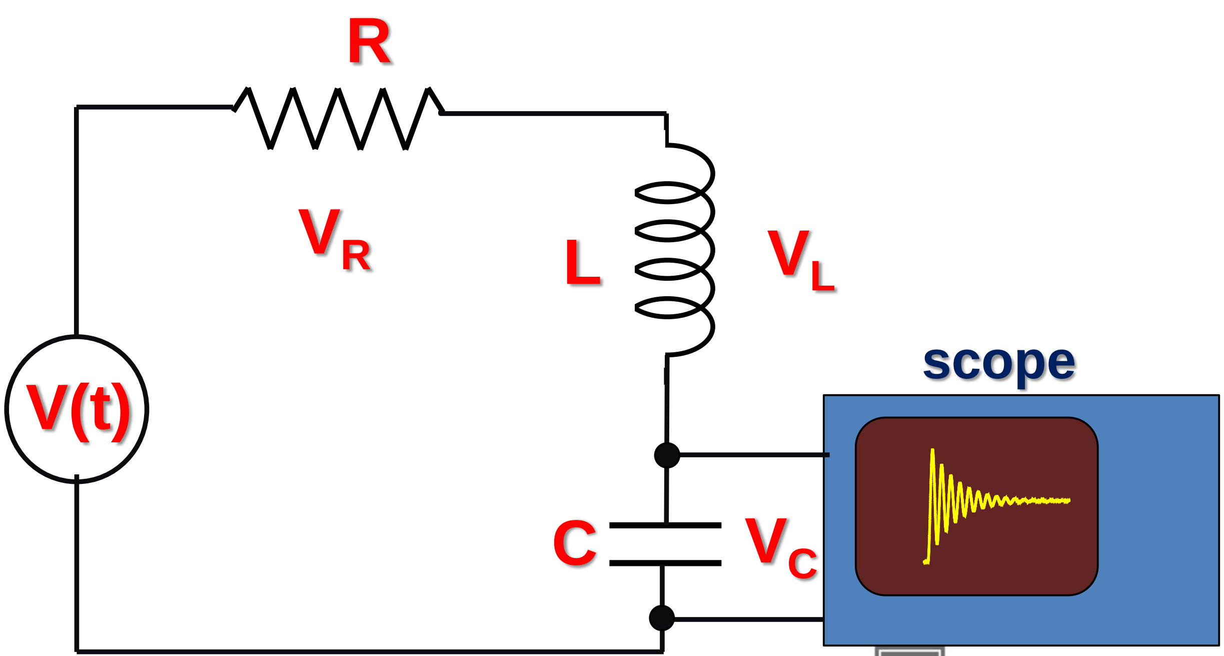
Transients in RLC Circuit.

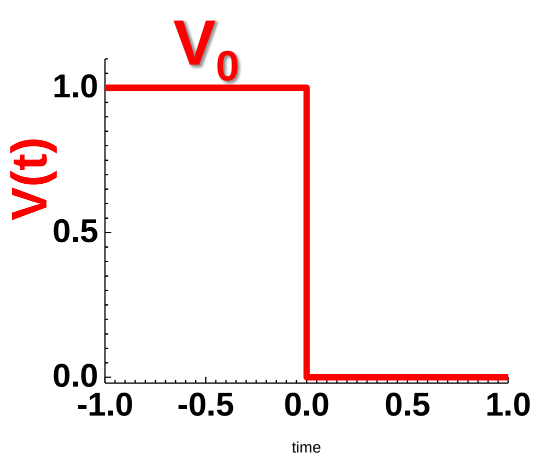
According the Kirchhoff's law $V_R+V_L+V_C=V(t)$

*

$$L\frac{d^2}{dt^2}q(t)+R\frac{d}{dt}q(t)+\frac{q(t)}{C}=0 \qquad (1)$$

*See Lab write-up for details





Transients in RLC Circuit. Three Solutions.

The solution of this differential equation can be found in the form

$$q(t) = Ae^{st}$$

This will convert (1) in quadratic equation

$$s^2 + \left(\frac{R}{L}\right)s + \frac{1}{LC} = 0$$

with solutions:

$$s_{1,2} = -\frac{R}{2L} \pm \sqrt{\left(\frac{R}{2L}\right)^2 - \left(\frac{1}{LC}\right)} \equiv -a \pm b$$

$$a = \frac{R}{2L} \quad , \quad b = \sqrt{\left(\frac{R}{2L}\right)^2 - \left(\frac{1}{LC}\right)}$$

$b^2>0$ over-damped solution
$b^2=0$ critically damped solution
$b^2<0$ under-damped solution

Transients in RLC Circuit. Over-damped Solution: $b^2>0$

In this case the solution will be aperiodic exponential decay function with no oscillations:

$$q(t) = e^{-at}\left(A_1 e^{bt} + B_1 e^{-bt}\right)$$

$$i(t) = \frac{dq}{dt} = -ae^{-at}(A_1 e^{bt} + B_1 e^{-bt}) + be^{-at}(A_1 e^{bt} - B_1 e^{-bt})$$

Transients in RLC Circuit. Over-damped Solution: $b^2>0$

Taken in account the initial conditions: $q(0)=q_0$ and $i(0)=0$

$$q(t)=q_0e^{-at}\left(\cosh bt+\frac{a}{b}\sinh bt\right)$$

$$\xrightarrow[(a-b)t>>1]{}\frac{q_0}{2}\left(1+\frac{a}{b}\right)e^{-(a-b)t}$$

$$i(t)=-\frac{q_0}{2}\left(\frac{a^2-b^2}{b}\right)e^{-(a-b)t}$$

This is exponential decay function

Transients in RLC Circuit. Critically-damped Solution: $b^2=0$

For this case the general solution can be found as

$q(t)=(A_2+B_2t)e^{-at}$. Applying the same initial condition the

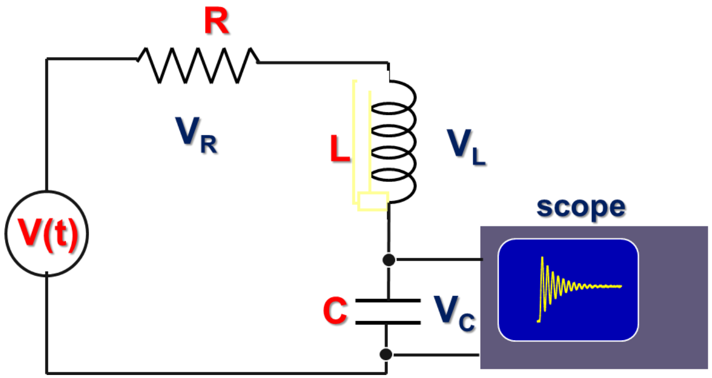
current can be written as $i=-a^2q_0te^{-at}$

$$b^2 = 0 \rightarrow R^2 = \frac{4L}{C}$$ and $$a = \frac{R}{2L}$$

Critically-damped conditions for our network

Critical damped case shows the fastest decay with no oscillations

Transients in RLC Circuit. Critically-damped Solution: $b^2=0$. Real Data Analysis.

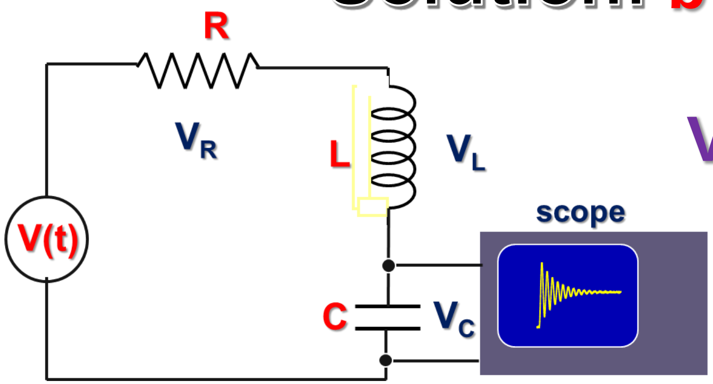


In this experiment R=300 ohms, C=1μF, L=33.43mH.

The output resistance of Wavetek is 50 ohms and resistance of coil was measured as 8.7 ohms, so actual resistance of the network is R_a=300+50+8.7=358.7

Decay coefficient $a = \frac{R}{2L} = \frac{358.7}{2*33.43E-3} \approx 5365$

Transients in RLC Circuit. Critically-damped Solution: $b^2=0$. Real Data Analysis.

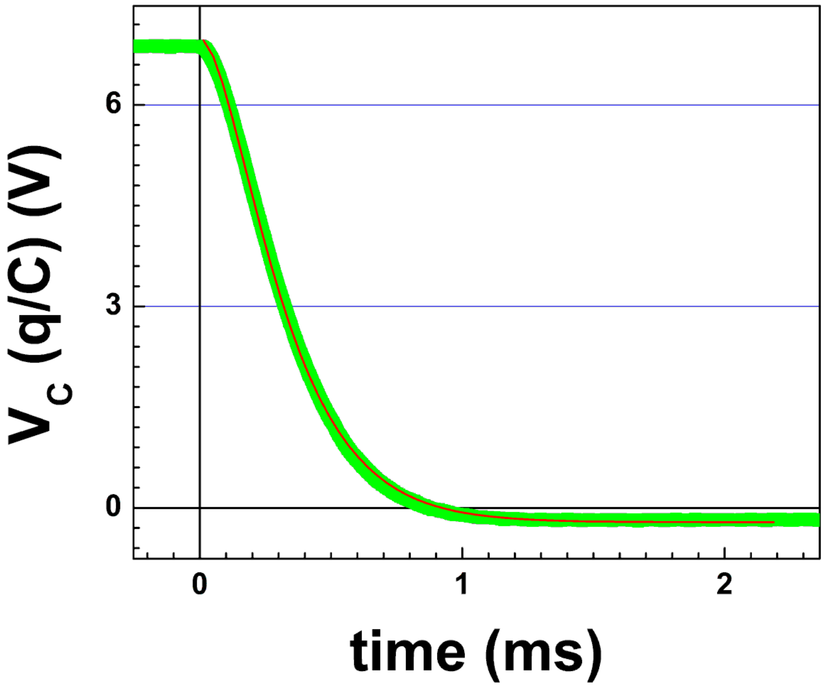


Vc ~q, fiiting function: $V_c=V_{co}(1+at)e^{-at}$

Now the experimental results:

Calculated decay coefficient ~5385,

Obtained from fitting - ~5820.
Possible reason – it is still slightly over damped
Calculated b^2 is
b^2=2.99e7-2.90e7>0



Transients in RLC Circuit. Under-damped Solution.

If $b^2<0$ we will have oscillating solution. Omitting the details (see Lab write-up) we have the equations for charge and current as:

$$q(t) = q_0 e^{-at}\left(\cos bt + \frac{a}{b}\sin bt\right) = q_0 e^{-at}\sqrt{1+\frac{a^2}{b^2}}\ \sin(bt+\varphi)$$

$$i(t) = q_0 e^{-at}\left(\frac{a^2+b^2}{b}\right)\sin bt$$

$$a = \frac{R}{2L}\ ,\ b = \sqrt{\left(\frac{R}{2L}\right)^2 - \left(\frac{1}{LC}\right)}; f = \frac{1}{2\pi}\sqrt{\left(\frac{1}{LC}\right) - \left(\frac{R}{2L}\right)^2}$$

Transients in RLC Circuit. Under-damped Solution. Log Decrement. Quality Factor.

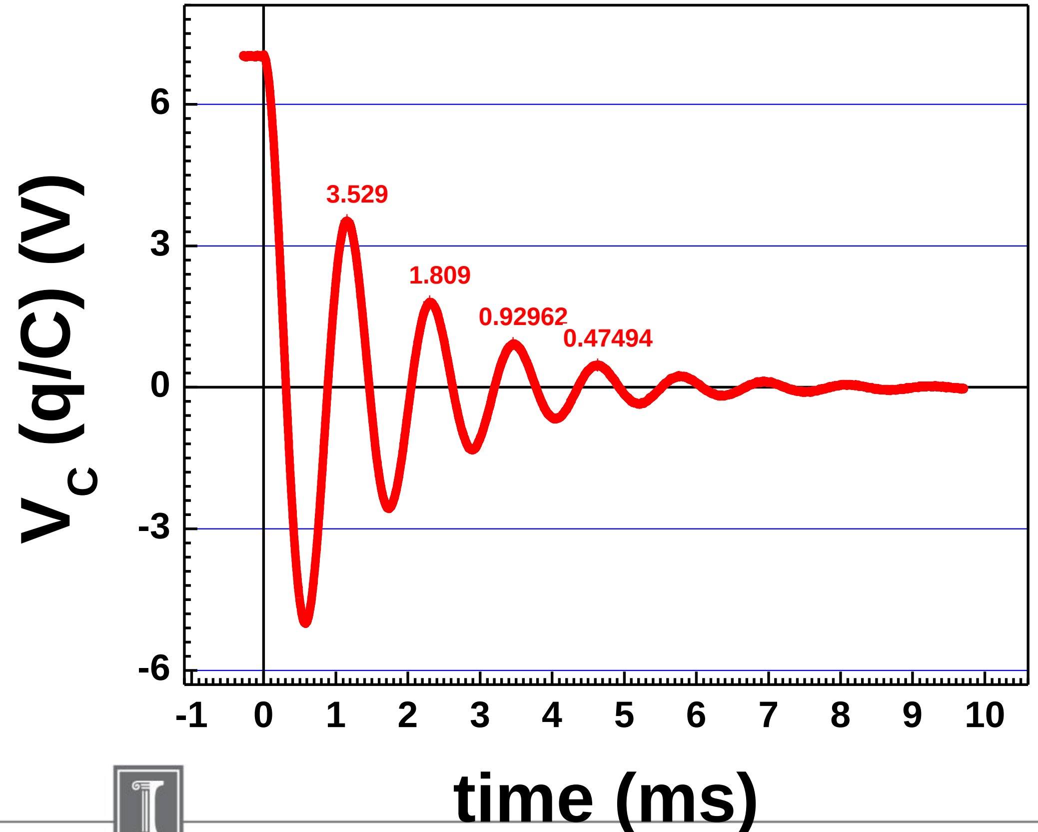
Log decrement can be defined as $\delta = ln\left(\frac{q(t_{max}}{q(t_{max}+T_1}\right) = ln\left(\frac{e^{-at_{max}}}{e^{-at_{max}+T_1}}\right) = aT_1$, where T_1=1/f

Quality factor can be defined as $Q = 2\pi\frac{E}{\Delta E}$,

For RLC $Q = \frac{\omega_1 L}{R} = \frac{\pi}{\delta}$

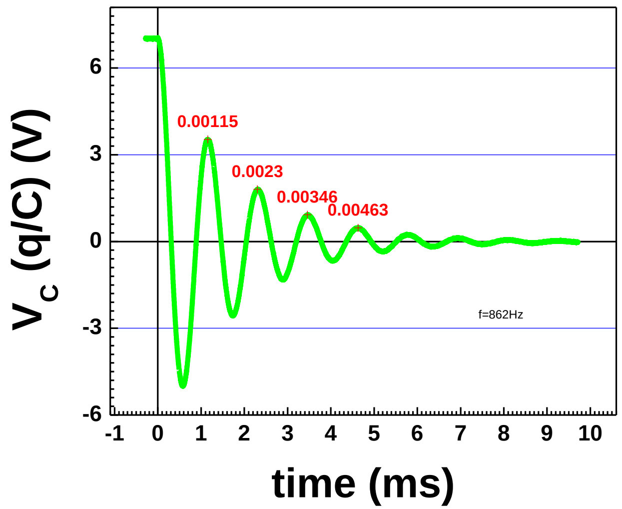
From this plot δ≈0.67

Q≈4.7

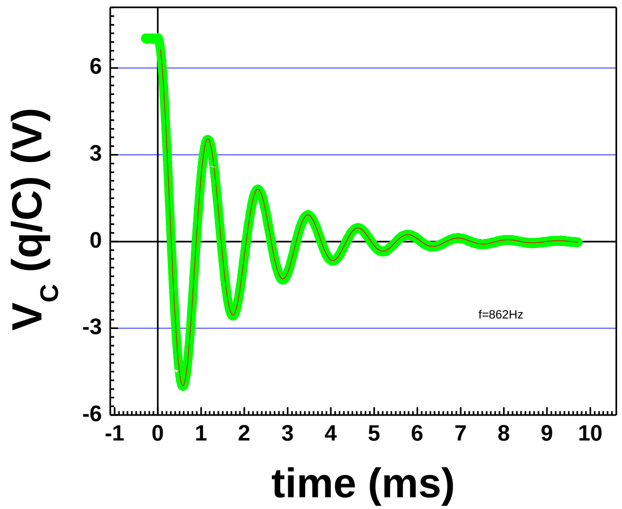


Transients in RLC Circuit. Data Analysis.

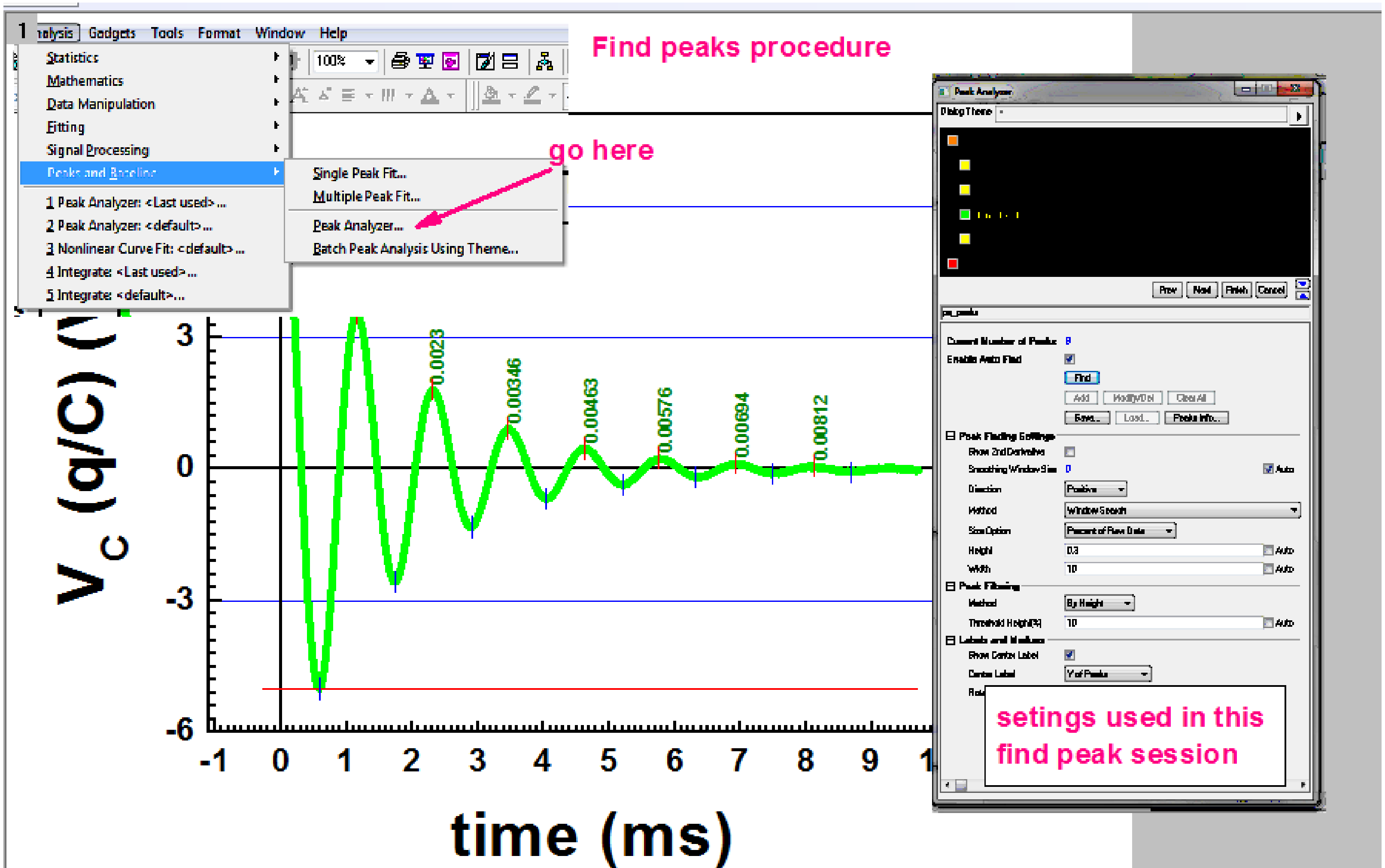
Using Origin Software.



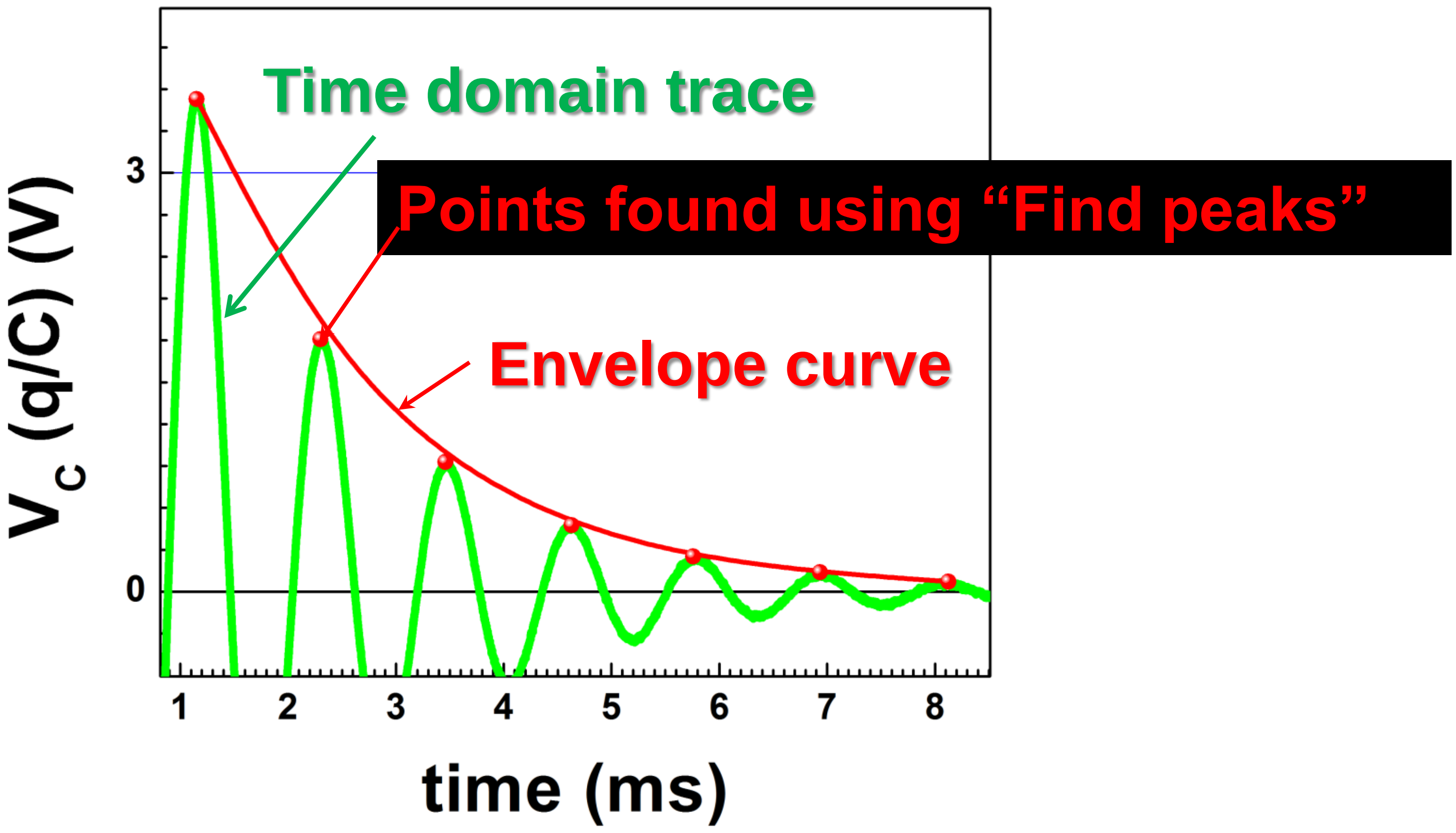
1. **Pick peaks**
2. **Envelope**
3. **Nonlinear fitting**



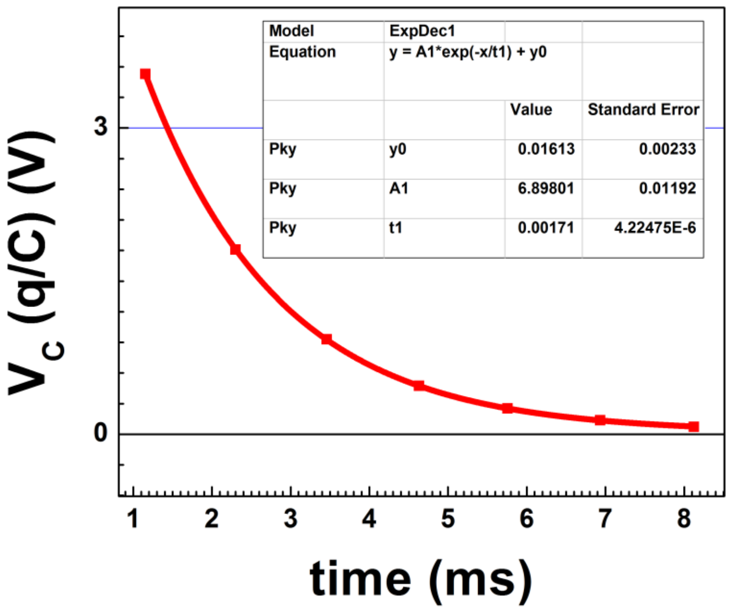
Transients in RLC Circuit. Under-damped Solution. Log Decrement. Quality Factor.

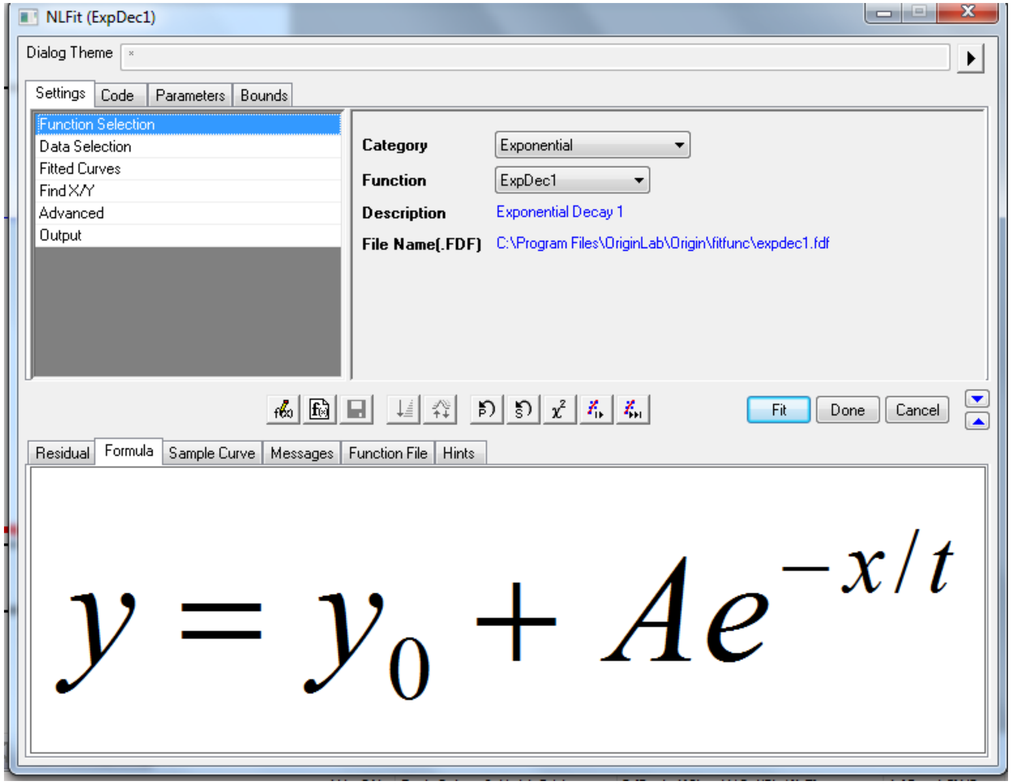


Transients in RLC Circuit. Data Analysis. Log Decrement. Using Origin Software. Results.



Transients in RLC Circuit. Data Analysis. Log Decrement. Using Origin Software. Results.

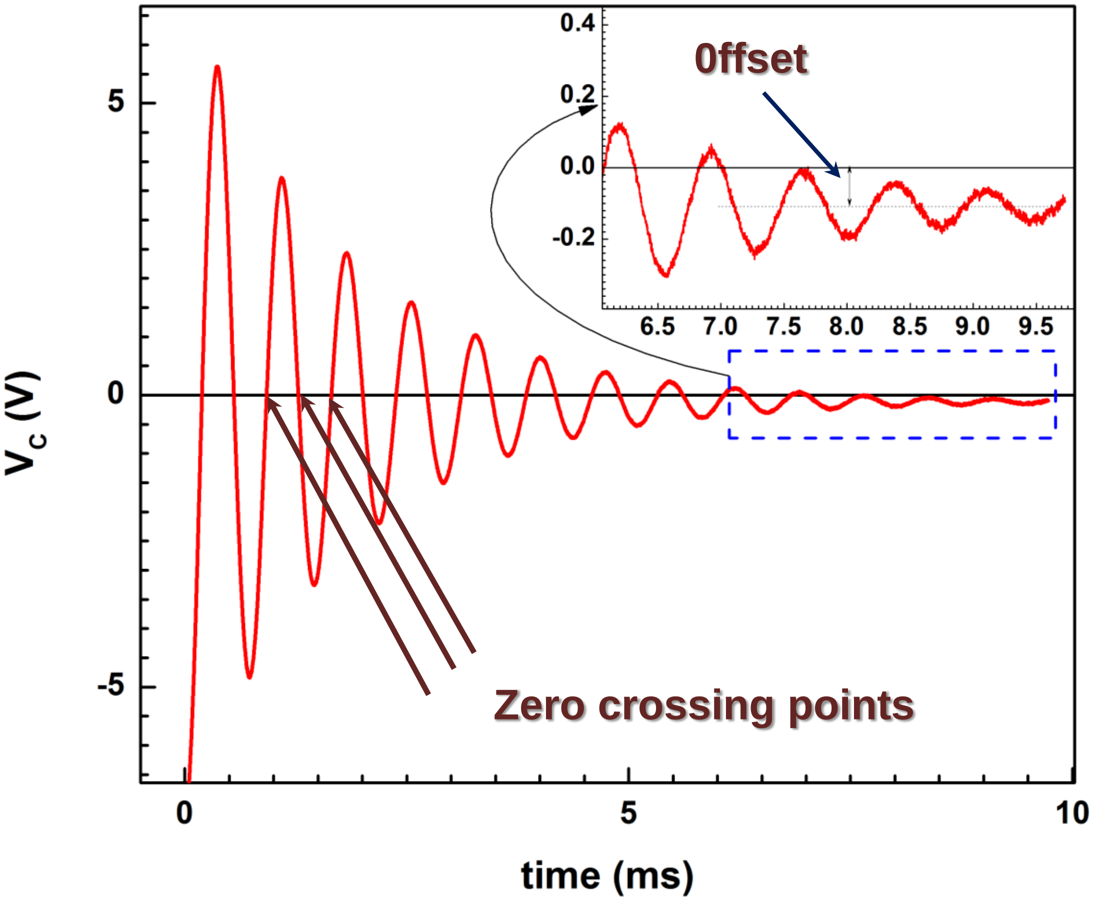




Fitting the "envelope data" to exponential decay function

Transients in RLC Circuit. Data Analysis. $(1/T)^2$ vs 1/C Experiment.

$$q(t) = Ae^{-at}\sin(\omega t + \varphi) + offset$$

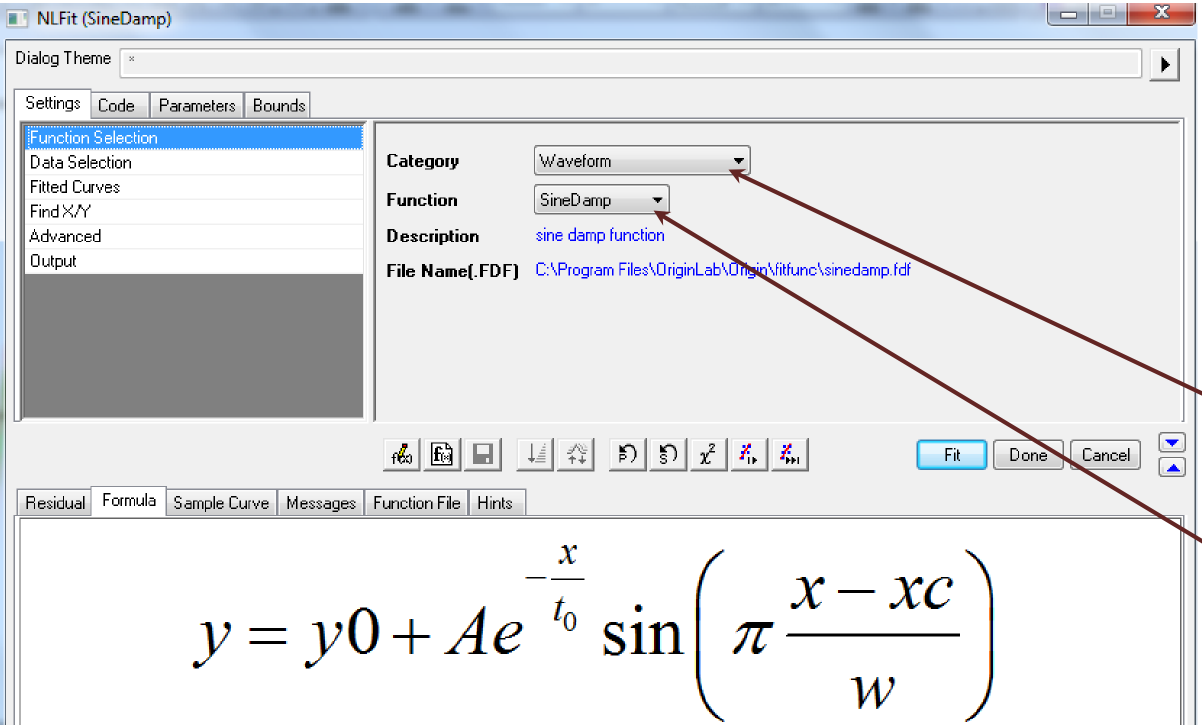


Manual evaluation of the period of the oscillations

Limited accuracy

Results can be effected by DC offset

Transients in RLC Circuit. Data Analysis. $(1/T)^2$ vs 1/C Experiment. Using Origin Software.



$$q(t) = Ae^{-at}\sin(\omega t + \varphi)$$

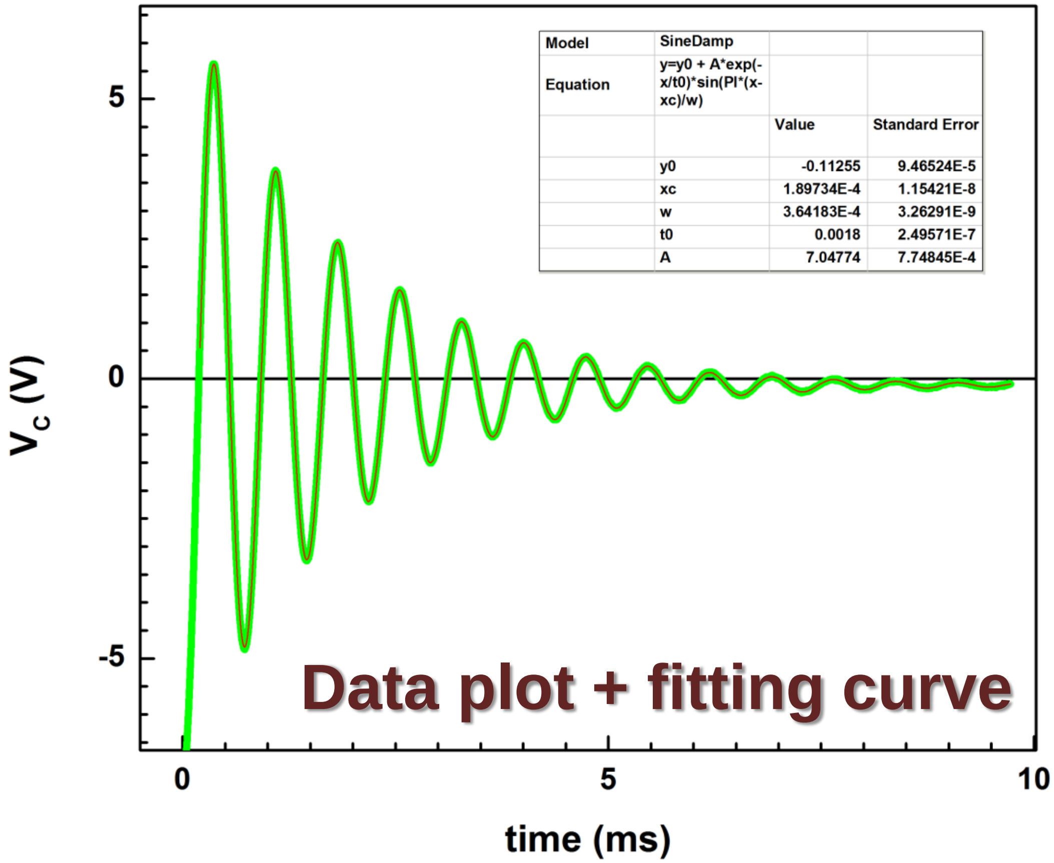
Use Origin standard function

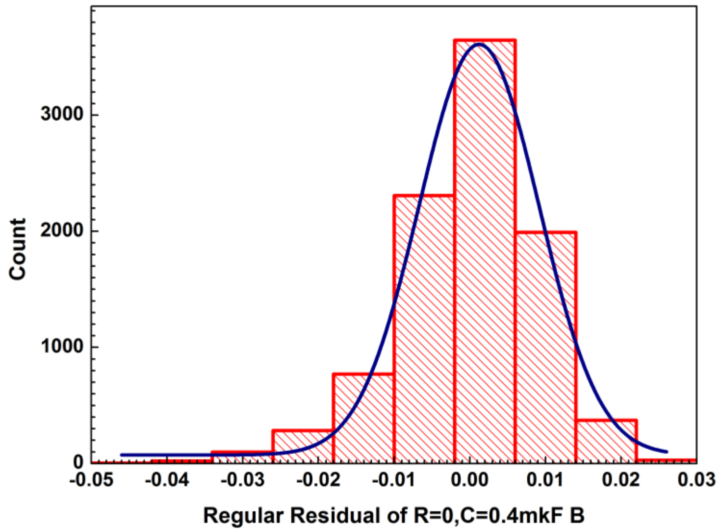
Category: Waveform
Function: SineDamp

Fitting function ; y0,A,t_0 xc, w – fitting parameters

Transients in RLC Circuit. Data Analysis. $(1/T)^2$ vs 1/C Experiment. Using Origin Software.

$$q(t) = Ae^{-at}\sin(\omega t + \varphi)$$

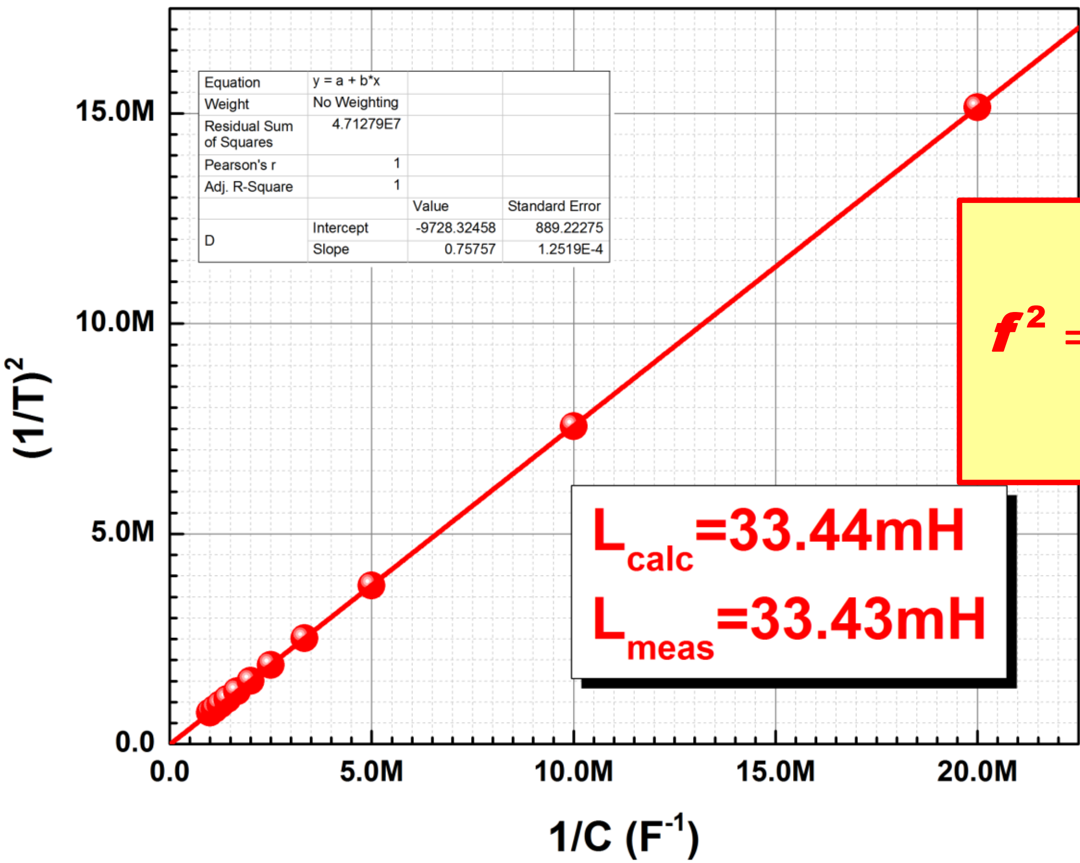




Residuals - criteria of quality of fitting

Transients in RLC Circuit. Data Analysis.
$(1/T)^2$ vs 1/C Experiment. Using Origin Software.

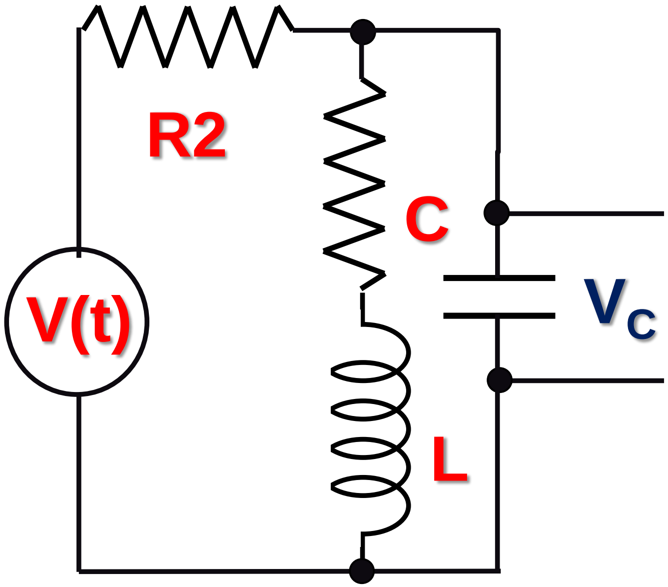
$$q(t) = Ae^{-at}\sin(\omega t + \varphi)$$

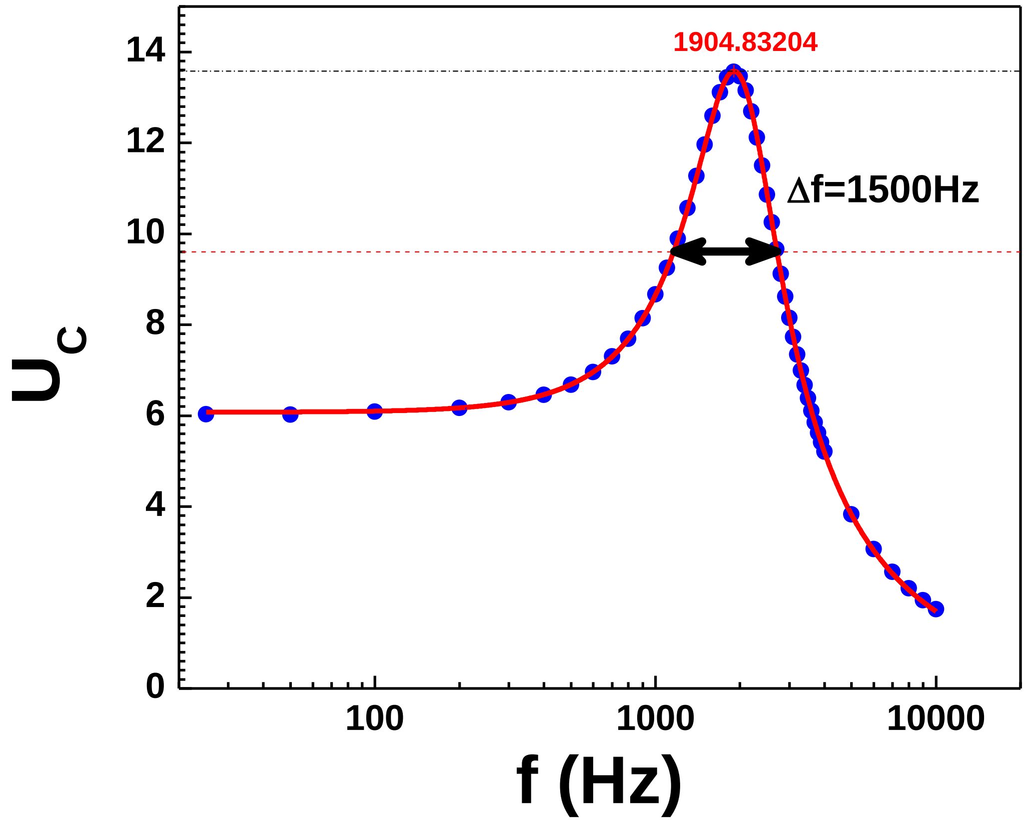


$$f^2 = \left(\frac{1}{T}\right)^2 = \frac{1}{2\pi}\left(\left(\frac{1}{LC}\right) - \left(\frac{R}{2L}\right)^2\right)$$

Final results

Resonance in RLC Circuit.





$$Q = \frac{f}{\Delta f} = \frac{1904}{1500} = 1.26$$

now

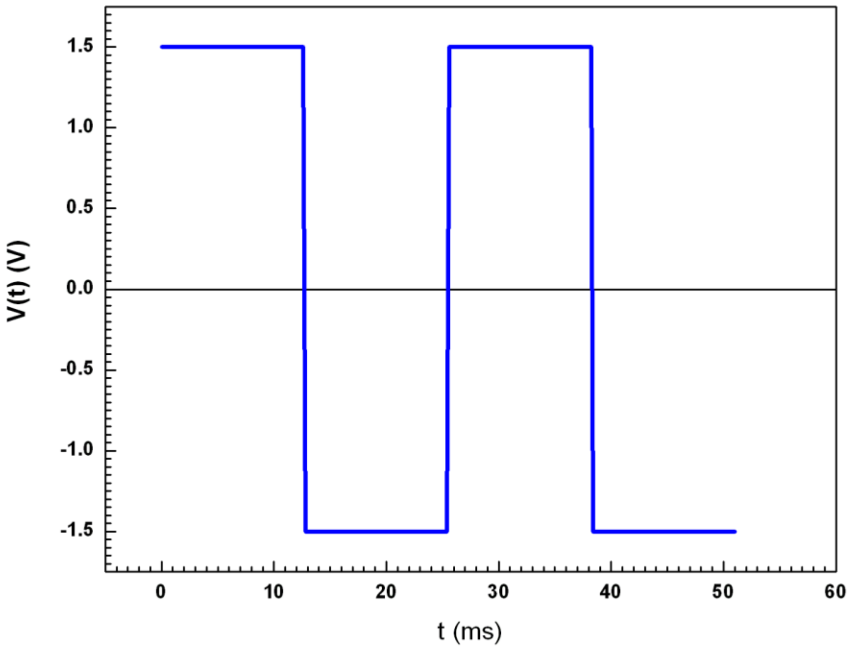
Frequency Domain Analysis of Linear Circuits Using Synchronous Detection

in 1822, Jean Baptiste Fourier developed the theory that shows that any real waveform can be represented by the sum of sinusoidal waves.

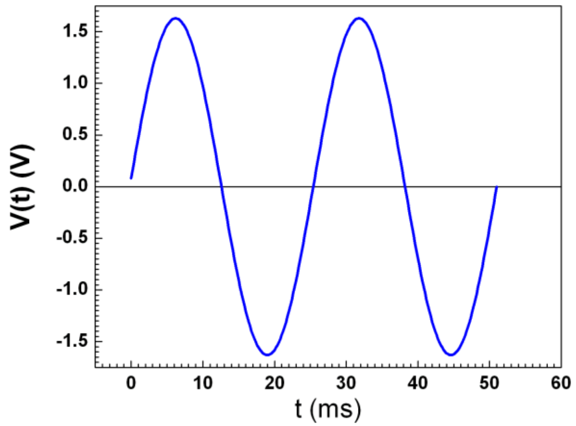
Jean Baptiste Joseph Fourier (1768 – 1830)

Let we try to create the square wave as a sum of sine waves of different frequencies

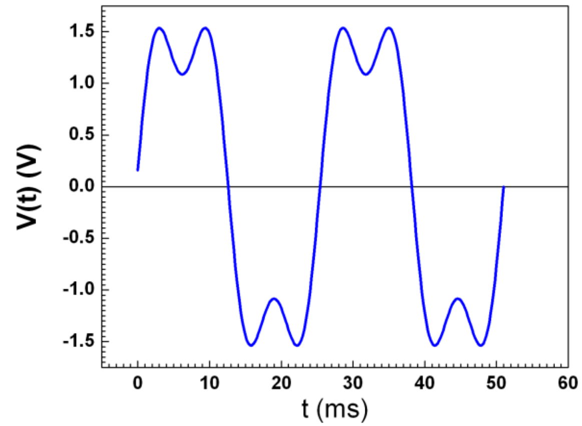
Square wave. F=40Hz, A=1.5V



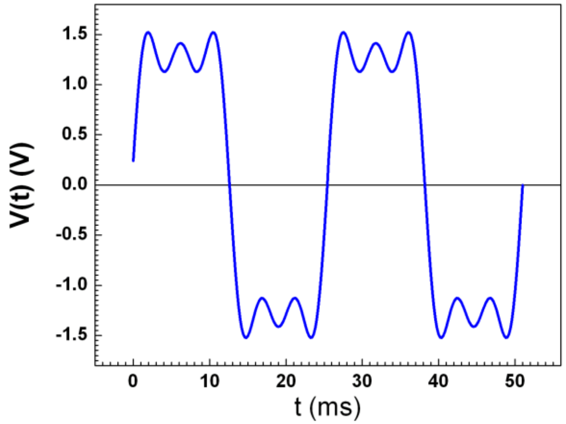
$$A_1\sin(2\pi\omega t)$$



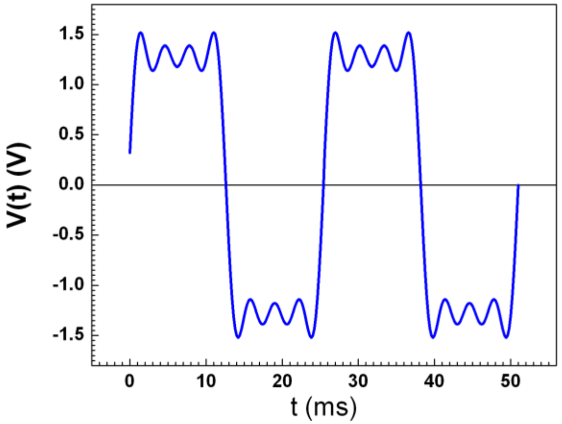
$$A_1\sin(2\pi\omega t) + A_3\sin(2\pi 3\omega t + \varphi_3)$$



$$A_1\sin(2\pi\omega t) + A_3\sin(2\pi 3\omega t + \varphi_3) + A_5\sin(2\pi 5\omega t + \varphi_5)$$



$$A_1\sin(2\pi\omega t) + A_3\sin(2\pi 3\omega t + \varphi_3) + A_5\sin(2\pi 5\omega t + \varphi_5) + A_7\sin(2\pi 7\omega t + \varphi_7)$$



Fourier Transform

The continues Fourier transformation of the signal h(t) can be written as:

$$H(f)=\int_{-\infty}^{+\infty} h(t)e^{2\pi jft}dt; \quad j=\sqrt{-1}$$

H(f) represents in frequency domain mode the time domain signal h(t)

Equation for inverse Fourier transform gives the correspondence of the infinite continues frequency spectra to the corresponding time domain signal.

$$h(t)=\int_{-\infty}^{+\infty} H(f)e^{-2\pi jft}df$$

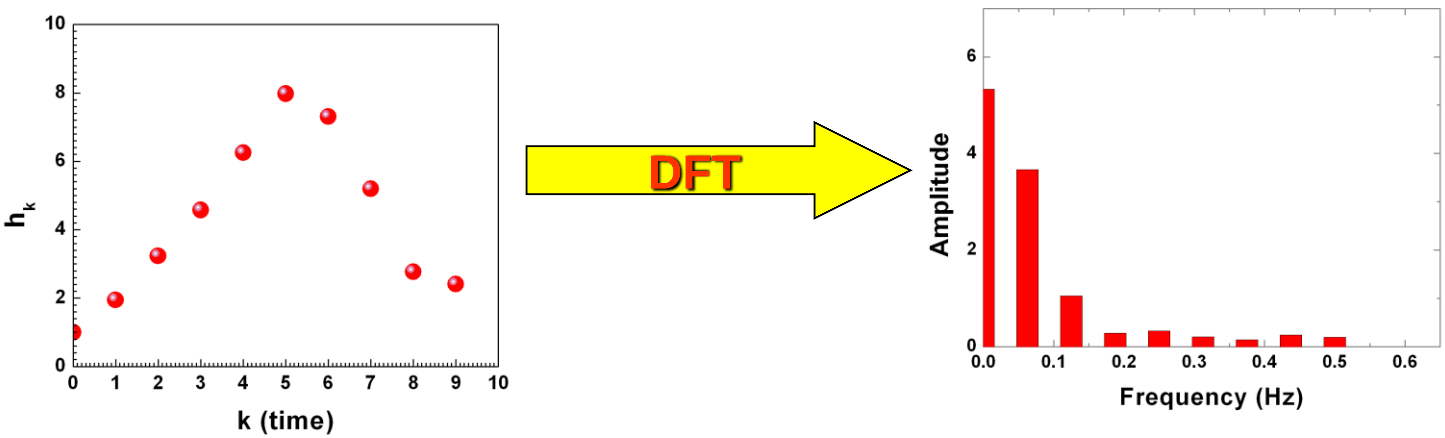
In real life we working with discrete representation of the time domain signal recorded during a finite time.

Discrete Fourier Transform

It comes out that in practice more useful is the representation the frequency domain pattern of the time domain signal h_k as sum of the frequency harmonic calculated as:

$$H_n = H(f_n) = \frac{1}{N}\sum_{k=0}^{N-1} h_k e^{2\pi kn/N}$$

Δ is the sampling interval, N – number of collected points



Time domain **Frequency domain**

Discrete Fourier Transform

For periodic signals with period T_0:

$$F(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos\left(\frac{2\pi nt}{T_0}\right) + \sum_{n=1}^{\infty} b_n \sin\left(\frac{2\pi nt}{T_0}\right)$$

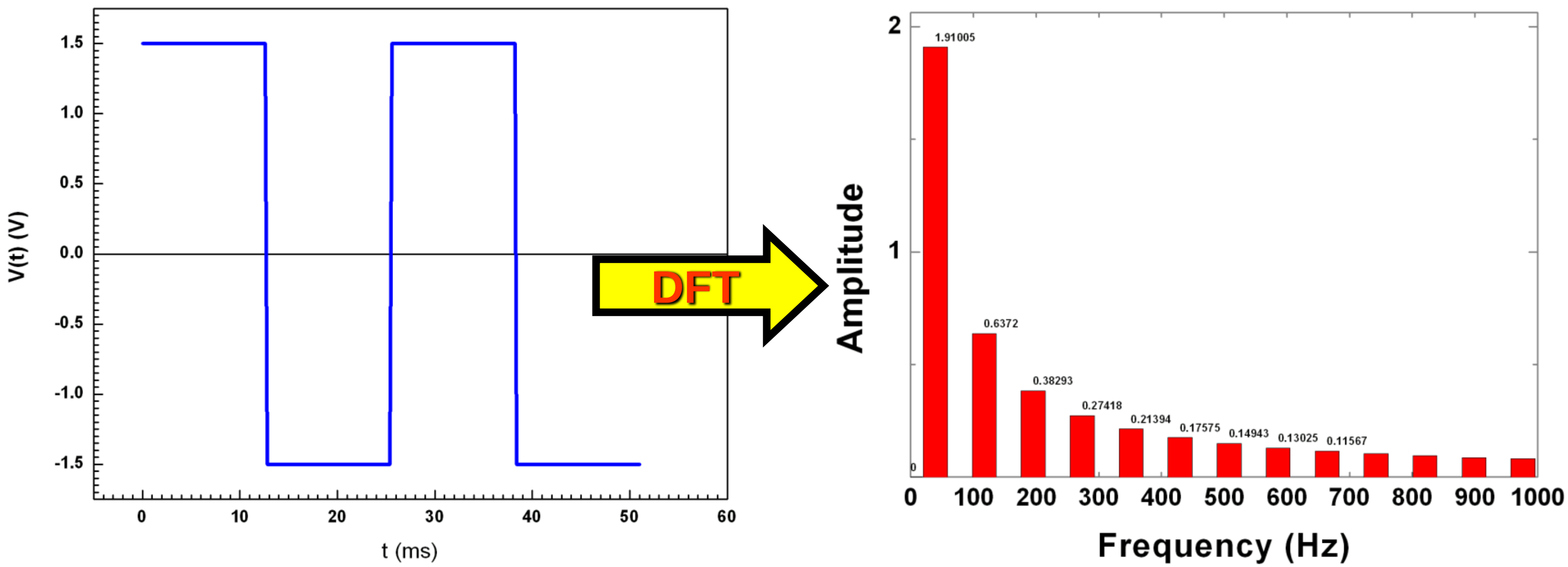
$$a_n = \frac{2}{T_0}\int_0^{T_0} F(t)\cos\left(\frac{2\pi nt}{T_0}\right)dt; \qquad b_n = \frac{2}{T_0}\int_0^{T_0} F(t)\sin\left(\frac{2\pi nt}{T_0}\right)dt;$$

$$a_0 = \frac{2}{T_0}\int_0^{T_0} F(t)dt;$$

Discrete Fourier Transform

Now how I found the amplitudes of the harmonics to compose the square wave signal from sine waves of different frequencies.

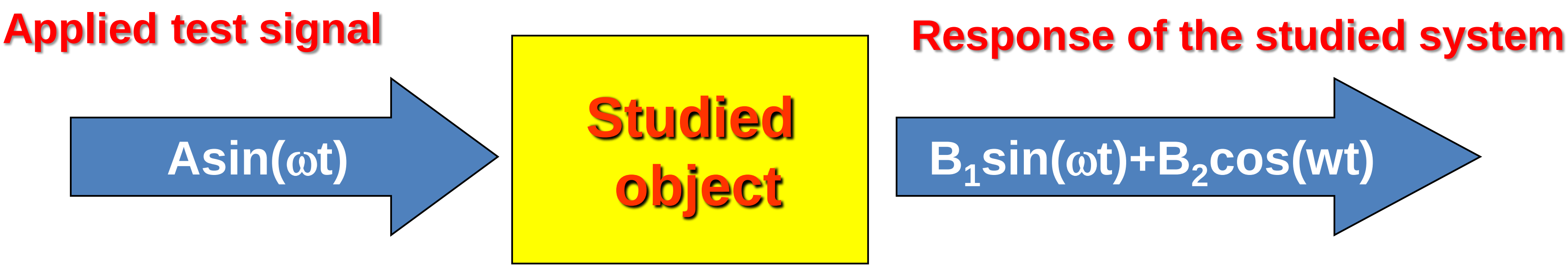
Time domain signal



Decomposition the signal into the sine wave harmonics. The only modulus's of the harmonics amplitudes are presented in this picture.

Frequency Domain Spectroscopy

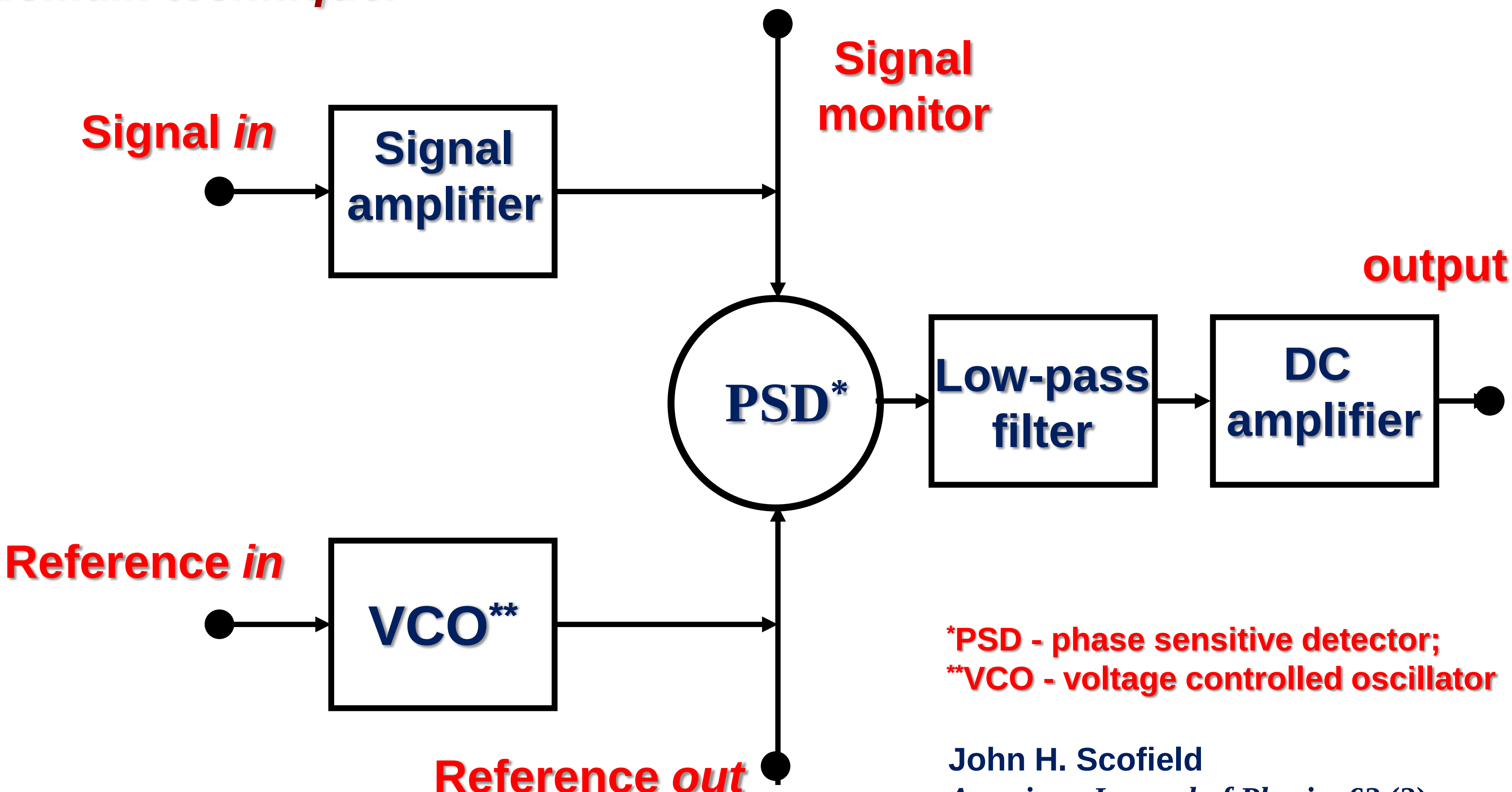
(linear system)



We applying the sine wave signal to the tested object and measuring the response. Varying the frequency we can study the frequency properties of the system.

Lock-in amplifier

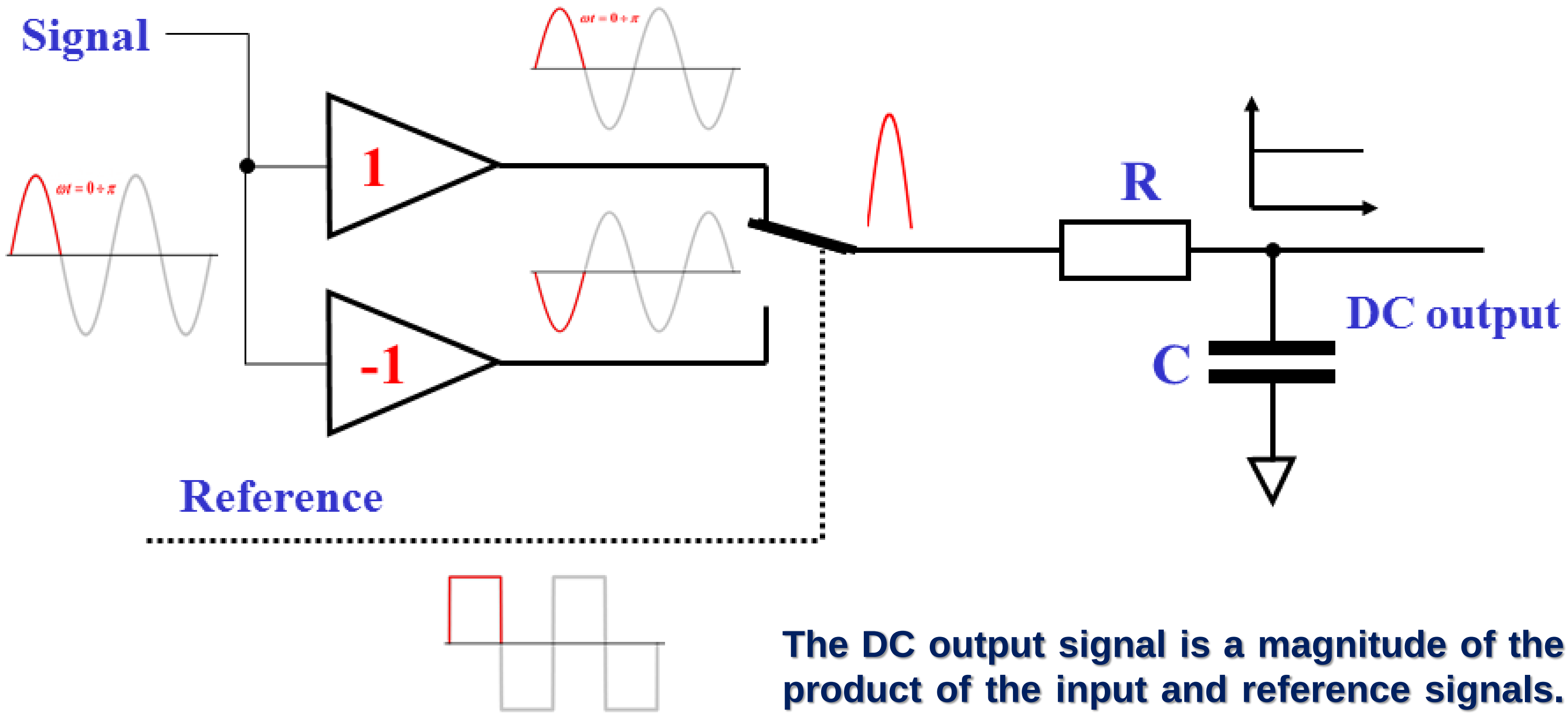
Now about the most powerful tool which can be used in frequency domain technique.



***PSD - phase sensitive detector;**
****VCO - voltage controlled oscillator**

John H. Scofield
American Journal of Physics 62 (2) 129-133 (Feb. 1994).

Lock-in amplifier. How it works.

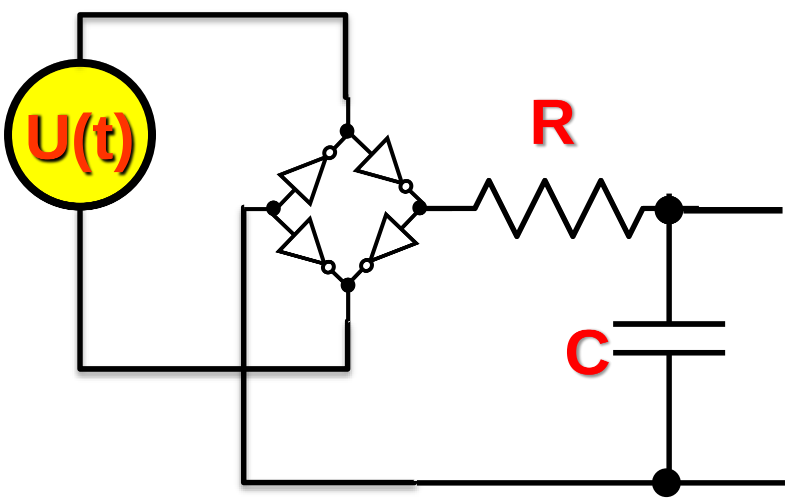


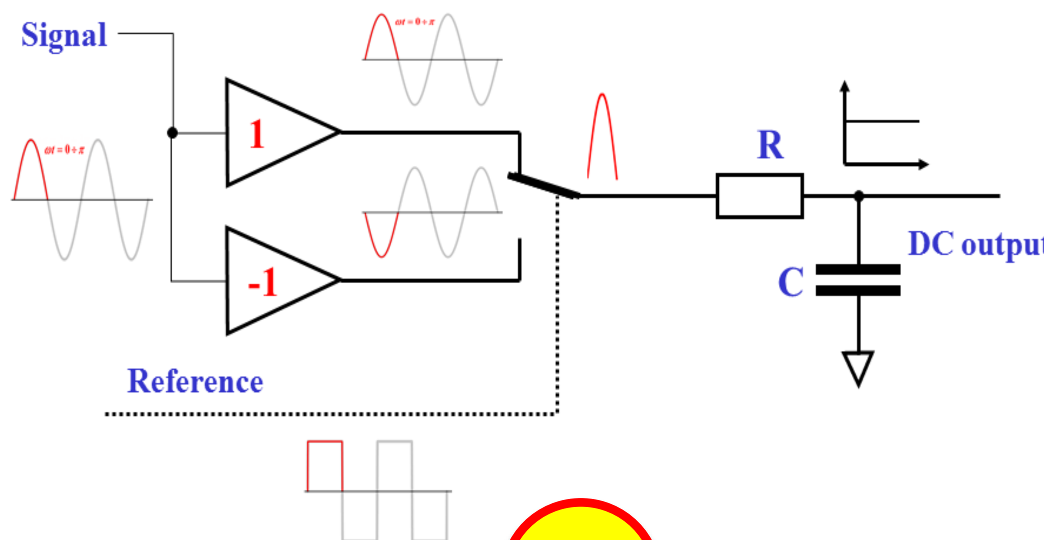
The DC output signal is a magnitude of the product of the input and reference signals. AC components of output signal are filtered out by the low-pass filter with time constant τ (her τ=RC)

Lock-in Amplifier. What is the Advantage of Using Synchronous Detecting?

DMM, lock-in etc.

Results as DC voltage corresponding U_{AMP}, U_{RMS} …





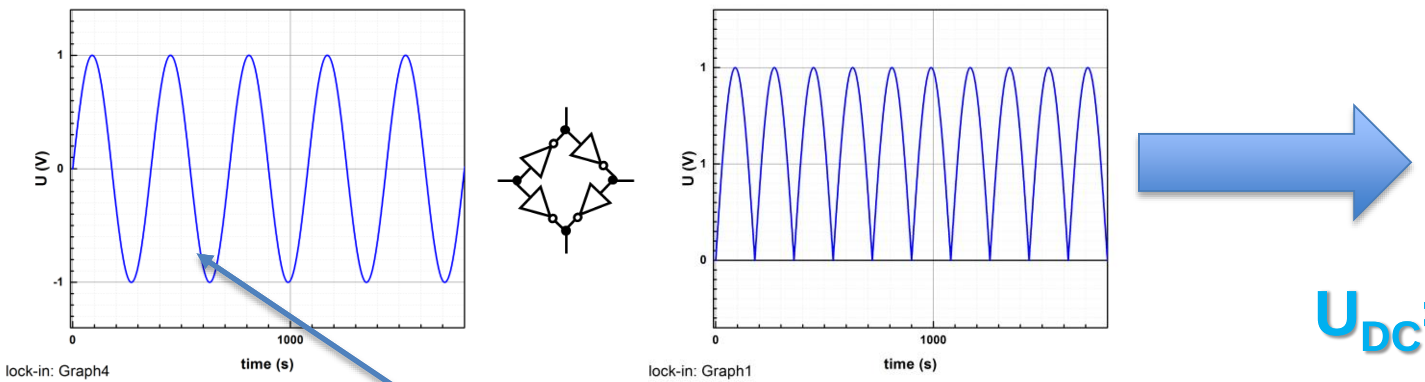
1

2

Lock-in Amplifier. What is the Advantage of Using Synchronous Detecting?

1

Clean sine wave – no “noise”



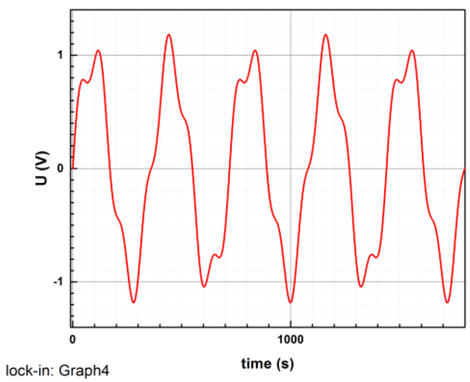
U_{DC}=0.63643V

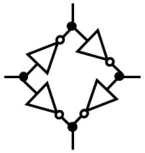
We need to measure the amplitude/rms value of the sine wave

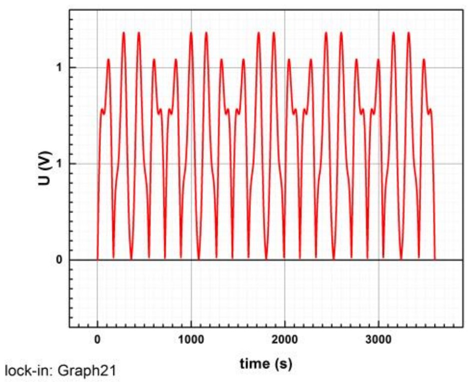
Lock-in Amplifier. What is the Advantage of Using Synchronous Detecting?

1

"Noisy" sine wave







U_{DC}=0.64208V

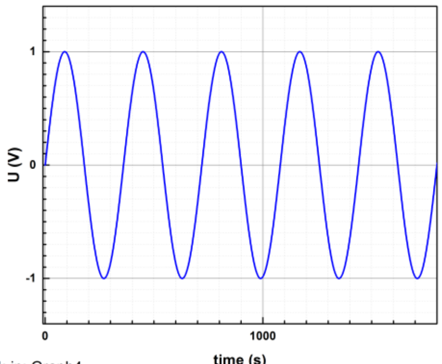
compare to

U_{DC}=0.63643V

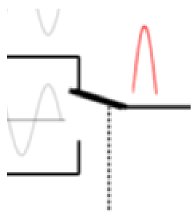
Lock-in Amplifier. What is the Advantage of Using Synchronous Detecting?

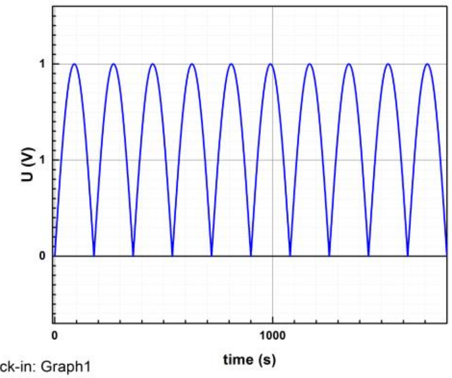
2

Clear sine wave – no "noise"



lock-in: Graph4



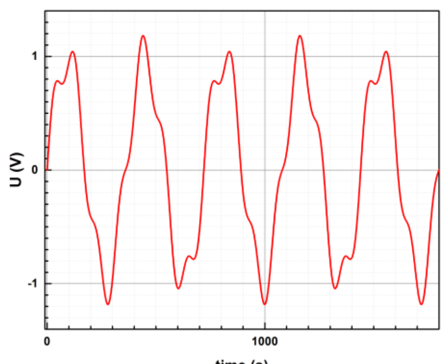


lock-in: Graph1

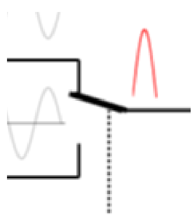
U_{DC}=0.63643V

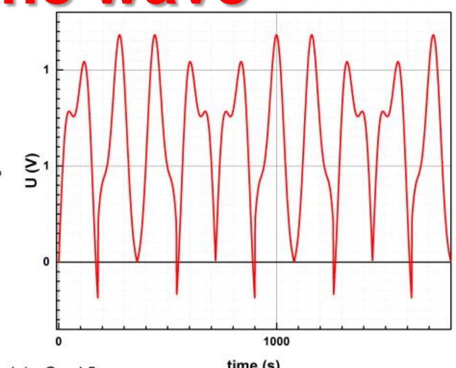
=

"Noisy" sine wave



lock-in: Graph4

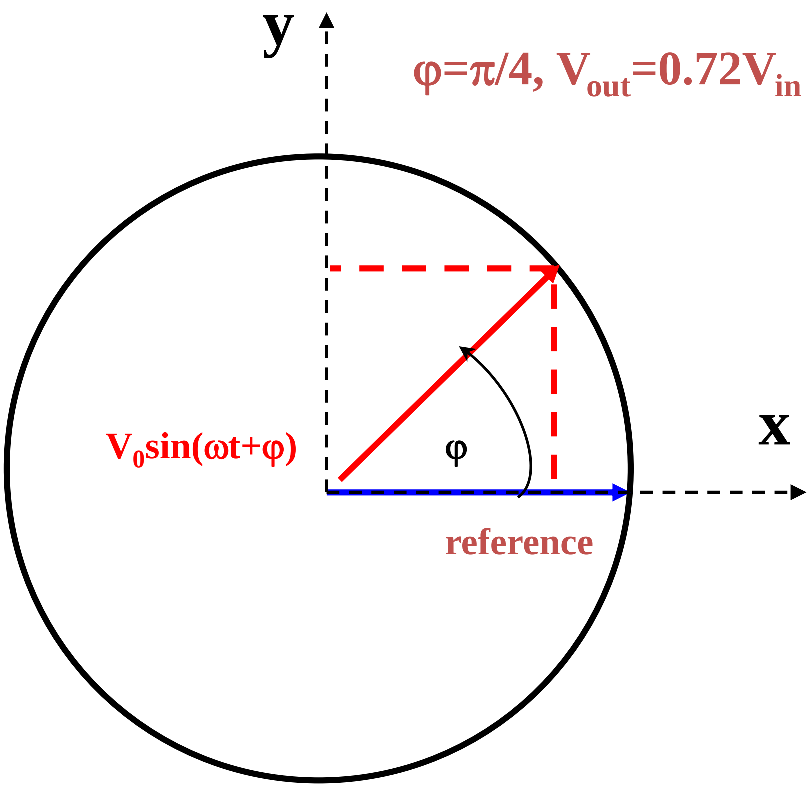


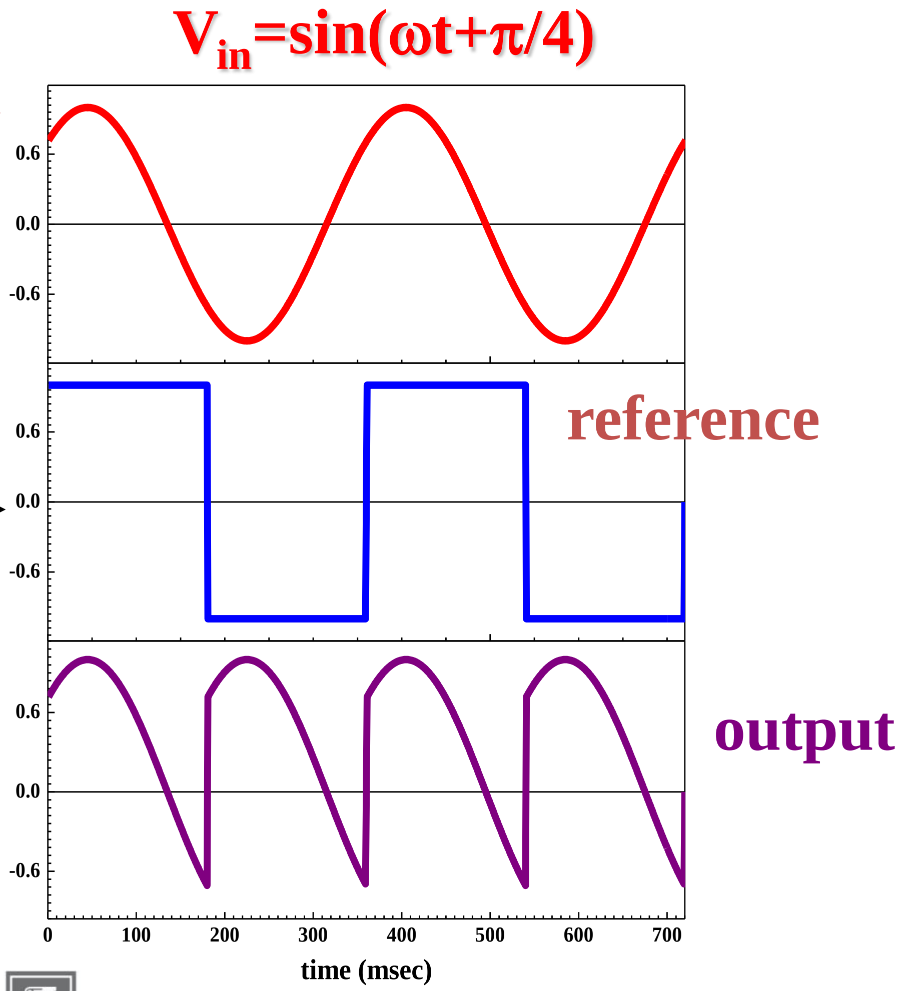


lock-in: Graph5

U_{DC}=0.63643V

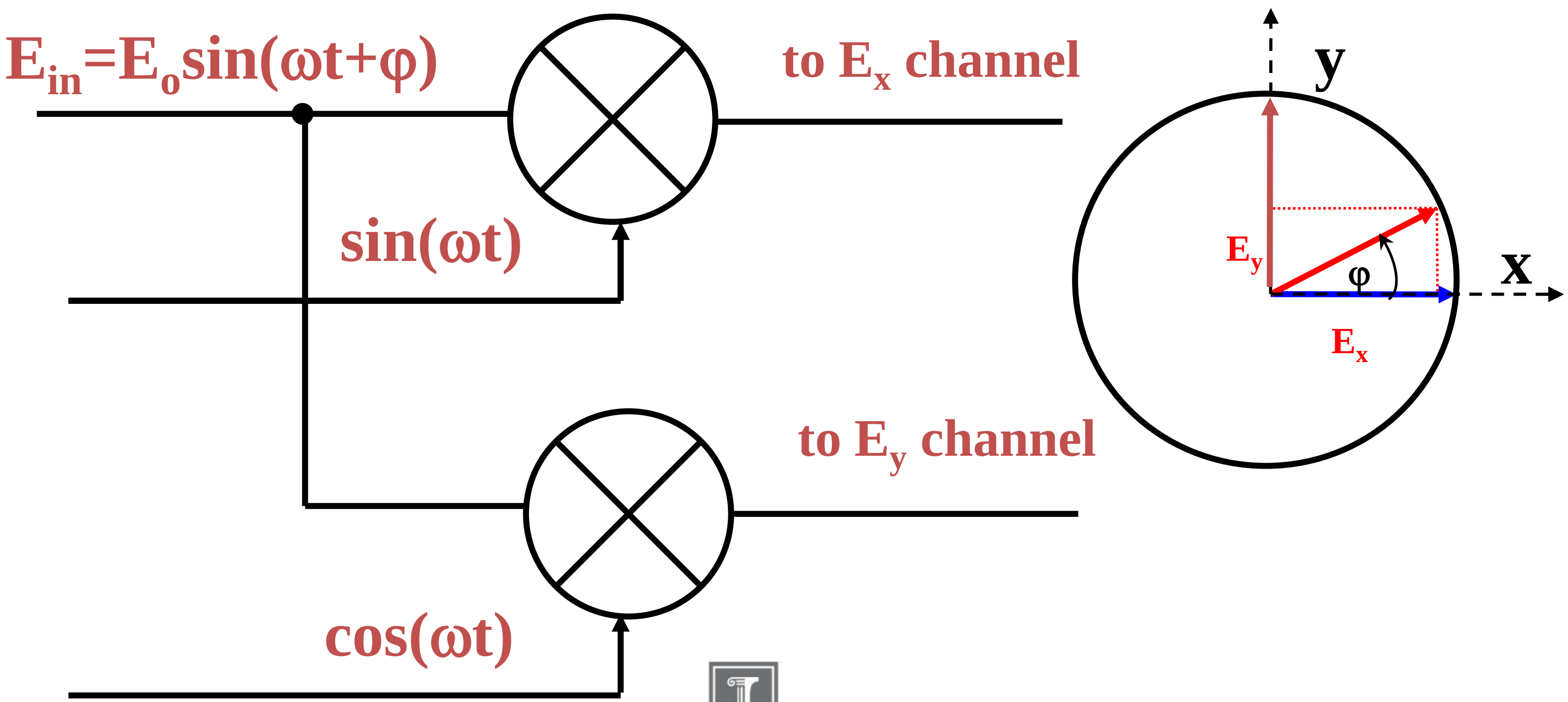
Lock-in Amplifier. Phase shift.



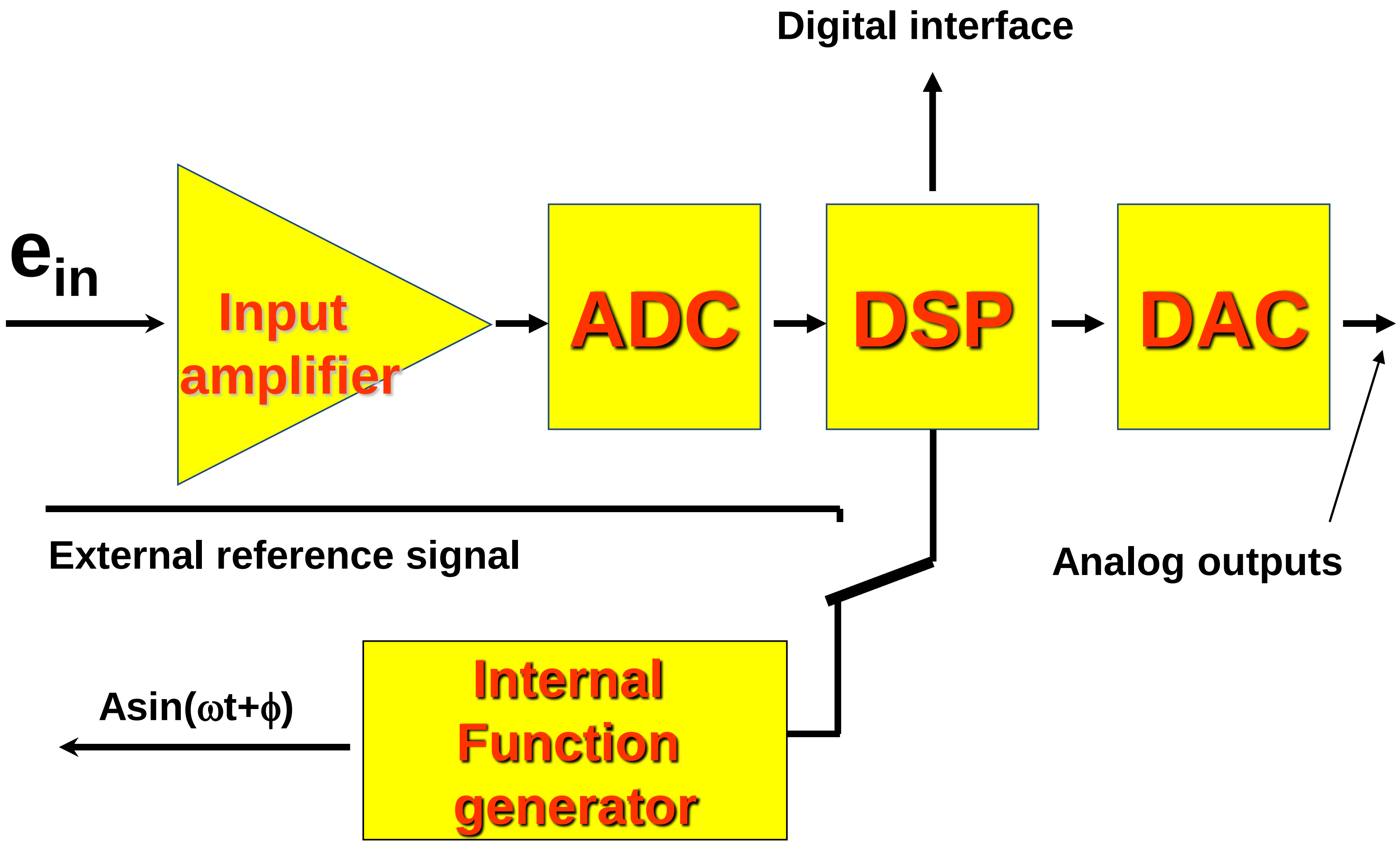


Lock-in Amplifier. Two Channels Demodulation.

In many scientific applications it is a great advantage to measure both components (E_x, E_y) of the input signal. We can use two lock-ins to do this or we can measure these value in two steps providing the phase shift of reference signal 0 and $\pi/2$. Much better solution is to use the lock-in amplifier equipped by two demodulators.



Digital Lock-in Amplifier



SR830. Digital Lock-in Amplifier

In SR830 manual you can find the chapter dedicated to general description of the lock-in amplifier idea

SR830 BASICS

WHAT IS A LOCK-IN AMPLIFIER?

Lock-in amplifiers are used to detect and measure very small AC signals - all the way down to a few nanovolts! Accurate measurements may be made even when the small signal is obscured by noise

experiment at the reference frequency. In the diagram below, the reference signal is a square wave at frequency ω_r. This might be the sync output from a function generator. If the sine output from

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Digital Lock-in amplifier. SR830

Time constant
And output filter

sensitivity

Auto functions

Channel#1

Channel#2

Inputs

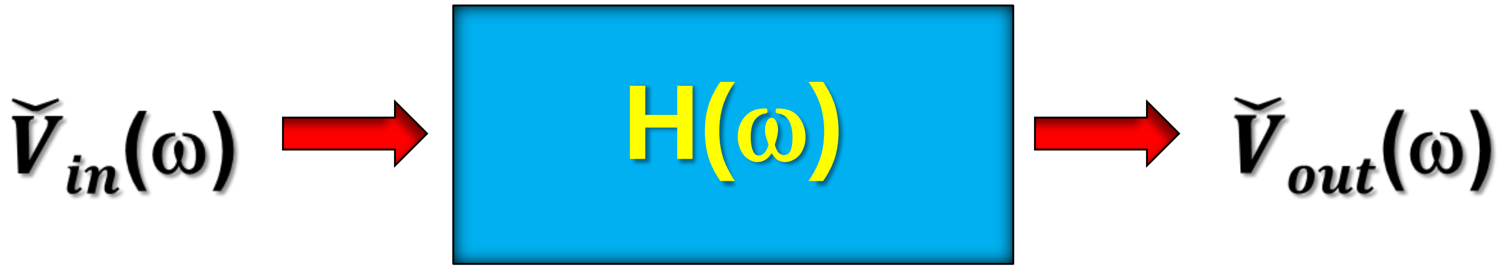
Notch filter settings

Analog outputs

Interface settings

Function generator

Experiments. Main idea. Investigating the frequency response of circuit.

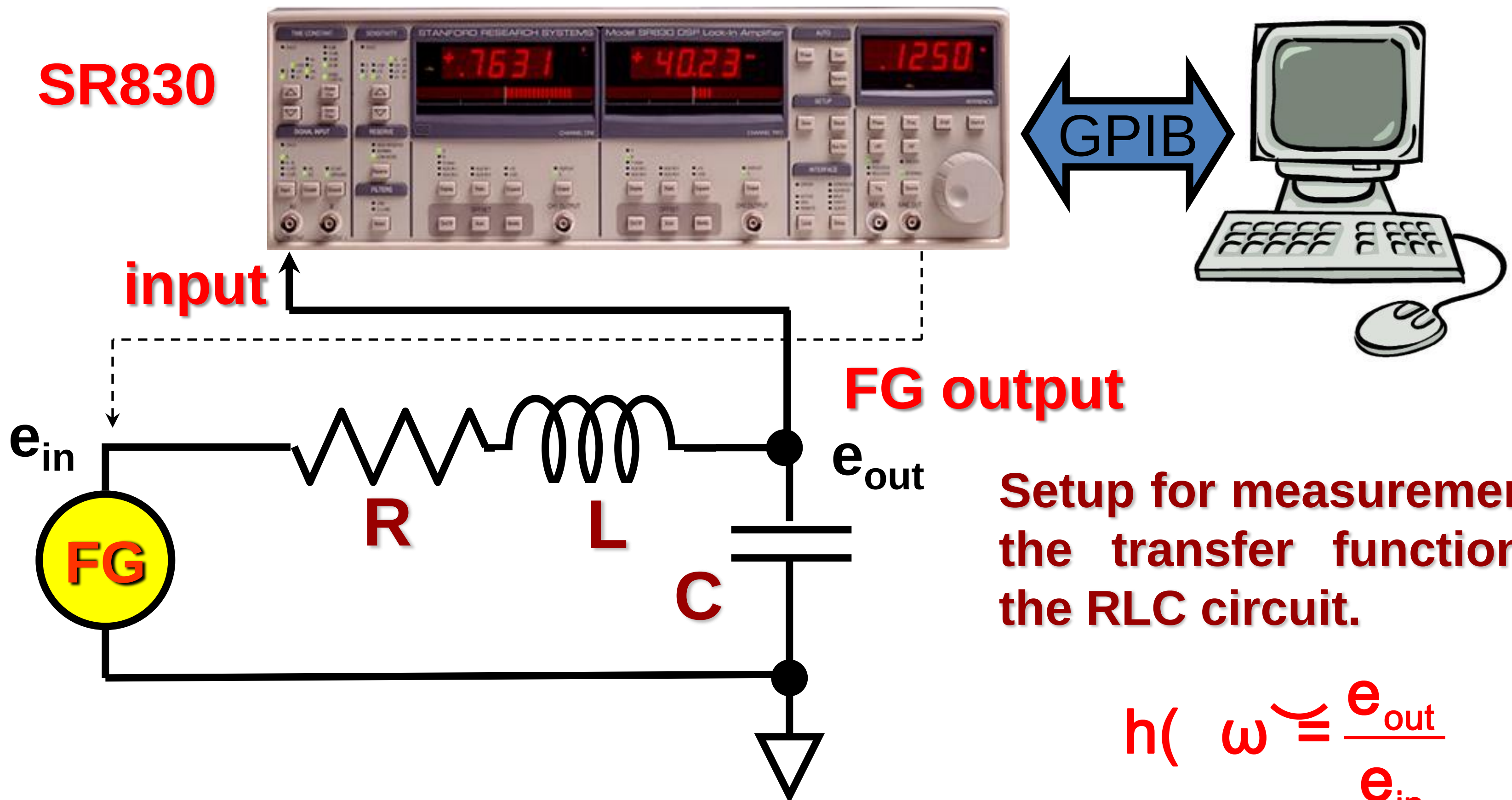


Frequency domain representation of the system

Response function → $\breve{H}(\omega) = \dfrac{\breve{V}_{out}(\omega)}{\breve{V}_{in}(\omega)}$

Linear systems are those that can be modeled by linear differential equations.

Application of the Lock-in Amplifier for Study of the Transfer Function of the RLC Circuit

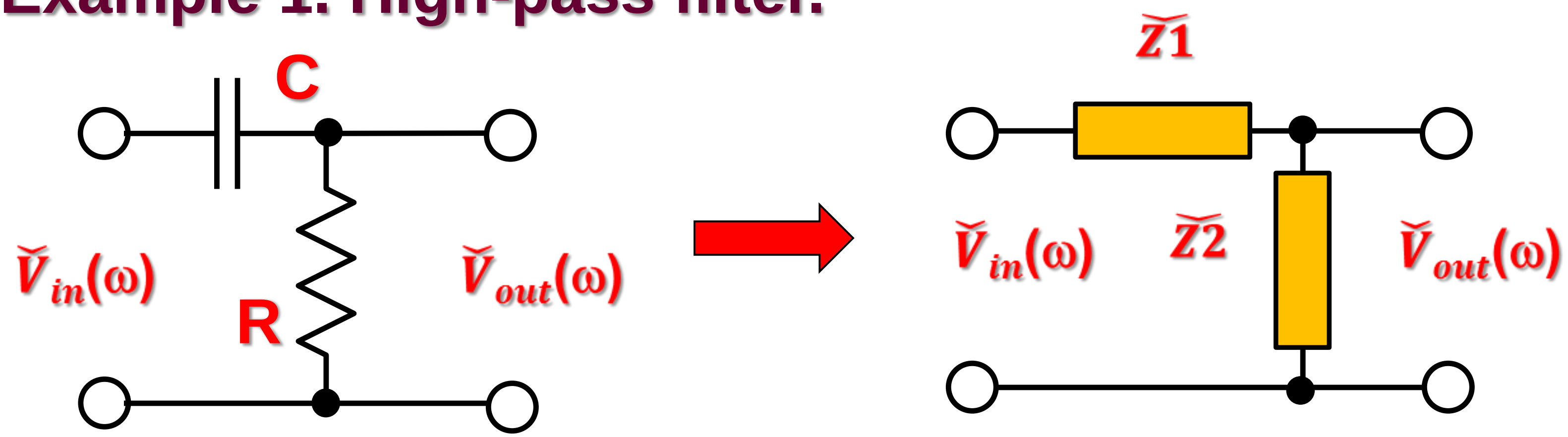


Setup for measurement of the transfer function of the RLC circuit.

$$h(\omega) = \frac{e_{out}}{e_{in}}$$

Experiments. Main Idea. Calculation of the Response Function in Frequency Domain Mode.

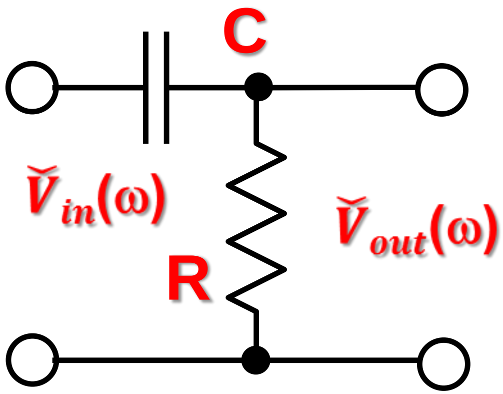
Example 1. High-pass filter.



Applying the Kirchhoff Law to this simple network

$$\tilde{V}_{out}(\omega) = \tilde{H}(\omega) * \tilde{V}_{in}(\omega) = \tilde{V}_{in}(\omega)\frac{\tilde{Z}2(\omega)}{\tilde{Z}1(\omega) + \tilde{Z}2(\omega)}$$

Experiments. Calculation of the Response Function in Frequency Domain Mode. High-pass Filter



Ideal case

$$\tilde{Z}_R = R$$

$$\tilde{Z}_L = j\omega L$$

$$\tilde{Z}_C = \frac{1}{j\omega C} = -\frac{j}{\omega C}$$

More realistic

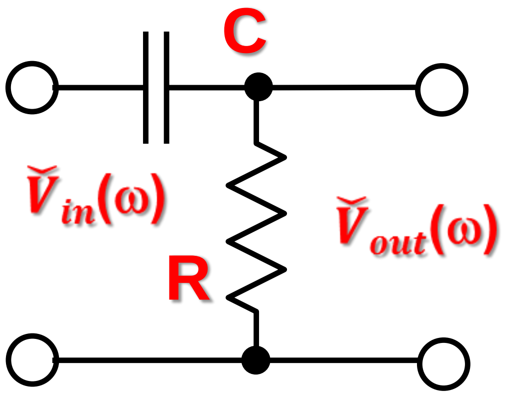
$$\tilde{Z}_R = R + \dots$$

$$\tilde{Z}_L = j\omega L + R_L$$

$$\tilde{Z}_C = \frac{1}{j\omega C} = \frac{1}{j\omega C + R_C^{-1}}$$

$$\tilde{V}_{out}(\omega) = \tilde{H}(\omega) * \tilde{V}_{in}(\omega) = \tilde{V}_{in}(\omega)\frac{\tilde{Z}2(\omega)}{\tilde{Z}1(\omega) + \tilde{Z}2(\omega)}$$

Experiments. Calculation of the Response Function in Frequency Domain Mode. High-pass Filter



τ – time constant of the filter

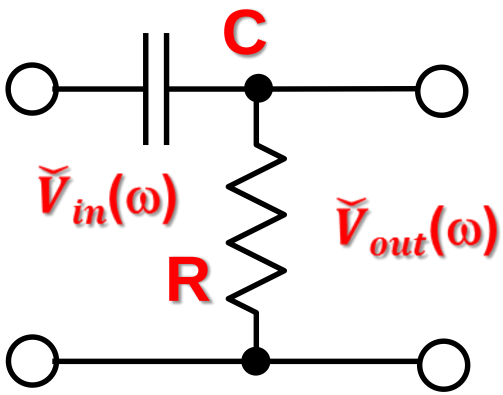
ω_C - cutoff frequency

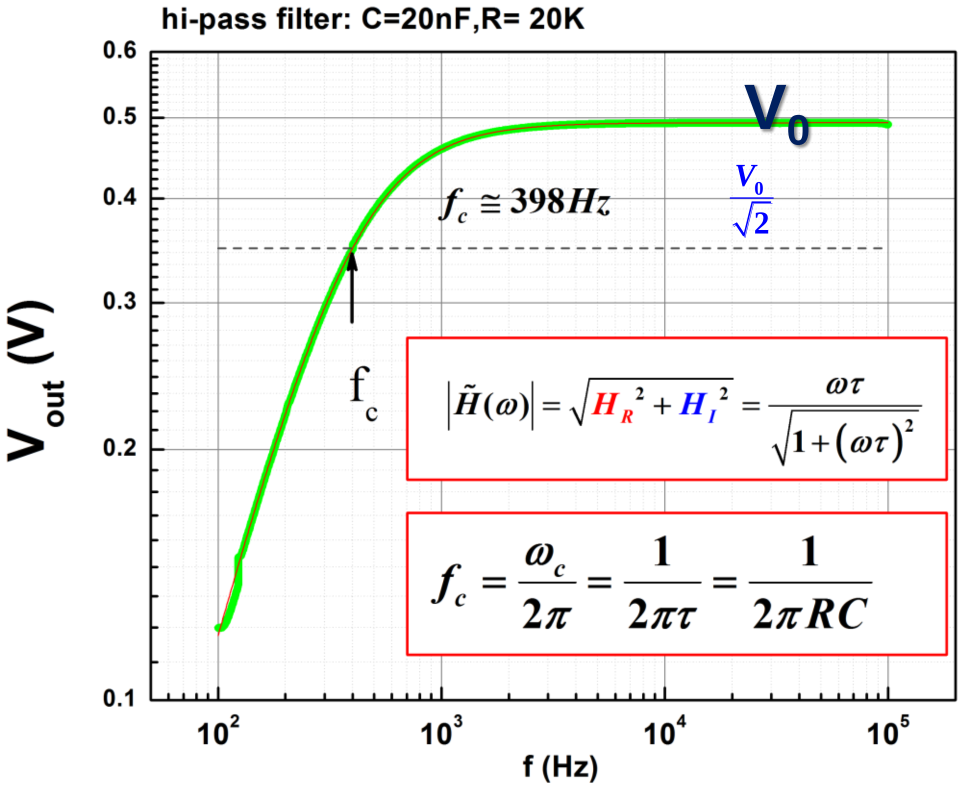
$$\tilde{H}(\omega) = H_R(\omega) + jH_I(\omega) = \frac{R}{R + \frac{1}{j\omega C}} = \frac{j\omega RC}{1 + j\omega RC} = \frac{j\omega\tau}{1 + j\omega\tau} = \frac{\omega\tau}{\left(1+\omega^2\tau^2\right)}(\omega\tau + j);$$

where $\tau = RC = \omega_c^{-1}$;

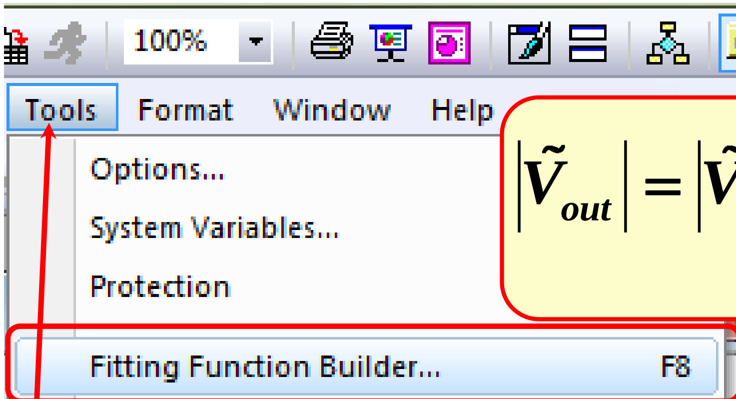
$$\left|\tilde{H}(\omega)\right| = \sqrt{H_R{}^2 + H_I{}^2} = \frac{\omega\tau}{\sqrt{1+(\omega\tau)^2}}; \quad \theta(\omega) = \arctan\left(\frac{H_I(\omega)}{H_R(\omega)}\right) = \arctan\left(\frac{1}{\omega\tau}\right)$$

Experiments. Calculation of the Response Function in Frequency Domain Mode. High-pass Filter





High-pass Filter. Fitting.



$$\left|\tilde{V}_{out}\right| = \left|\tilde{V}_{in}\right| * \left|\tilde{H}(\omega)\right| = V_0 * \frac{\omega\tau}{\sqrt{1+(\omega\tau)^2}}; \quad \tau = RC$$

Fitting parameters: V_0, τ, Voff

V0,tau,Voff

Parameters	Constants

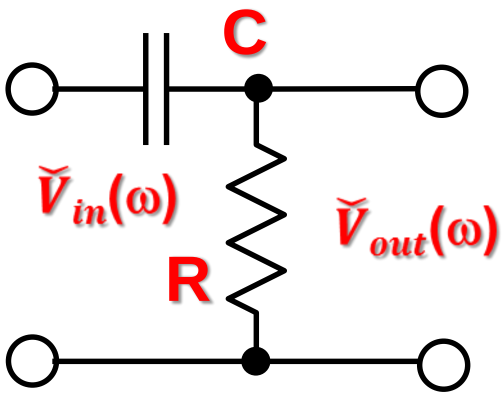
Param	Unit	Meaning	Fixed	Initial Value	Significant Digits
V0		?	☐	1	System
tau		?	☐	1	System
Voff		?	☐	1	System

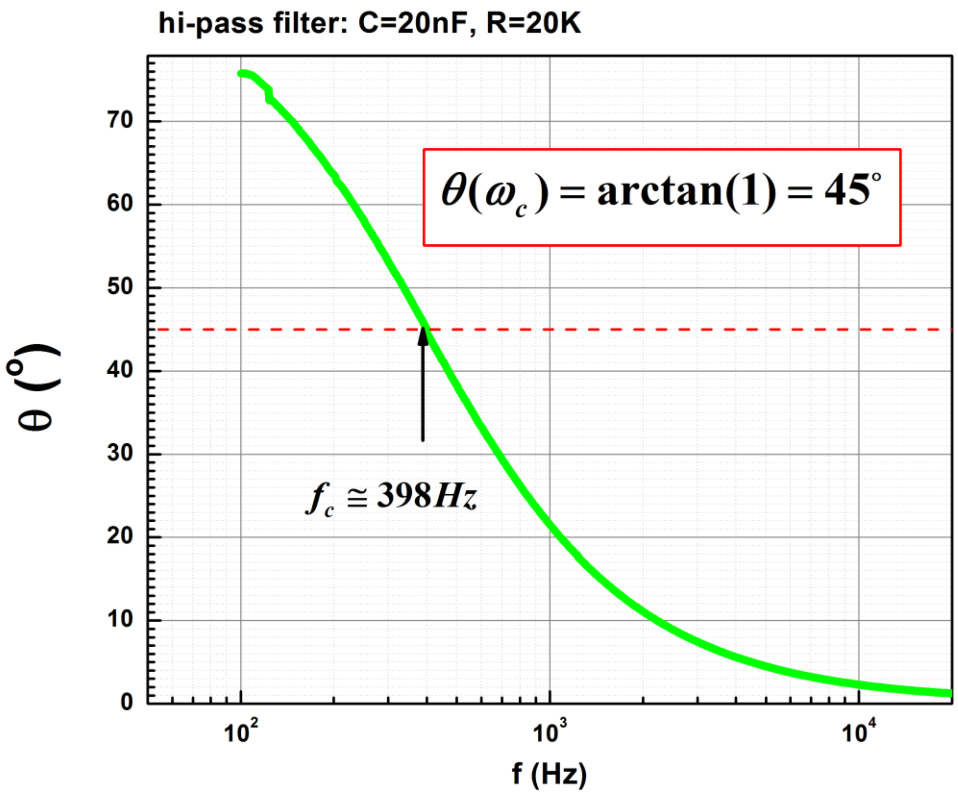
Fitting function →

Function Body (Dependent Variables : y)

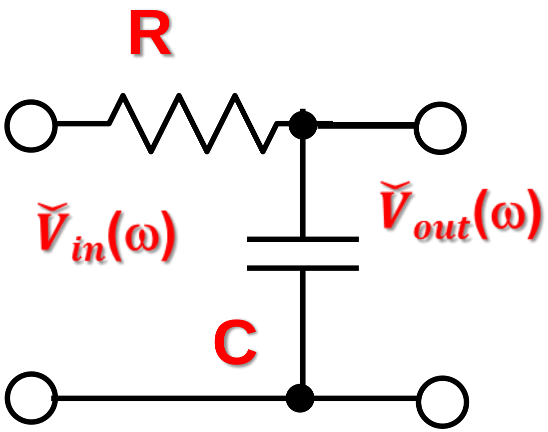
y=V0*2*pi*x*tau/sqrt(1+(2*pi*tau)^2)+Voff

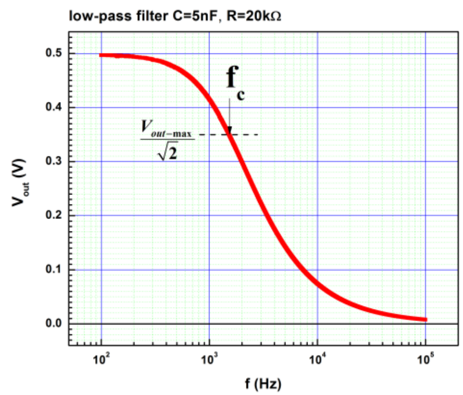
Experiments. Calculation of the Response Function in Frequency Domain Mode. High-pass Filter.

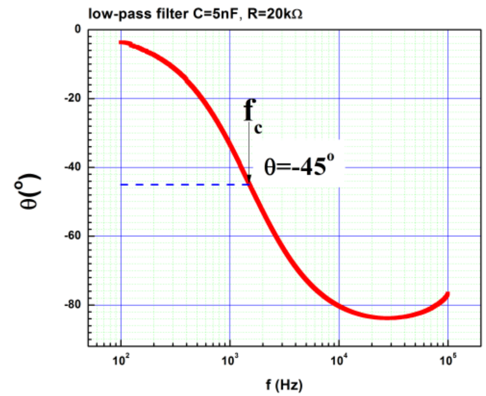




Experiments. Calculation of the Response Function in Frequency Domain Mode. Low-pass Filter





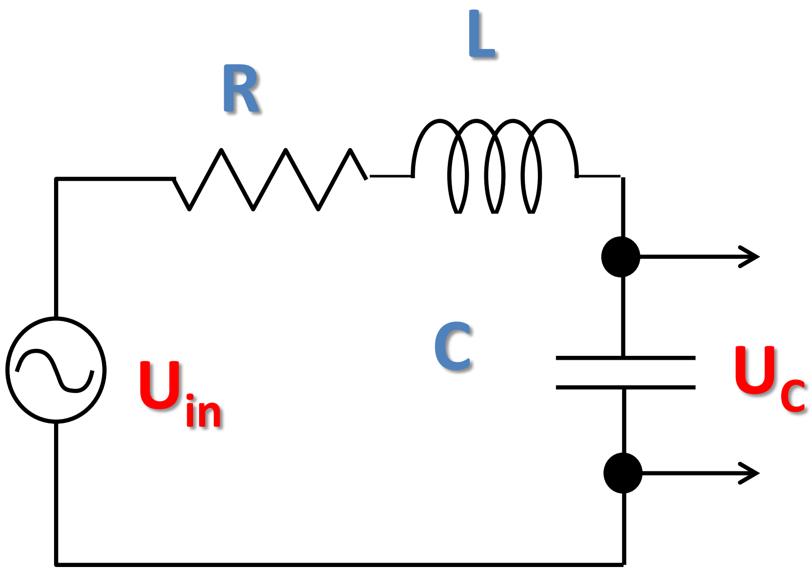


$$\tilde{H}(\omega) = H_R(\omega) + jH_I(\omega) = \frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} = \frac{1}{1 + j\omega RC} = \frac{1}{1 + j\omega\tau} = \frac{(1 - j\omega\tau)}{(1 + \omega^2\tau^2)};$$

where $\tau = RC = \omega_c^{-1}$;

$$\left|\tilde{H}(\omega)\right| = \sqrt{H_R{}^2 + H_I{}^2} = \frac{1}{\sqrt{1 + (\omega\tau)^2}}; \quad \theta(\omega) = \arctan\left(\frac{H_I(\omega)}{H_R(\omega)}\right) = -\arctan(\omega\tau)$$

Application of the Lock-in Amplifier for Study of the Transfer Function of the RLC Circuit .



$$U_C = U_{in} \bullet \frac{Z_C}{Z_C + Z_L + R} =$$

$$= \frac{\frac{1}{j\omega C}}{\frac{1}{j\omega C} + j\omega L + R}$$

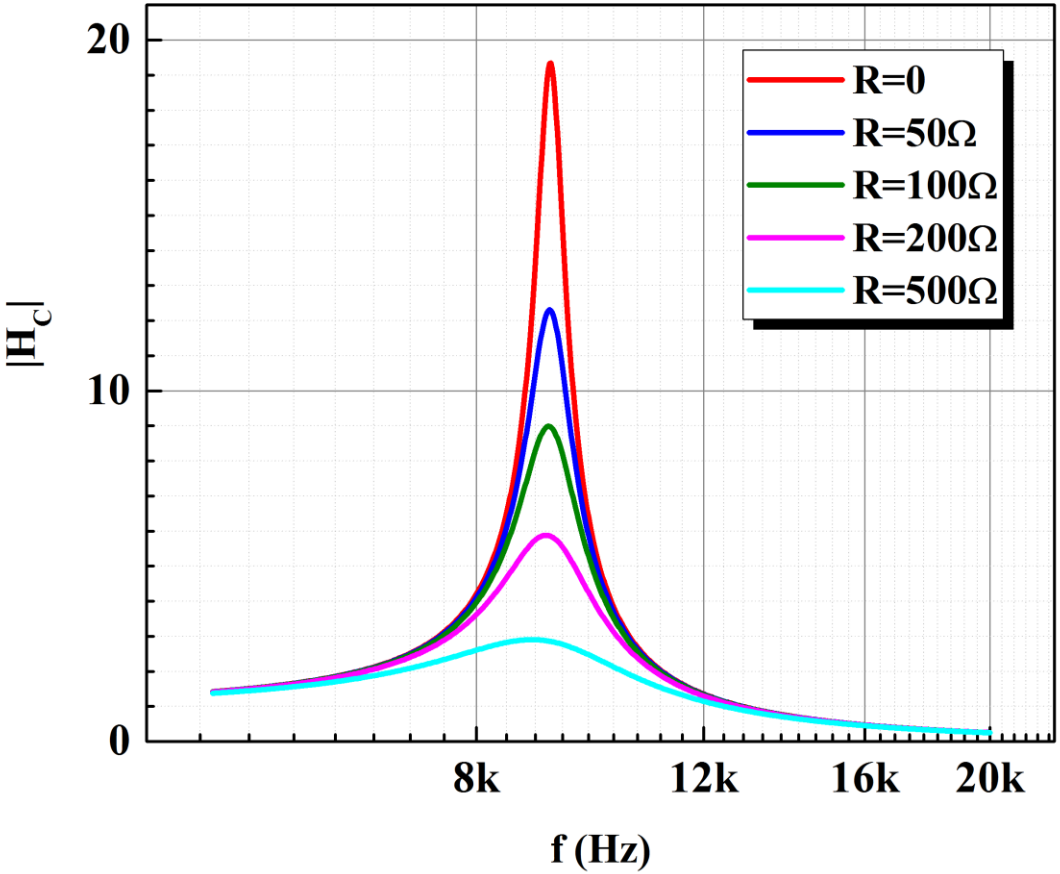
Application of the Lock-in Amplifier for Study of the Transfer Function of the RLC Circuit .

$$H=\frac{U_C}{U_{in}}=\frac{1}{(1-\omega^2 LC)+j\omega CR}=\frac{\left(1-\left(\frac{\omega}{\omega_0}\right)^2\right)-j\omega CR}{\left(1-\left(\frac{\omega}{\omega_0}\right)^2\right)^2+\omega^2C^2R^2}\times;$$

$$\omega_0=\frac{1}{\sqrt{LC}};\nu\equiv\frac{\omega}{\omega_0};Q=\frac{1}{R}\sqrt{\frac{L}{C}};$$

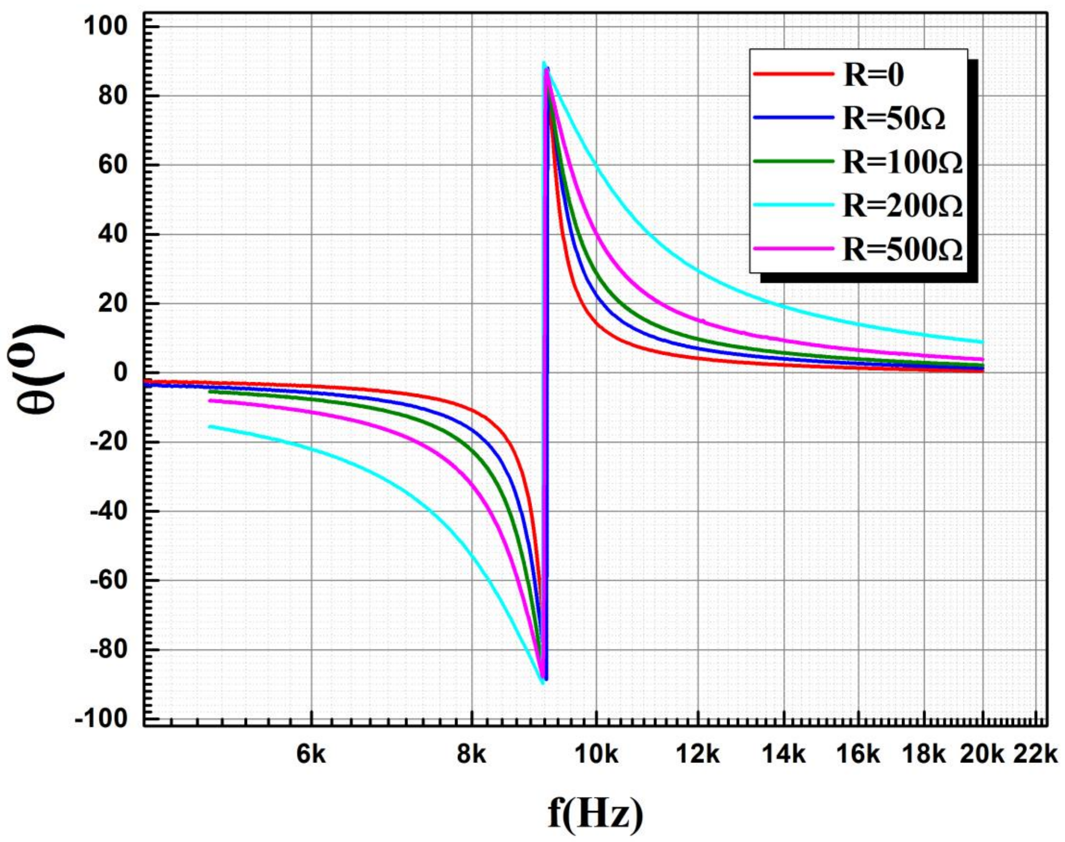
$$H=\frac{(1-\nu^2)-j\frac{\nu}{Q}}{(1-\nu^2)^2+\frac{\nu^2}{Q^2}};\theta=-\tan^{-1}\left(\frac{\nu}{Q\left(1-\nu^2\right)}\right)$$

Application of the Lock-in Amplifier for Study of the Transfer Function of the RLC Circuit .



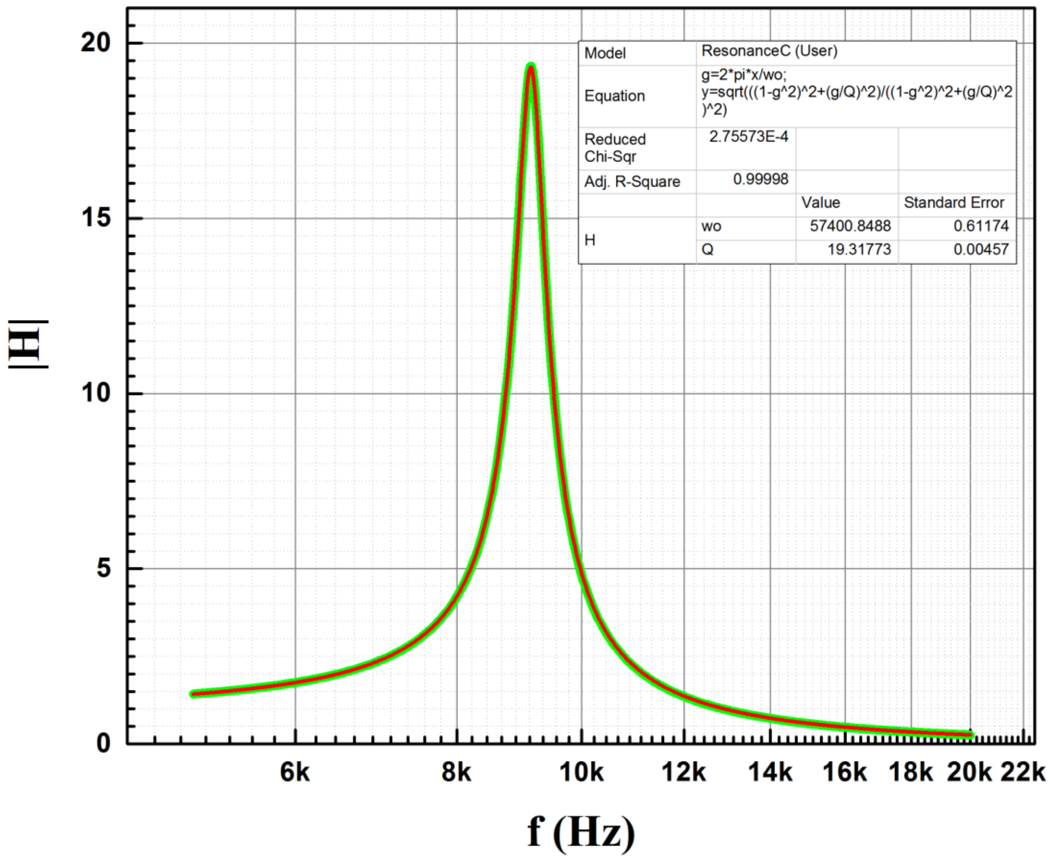
The resonance curves obtained on RLC circuits with different damping resistors.

Application of the Lock-in Amplifier for Study of the Transfer Function of the RLC Circuit



The resonance curves obtained on RLC circuits with different damping resistors

Fitting. RLC Resonance Circuit.

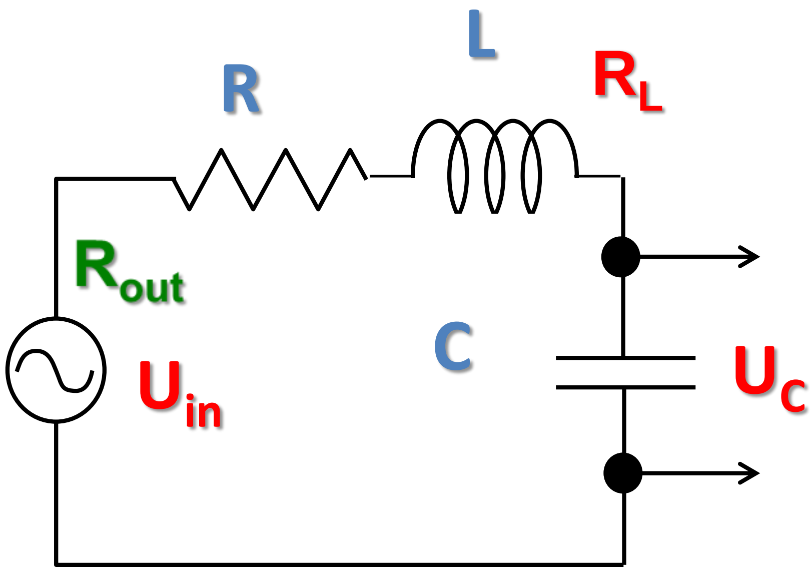


$$|H| = \frac{\sqrt{(1-\gamma^2)^2 + \left(\frac{\gamma}{Q}\right)^2}}{(1-\gamma^2)^2 + \left(\frac{\gamma}{Q}\right)^2}; \gamma = \frac{\omega}{\omega_0}$$

fitting function for |H|

variable parameters:
ω_0 and Q

Application of the Lock-in Amplifier for Study of the Transfer Function of the RLC Circuit

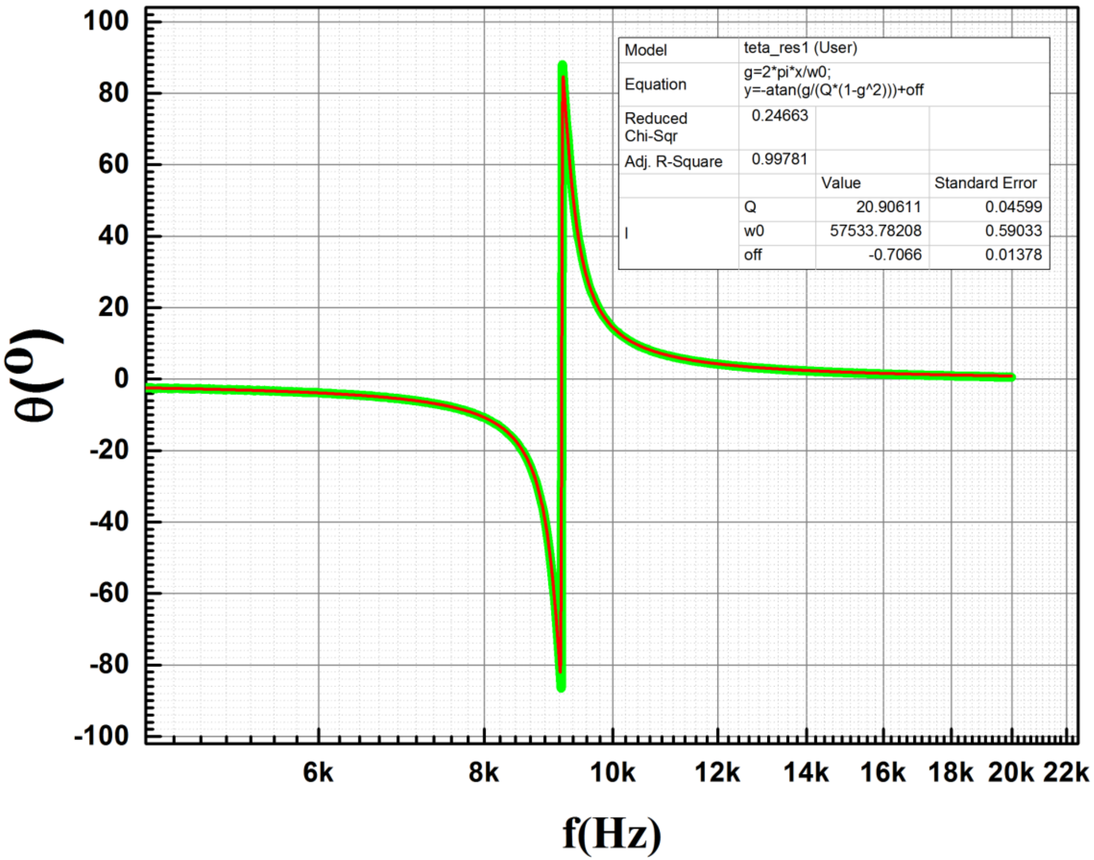


Actual damping resistance is a sum of R, R_L (resistance of the coil) and R_{out} (output resistance of the function generator)

$R=0$; $R_L=35.8\Omega$; $R_{out}=50\Omega$

Actual R calculated from fitting pars is~88.8Ω what is reasonable close to 85.8Ω

Fitting. RLC Resonance Circuit.



$$\theta = \tan^{-1}\left(\frac{Y}{X}\right)$$

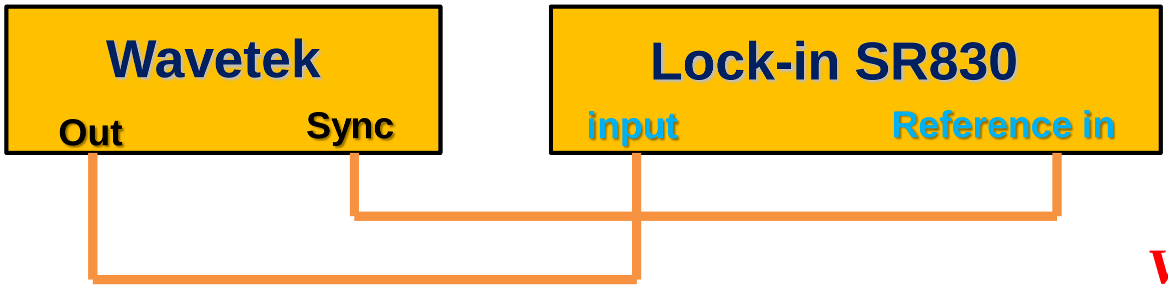
measured

$$\theta = -\tan^{-1}\left(\frac{\gamma}{Q\left(1-\gamma^2\right)}\right); \gamma = \frac{\omega}{\omega_0}$$

fitting function

variable parameters:
ω_0 and Q

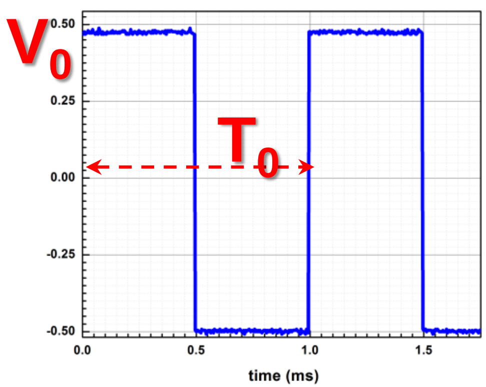
From Time Domain to Frequency Domain. Experiment.



F(t) – periodic function $F(t)=F(t+T_0)$:

$$V = V_0 \left(0 < t \le \frac{T_0}{2}\right);$$

$$-V_0 \left(\frac{T_0}{2} < t \le T_0\right)$$



Time domain pattern

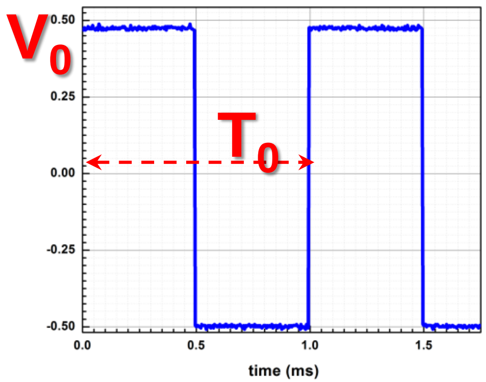
Frequency domain ?

$$a_n = \frac{2}{T_0}\int_0^{T_0} F(t)\cos\left(\frac{2\pi n t}{T_0}\right)dt;$$

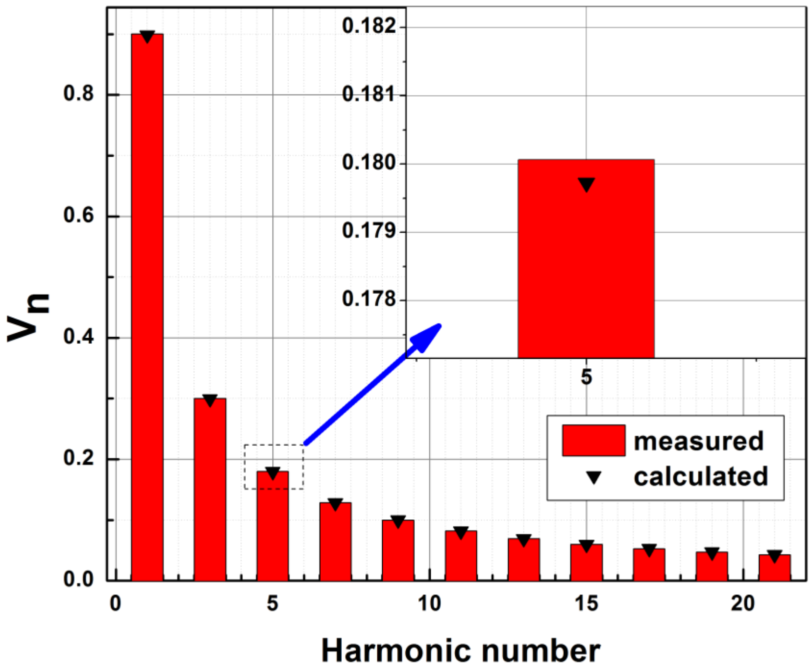
$$b_n = \frac{2}{T_0}\int_0^{T_0} F(t)\sin\left(\frac{2\pi n t}{T_0}\right)dt;$$

$$a_0 = \frac{2}{T_0}\int_0^{T_0} F(t)dt$$

From Time Domain to Frequency Domain. Experiment with SR830. Results.



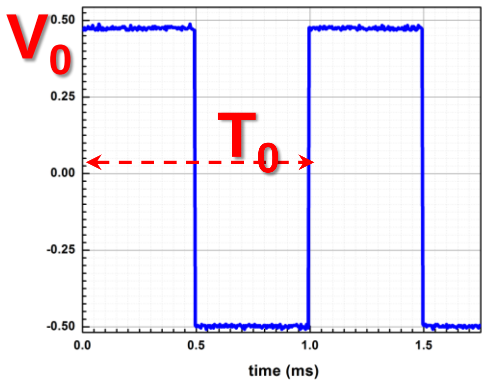
Time domain



Spectrum measured by SR 830 lock-in amplifier

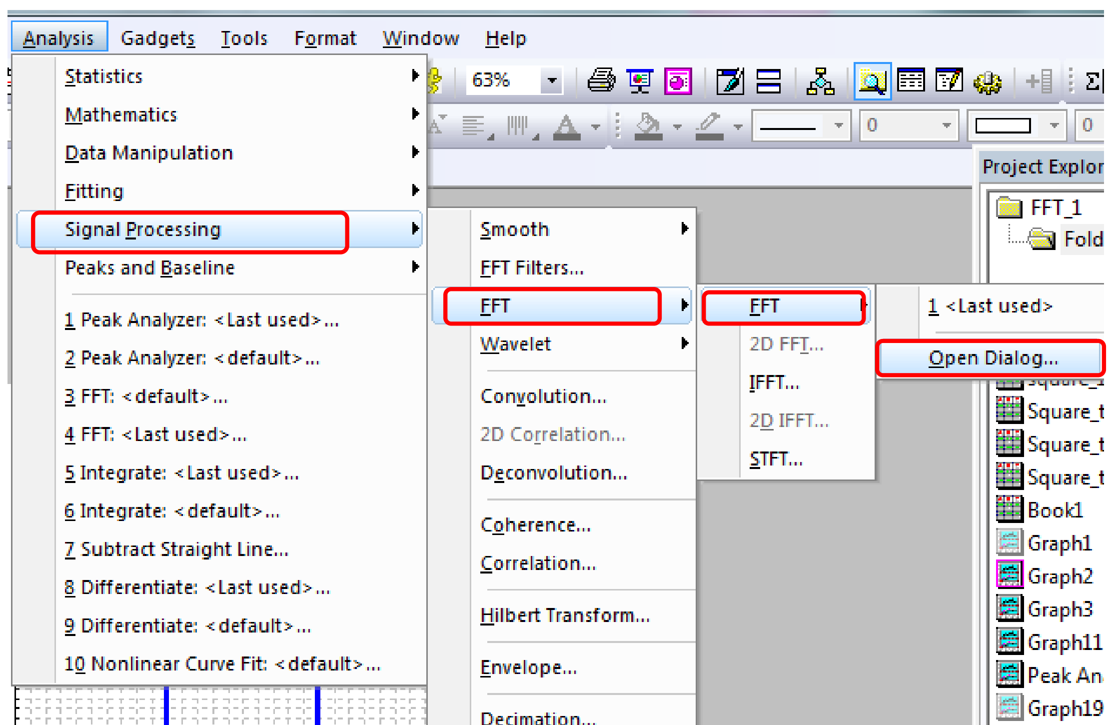
Frequency domain

From Time Domain To Frequency Domain. FFT using Origin. Results.

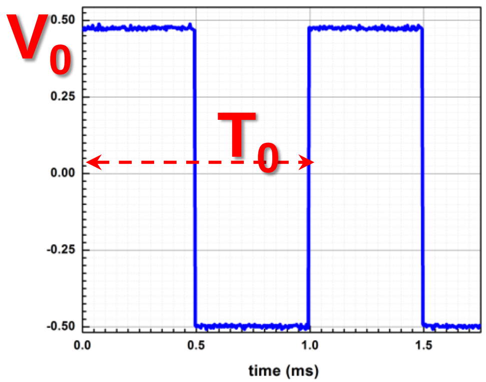


Data file can be used to convert time domain to frequency domain

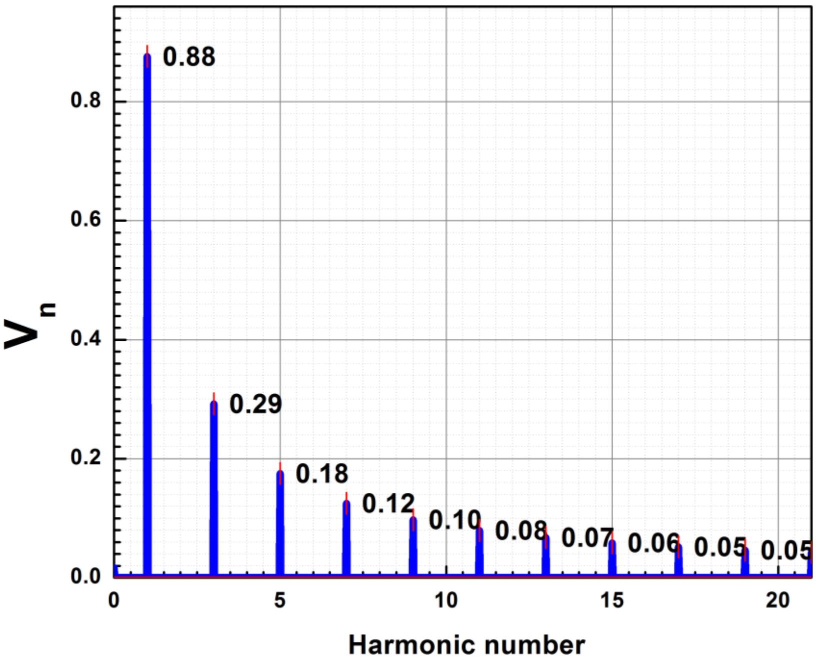
Time domain taken by Tektronix scope



From Time Domain to Frequency Domain. FFT using Origin. Results.

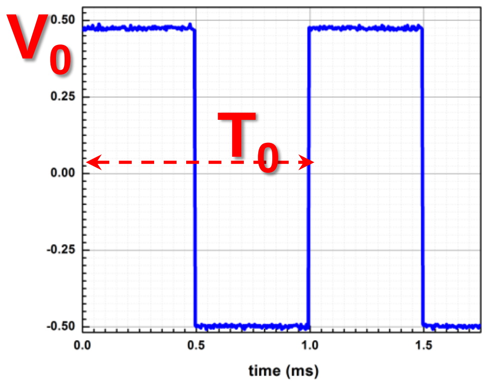


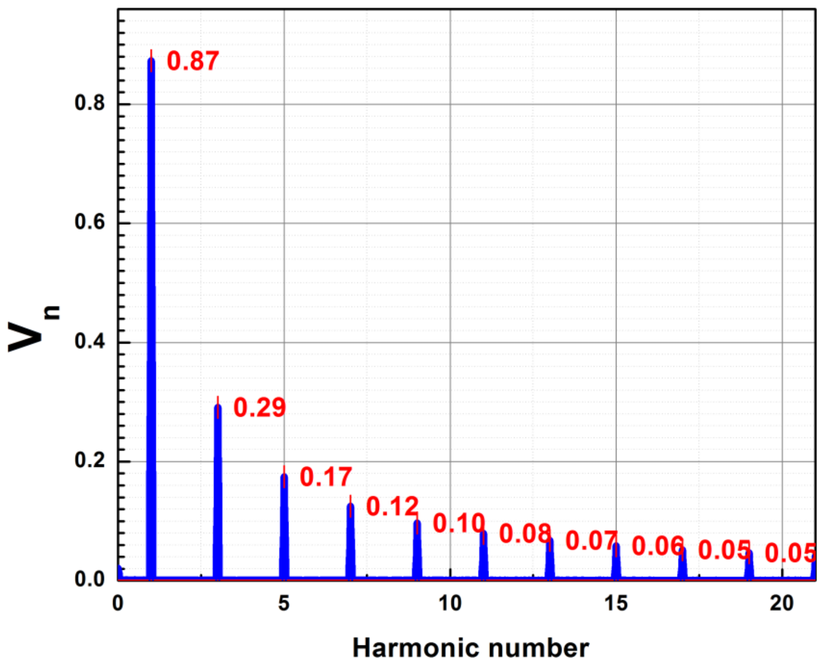
Time domain taken by Tektronix scope



Spectrum calculated by Origin. Accuracy is limited because of the limited resolution of the scope

From Time Domain to Frequency Domain. Using of the Math Option of the Scope.

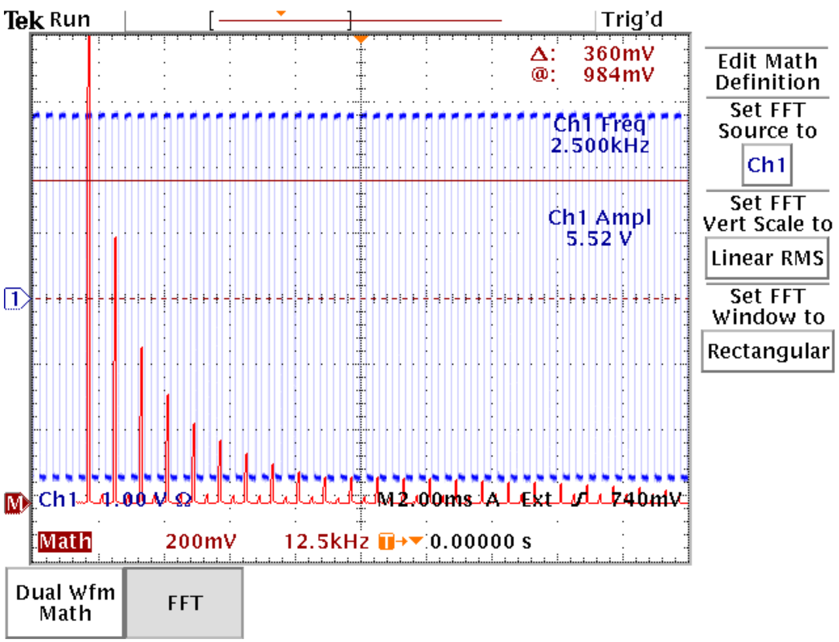




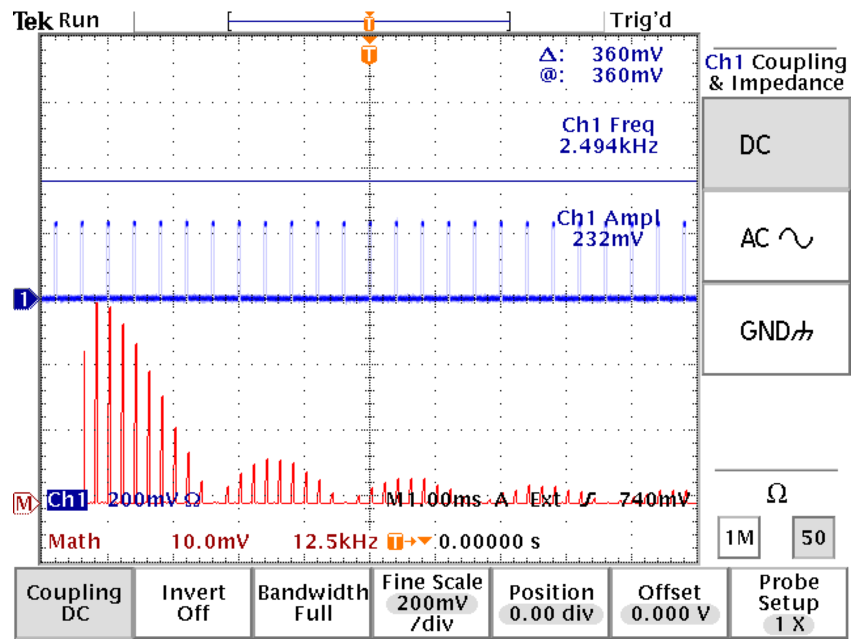
Time domain taken by Tektronix scope

Spectrum calculated by Tektronix scope.
Accuracy is limited because of the limited resolution of the scope

From Time Domain to Frequency Domain. Using of the Math Option of the Scope.

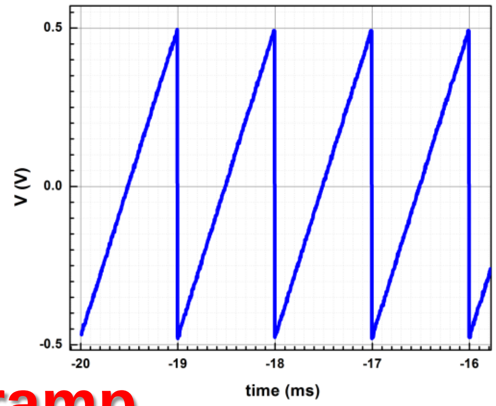


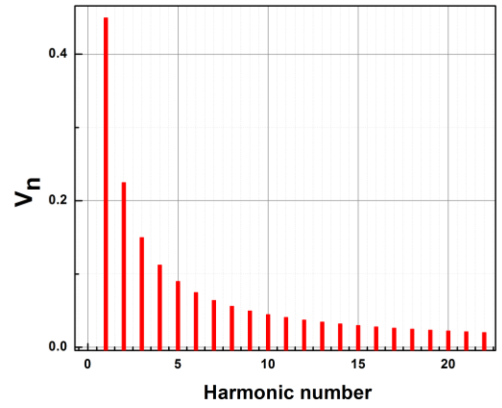
Spectrum of the square wave signal



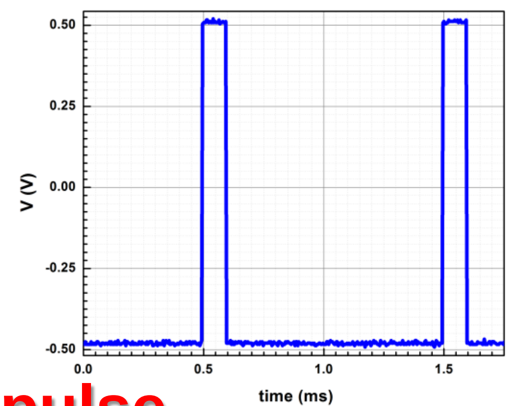
Spectrum of the pulse signal

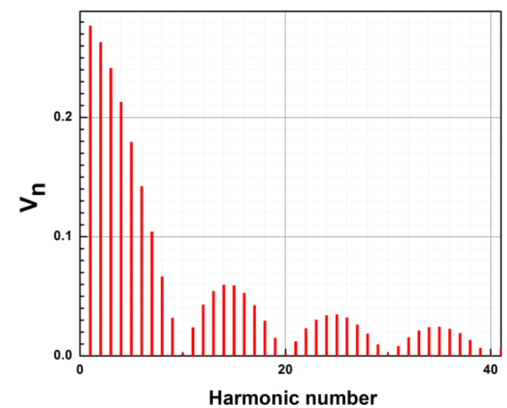
From Time Domain to Frequency Domain. Different Waveforms. Using Lock-in.





ramp





pulse

Appendix #1 Origin templates for this week Lab.

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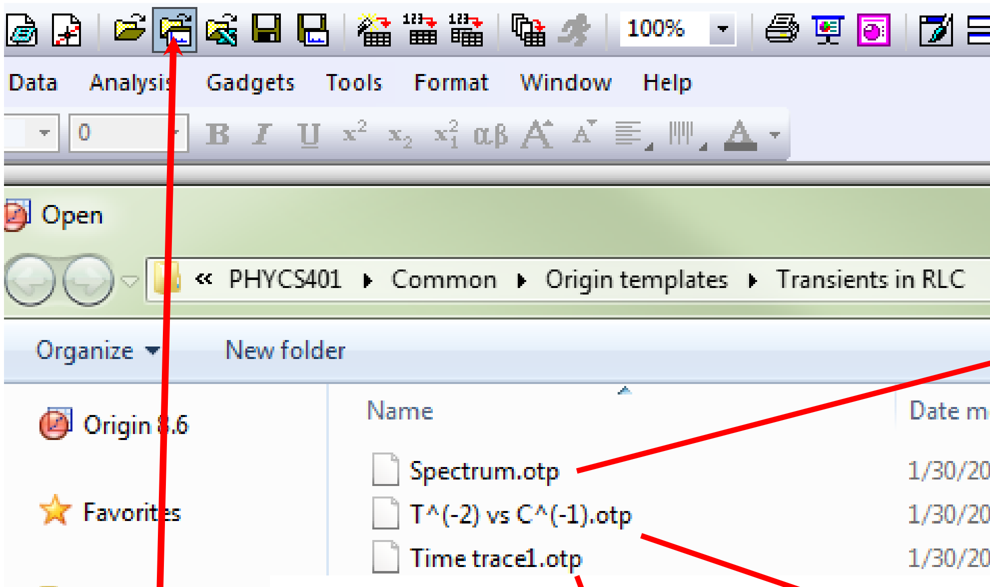
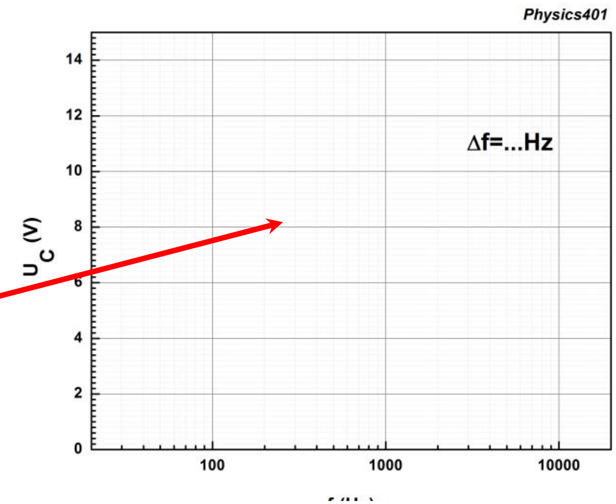
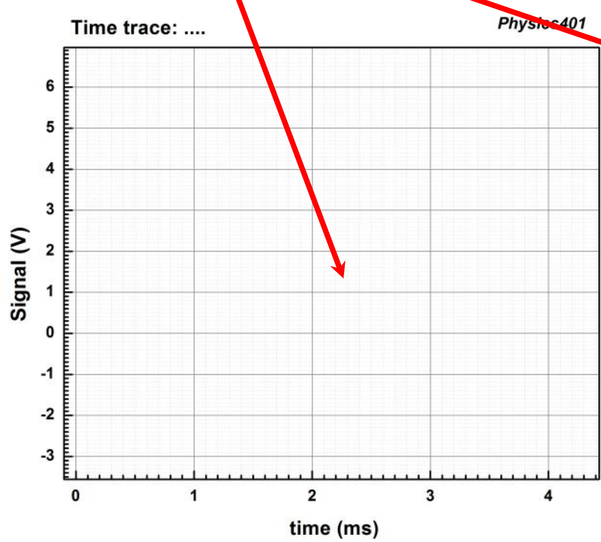
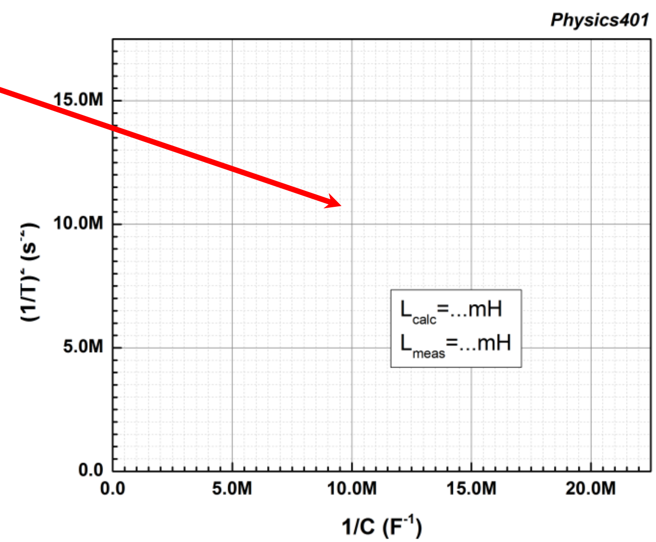




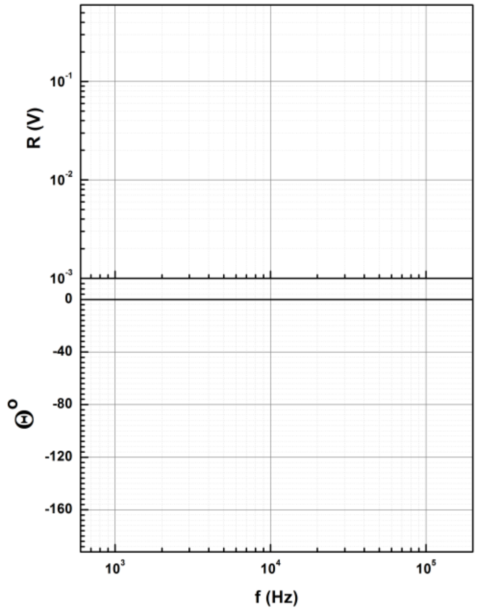
Open template **button**

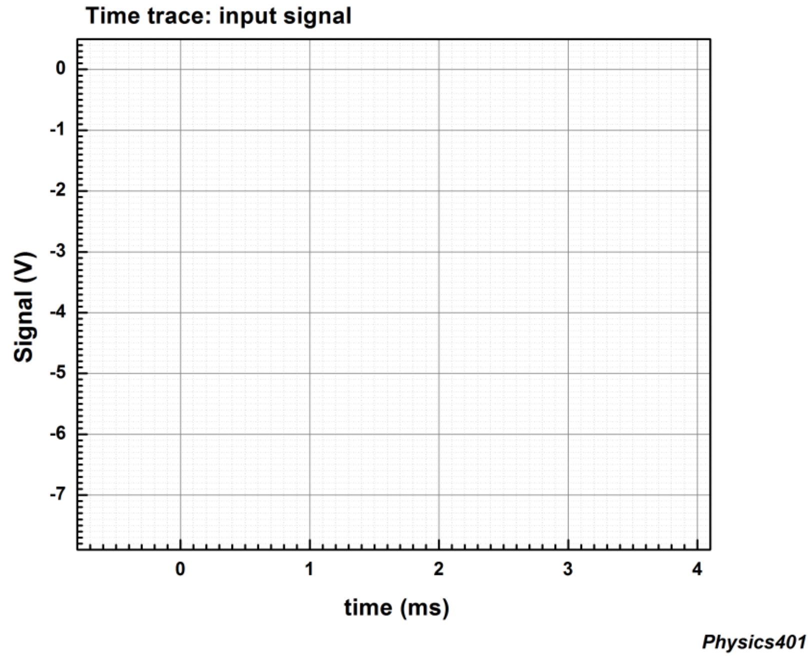




Appendix #2

Origin templates for the next week Lab:





References:

1. John H. Scofield, "A Frequency-Domain Description of a Lock-in Amplifier" *American Journal of Physics* 62 (2) 129-133 (Feb. 1994).
2. *Steve Smith* "The Scientist and Engineer's Guide to Digital Signal Processing*" copyright ©1997-1998 by Steven W. Smith. For more information visit the book's website at: www.DSPguide.com" **

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