Pickup coil design and selection of the devices

Contents

Measurement setup

The measurement setup for a typical inductive BH looper is shown in Fig. 1. It includes an excitation coil (Helmholtz or solenoid), and two identical solenoidal pickup coils. A current I (A; SI units) passed through the excitation coil induces the magnetising force H (Am^{-1}; SI units) around the pickup coils:

$$H(t) = \alpha I(t) \quad (1)$$

where α is a proportionality coefficient (m^{-1} when using SI units).

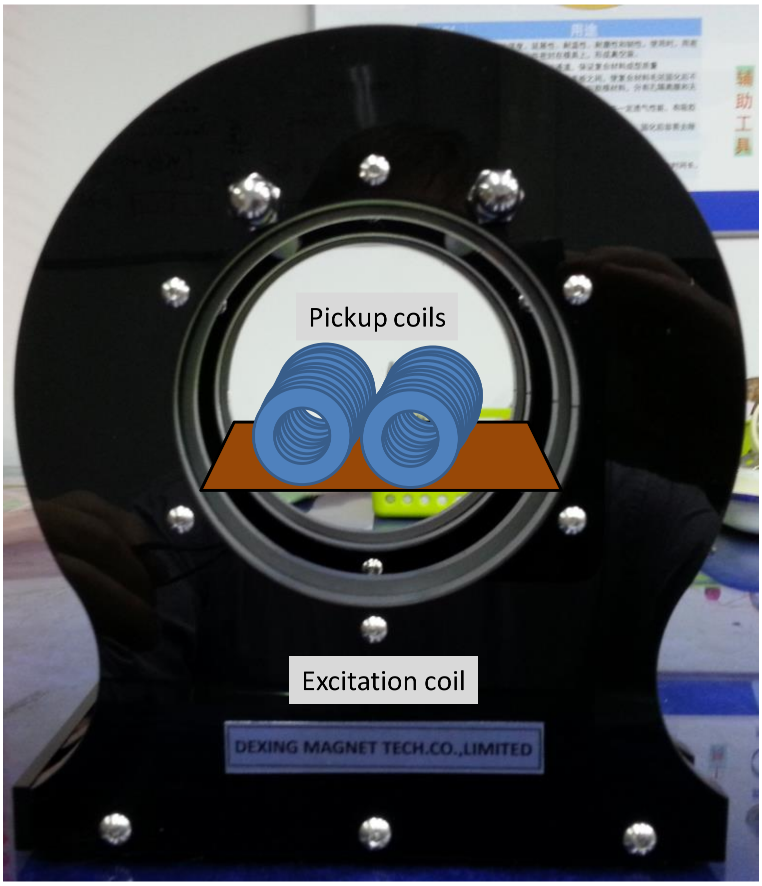

Fig. 1. Measurement setup for an inductive BH looper.

The coil parameters, including its resistance and inductance, can be measured using a digital multimeter (DMM), as shown in Fig. 2.

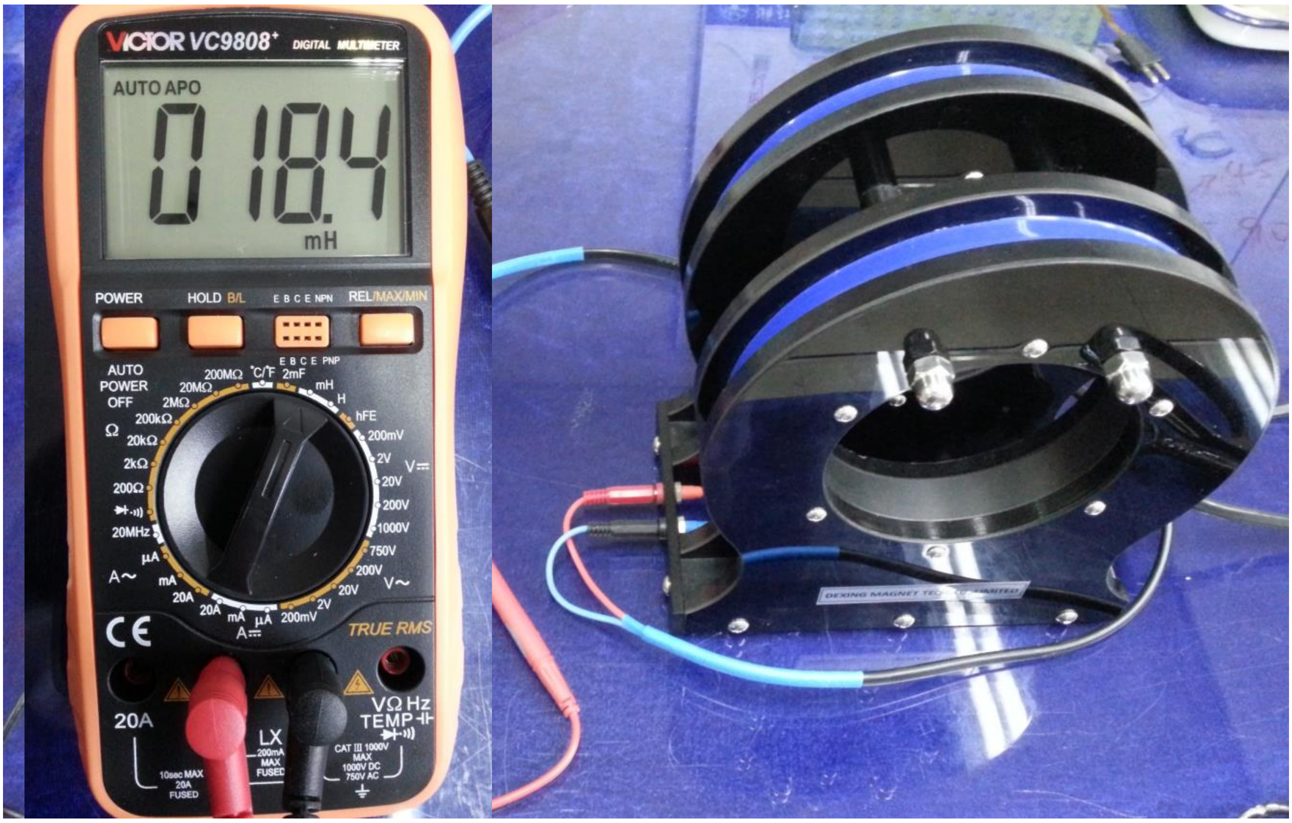

Fig. 2. Measurement of the coil inductance using a DMM.

Non-resonant excitation method

In the non-resonant method, the excitation coil (LOAD or DUT), having a resistance R (Ω; SI units) and an inductance L (H; SI units), will be connected directly to the waveform amplifier TS250-2 from Accel Instruments (https://www.accelinstruments.com/index.html), as shown in Fig. 3. The waveform will be supplied by our Rohde&Schwartz function generator having the maximum output 10 V at the 50 Ω BNC port.

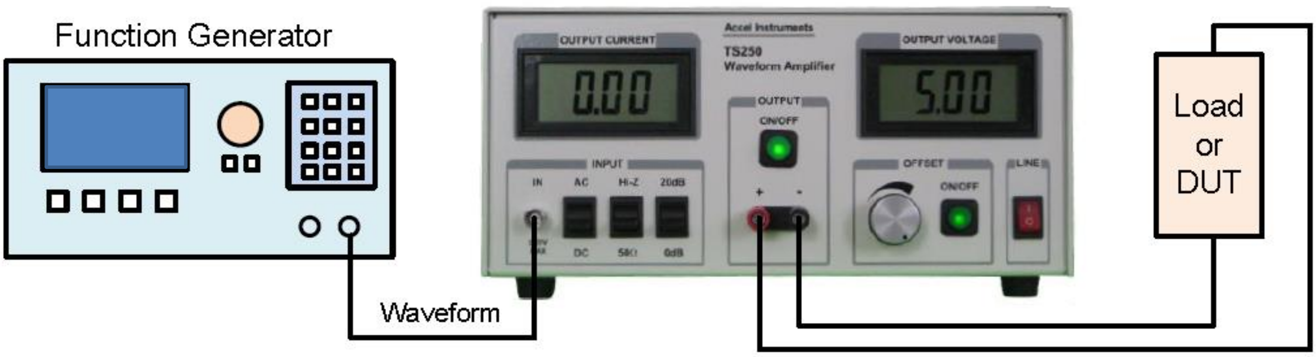

Fig. 3. Non-resonant excitation method.

The main parameters of TS250-2:

- Maximum input voltage ±20 V
- Maximum output voltage ±30 V
- Maximum output currents DC ±2.1 A and AC ±3.0 A (peak)
- Maximum operation frequency 75 kHz
- Voltage gains 1 and 10

For a harmonic excitation voltage $V(t) = V_0 \exp(-i\omega t)$, we obtain from (1):

$$H(t) = \frac{\alpha V_0 \exp(-i\omega t)}{R + i\omega L} \tag{2}$$

where $\omega = 2\pi f$ is the angular frequency (rads^{-1}; SI units), V_0 is the voltage amplitude (V; SI units), $R + i\omega L$ is the coil impedance. For the selected TS250-2, the maximum amplitude is $V_0 = 30$ V. Let us note that (2) is true only for a constant or harmonic excitation voltage. In general case, $I(t)$ can be expressed through $V(t)$ using a convolution.

For the amplitude of the magnetising force (Am^{-1}; SI units), we obtain:

$$H_0 = \frac{\alpha[\mathrm{m}^{-1}] V_0}{\sqrt{R^2 + (\omega L)^2}} \tag{3}$$

or

$$H_0 = \frac{10^3 \alpha[\mathrm{OeA}^{-1}] V_0}{4\pi\sqrt{R^2 + (\omega L)^2}} \tag{4}$$

if the excitation coil was calibrated with $\alpha[\mathrm{m}^{-1}]$ or $\alpha[\mathrm{OeA}^{-1}]$ respectively. Using Faraday's law, for the voltage $v(t)$ induced in a one-layer pickup coil, we obtain:

$$v(t) = -N\frac{d\Phi(t)}{dt} = -\frac{\pi D^2 N}{4}\frac{dB(t)}{dt} = -\frac{\pi D^2 N \mu_0}{4} \times \frac{dH(t)}{dt} = \frac{\alpha \mu_0 \pi D^2 N V_0 \omega}{4(R + i\omega L)} i \exp(-i\omega t) \tag{5}$$

$$v_0 = |v(t)| = \frac{\alpha[\mathrm{m}^{-1}] \mu_0 \pi V_0 \omega}{4\sqrt{R^2 + (\omega L)^2}} N D^2 \tag{6}$$

or

$$v_0 = \frac{10^{-4} \alpha[\mathrm{OeA}^{-1}] \pi V_0 \omega}{4\sqrt{R^2 + (\omega L)^2}} N D^2 \tag{7}$$

where Φ is the magnetic flux (Wb; SI units) through the pickup coil, v_0 is the amplitude of the pickup voltage, N is the number of turns in the layer, $\mu_0 = 4\pi \times 10^{-7}$ (Hm^{-1}; SI units) is the permeability of vacuum, and D is the coil frame diameter. In (5), we assumed that the coil is placed in a homogenous magnetic field.

However, for a multilayer pickup coil, the term ND in Eqs. (6),(7) must be modified because for each new layer we will have a slightly different diameter. In addition to D, let us introduce the coil length l (m; SI units), the wire diameter d (m; SI units), and the number of fully occupied layers N_l. Then, for the number of turns in each layer we obtain: $N = [l/d]$, where the square brackets mean rounding to the integer. Each layer will add a gradually increasing e.m.f. (from layer to layer) to the total voltage output. So, instead of D^2 in (6),(7) we have to use the following sum (https://brilliant.org/wiki/sum-of-n-n2-or-n3/):

$$\begin{aligned}\sum_{n=0}^{N_l-1}(D+nd)^2 &= \sum_{n=0}^{N_l-1}\left(D^2+2Ddn+n^2d^2\right)= \\ &=\left(\sum_{n=0}^{N_l-1}D^2+2Dd\sum_{n=0}^{N_l-1}n+d^2\sum_{n=0}^{N_l-1}n^2\right)= \\ &= N_lD^2\left(1+\frac{d(N_l-1)}{D}+\frac{d^2(N_l-1)(2N_l-1)}{6D^2}\right)\end{aligned} \tag{8}$$

Submitting (8) and $N = [l/d]$ into (6),(7), we obtain for the pickup voltage output:

$$v_0 = |v(t)| = \frac{\alpha[\mathrm{m}^{-1}]\mu_0\pi V_0\omega}{4\sqrt{R^2+(\omega L)^2}}\left[\frac{l}{d}\right]N_lD^2\left(1+\frac{d(N_l-1)}{D}+\frac{d^2(N_l-1)(2N_l-1)}{6D^2}\right) \tag{9}$$

or

$$v_0 = \frac{10^{-4}\alpha[\mathrm{OeA}^{-1}]\pi V_0\omega}{4\sqrt{R^2+(\omega L)^2}}\left[\frac{l}{d}\right]N_lD^2\left(1+\frac{d(N_l-1)}{D}+\frac{d^2(N_l-1)(2N_l-1)}{6D^2}\right) \tag{10}$$

where $[l/d]N_l$ is the total number of turns in a multilayer pickup coil. Using (8), we can introduce the effective diameter of the pickup coil that must be used for calculating its voltage output together with the total number of turns $[l/d]N_l$:

$$D_{eff} = D\sqrt{1+\frac{d(N_l-1)}{D}+\frac{d^2(N_l-1)(2N_l-1)}{6D^2}} \tag{11}$$

For $N_l = 1$, we obviously have $D_{eff} = D$.

Resonance excitation

In the resonance excitation method shown in Fig. 4, an additional capacitor C (Farad; Si units) is connected in series with the coil to compensate the inductive part of its impedance:

$$Z(\omega) = R + i\left(L\omega - \frac{1}{C\omega}\right) \tag{12}$$

The current resonance condition means that $L\omega_{res} - 1/C\omega_{res} = 0$:

$$\omega_{res} = \frac{1}{\sqrt{LC}} \tag{13}$$

At the resonance, the coil impedance becomes purely real $Z(\omega_{res}) = R$.

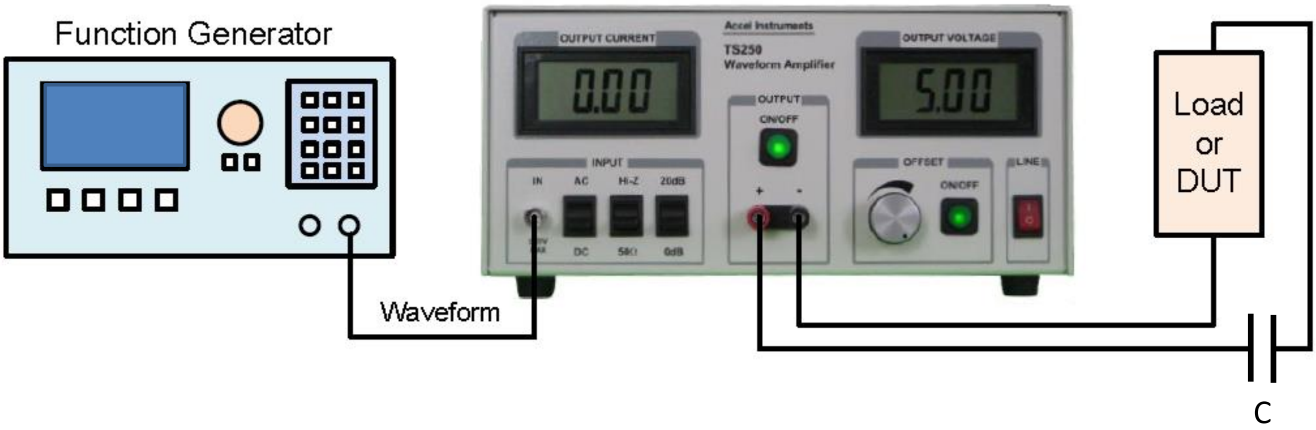

Fig. 4. Resonance excitation method with an additional capacitor connected in series with the coil.

Further reading: https://www.accelinstruments.com/Applications/WaveformAmp/Electromagnetic-Coil-Resonant.html

Using (9),(10), we obtain at the resonance condition:

$$v_0 = \frac{\alpha[\mathrm{m}^{-1}]\mu_0 \pi V_0 \omega}{4R}\left[\frac{l}{d}\right] N_l D^2 \left(1 + \frac{d(N_l - 1)}{D} + \frac{d^2(N_l - 1)(2N_l - 1)}{6D^2}\right) \tag{14}$$

or

$$v_0 = \frac{10^{-4}\alpha[\mathrm{OeA}^{-1}]\pi V_0 \omega}{4R}\left[\frac{l}{d}\right] N_l D^2 \left(1 + \frac{d(N_l - 1)}{D} + \frac{d^2(N_l - 1)(2N_l - 1)}{6D^2}\right) \tag{15}$$

Other parameters:

$$H_0 = \frac{\alpha[\mathrm{m}^{-1}]V_0}{R} \tag{14}$$

or

$$H_0 = \frac{10^3 \alpha[\mathrm{OeA}^{-1}]V_0}{4\pi R} \tag{15}$$

$$V_C = \frac{V_0}{RC\omega_{res}} = \frac{V_0 L \omega_{res}}{R} \tag{16}$$

$$C = \frac{1}{L\omega_{res}^2} \tag{17}$$

where V_C is the voltage amplitude across the capacitor. The magnitude of V_C is important to select the proper voltage rate (kV) of the capacitor. We will use high voltage capacitors.

Performance of the excitation and pickup coils vs frequency

The algorithm in Fortran used for analysing the excitation and pickup coils is shown below. It was compiled as a console application (PickupCoil.exe) and combines all equations derived above.

Fortran code

```
INTEGER flag,i,N,Nl
DOUBLE PRECISION pi,R,L,V0,v,vind,vres,maxf,f,df,mu0,Z,Iex
DOUBLE PRECISION VC,C,a,H1,H2,D,lc,dw,startfres,stopfres
PARAMETER(pi=3.14159265358979323846264338327950, N=5000)

mu0=4.0*pi*1.0E-7

WRITE(*,*)'Enter the resistance of the excitation coil (Ohm).'
READ(*,*) R
WRITE(*,*)''

WRITE(*,*)'Enter the inductance of the excitation coil (mH).'
READ(*,*) L
WRITE(*,*)''
L=L*1.0E-3

WRITE(*,*)'Enter the diameter of the pickup coil (mm).'
READ(*,*) D
WRITE(*,*)''
D=D*1.0E-3

WRITE(*,*)'Enter the length of the pickup coil (mm).'
READ(*,*) lc
WRITE(*,*)''
lc=lc*1.0E-3
```

```
      WRITE(*,*)'Enter the wire diameter used in the pickup coil (mm).'
      READ(*,*) dw
      WRITE(*,*)''
      dw=dw*1.0E-3

      WRITE(*,*)'Enter the number of layers in the pickup coil.'
      READ(*,*) Nl
      WRITE(*,*)''

      WRITE(*,*)'Enter the amplitude of the excitation voltage (V).'
      READ(*,*) V0
      WRITE(*,*)''

      WRITE(*,*)'Enter the maximum excitation frequency (Hz).'
      READ(*,*) maxf
      WRITE(*,*)''

      WRITE(*,*)'Enter the start resonance frequency (Hz).'
      READ(*,*) startfres
      WRITE(*,*)''

      WRITE(*,*)'Enter the stop resonance frequency (Hz).'
      READ(*,*) stopfres
      WRITE(*,*)''

      df=maxf/N
      OPEN(10,FILE='Excitation_coil_impedance.CSV')
      WRITE(10,*)'Hertz',',','Ohm'
      DO i=0,N
        f=df*i
        Z=DSQRT(R**2+(2.0*pi*f*L)**2)
        WRITE(10,100) f,Z
      END DO
      CLOSE(10)
100   FORMAT(F20.8,',',F20.8)

      df=(stopfres-startfres)/N
      OPEN(20,FILE='Resonance_capacitor.CSV')
      WRITE(20,*)'Hertz',',','Farad',',','V across C'
      DO i=0,N
        f=startfres+df*i
        C=1.0/(L*(2.0*pi*f)**2)
        VC=V0*L*2.0*pi*f/R
        WRITE(20,200) f,C,VC
      END DO
      CLOSE(20)
200   FORMAT(F20.8,',',F20.20,',',F20.8)

      WRITE(*,*)'Units for the coil calibration coefficient H=a*I:'
      WRITE(*,*)'Enter 1 for a[1/m]'
      WRITE(*,*)'Enter 2 for a[Oe/A]'
      READ(*,*) flag
      WRITE(*,*)''
```

```
      df=maxf/N

      OPEN(25,FILE='Excitation_current.CSV')
      WRITE(25,*)'Hz',',','A'
      DO i=0,N
        f=df*i
        Iex=V0/DSQRT(R**2+(2.0*pi*f*L)**2)
        WRITE(25,250) f,Iex
      END DO
      CLOSE(25)
250   FORMAT(F20.8,',',F20.8)

c     ********************************************
      SELECT CASE(flag)

      CASE(1)

      WRITE(*,*)'Enter the coil calibration coefficient (1/m)'
      READ(*,*) a
      WRITE(*,*)''

      df=maxf/N

      OPEN(30,FILE='Scanning_field.CSV')
      WRITE(30,*)'Hz',',','A/m',',','Oe'
      DO i=0,N
        f=df*i
        H1=a*V0/DSQRT(R**2+(2.0*pi*f*L)**2)
        H2=H1*4.0*pi/1000.0
        WRITE(30,300) f,H1,H2
      END DO
      CLOSE(30)
300   FORMAT(F20.8,',',F20.8,',',F20.8)

      OPEN(40,FILE='Pickup_voltage.CSV')
      WRITE(40,*)'Hz',',','vind',',','vres'
      DO i=0,N
        f=df*i
        v=a*mu0*pi*V0*2.0*pi*f*DINT(lc/dw)*Nl*D**2/4.0
        v=v*(1.0+dw*(Nl-1)/D+dw**2*(NL-1)*(2*Nl-1)/(6.0*D**2))
              vind=v/DSQRT(R**2+(2.0*pi*f*L)**2)
              vres=v/R
        WRITE(40,400) f,vind,vres
      END DO
      CLOSE(40)
400   FORMAT(F20.8,',',F20.8,',',F20.8)

      CASE(2)

      WRITE(*,*)'Enter the coil calibration coefficient (Oe/A)'
      READ(*,*) a
      WRITE(*,*)''
```

```
      df=maxf/N

      OPEN(50,FILE='Scanning_field.CSV')
      WRITE(50,*)'Hz',',','A/m',',','Oe'
      DO i=0,N
        f=df*i
        H2=a*V0/DSQRT(R**2+(2.0*pi*f*L)**2)
        H1=H2*1000.0/(4.0*pi)
        WRITE(50,500) f,H1,H2
      END DO
      CLOSE(50)
500   FORMAT(F20.8,',',F20.8,',',F20.8)

      OPEN(60,FILE='Pickup_voltage.CSV')
      WRITE(60,*)'Hz',',','vind',',','vres'
      DO i=0,N
        f=df*i
        v=1.0E-4*a*pi*V0*2.0*pi*f*DINT(lc/dw)*Nl*D**2/4.0
        v=v*(1.0+dw*(Nl-1)/D+dw**2*(NL-1)*(2*Nl-1)/(6.0*D**2))
              vind=v/DSQRT(R**2+(2.0*pi*f*L)**2)
              vres=v/R
        WRITE(60,600) f,vind,vres
      END DO
      CLOSE(60)
600   FORMAT(F20.8,',',F20.8,',',F20.8)

      END SELECT

      OPEN(70,FILE='Coil_parameters.txt')
      WRITE(70,*)'Excitation coil resistance (Ohm) = ',R
      WRITE(70,*)'Excitation coil inductance (mH) = ',L*1000.0
      WRITE(70,*)'Excitation voltage amplitude (V) = ',V0
      WRITE(70,*)''
      WRITE(70,*)'****************************************************'
      WRITE(70,*)''
      WRITE(70,*)'Pickup coil diameter (mm) = ',D*1000.0
      WRITE(70,*)'Pickup coil length (mm) = ',lc*1000.0
      WRITE(70,*)'Pickup coil wire diameter (mm) = ',dw*1000.0
      WRITE(70,*)'Number of layers = ',Nl
      WRITE(70,*)'Turns in each layer = ',DINT(lc/dw)
      WRITE(70,*)'Total turns = ',Nl*DINT(lc/dw)
      WRITE(70,*)'Total diameter (mm) = ',(D+2*NL*dw)*1000.0
      CLOSE(70)

   STOP

   END
```

Small Helmholtz coil – low frequency BH-loops

The pickup coils will be designed for two Dexing Helmholtz excitation coils we already have in the laboratory:

- "Small coil" (shown in Fig. 1)
  - $R = 2.5\ \Omega$
  - $L = 18.4\ \text{mH}$
  - $a = 21\ \text{Oe/A}$
- "Large coil" (used for MI measurements)
  - $R = 8.38\ \Omega$
  - $L = 320\ \text{mH}$
  - $a = 35.95\ \text{Oe/A}$

Our analysis shows that the small excitation coil cannot be used for the resonance excitation because its inductance is quite small that results in a large compensation capacitor required to provide the resonance condition (13) for reasonable frequencies. So, this coil will be used only for low frequency BH-loops with the excitation scheme in Fig. 3. In Fig. 5, the frequency performance of the coil is shown calculated for $V_0 = 30$ V (maximum output voltage for the waveform amplifier TS250-2). Up to 200 Hz, the coil can provide enough fields to scan ferromagnetic wires. For frequencies below 85 Hz, the amplifier output V_0 must be reduced to keep the AC current amplitude below 3 A for TS250-2. So, the maximum scanning field will be no more than 63 Oe.

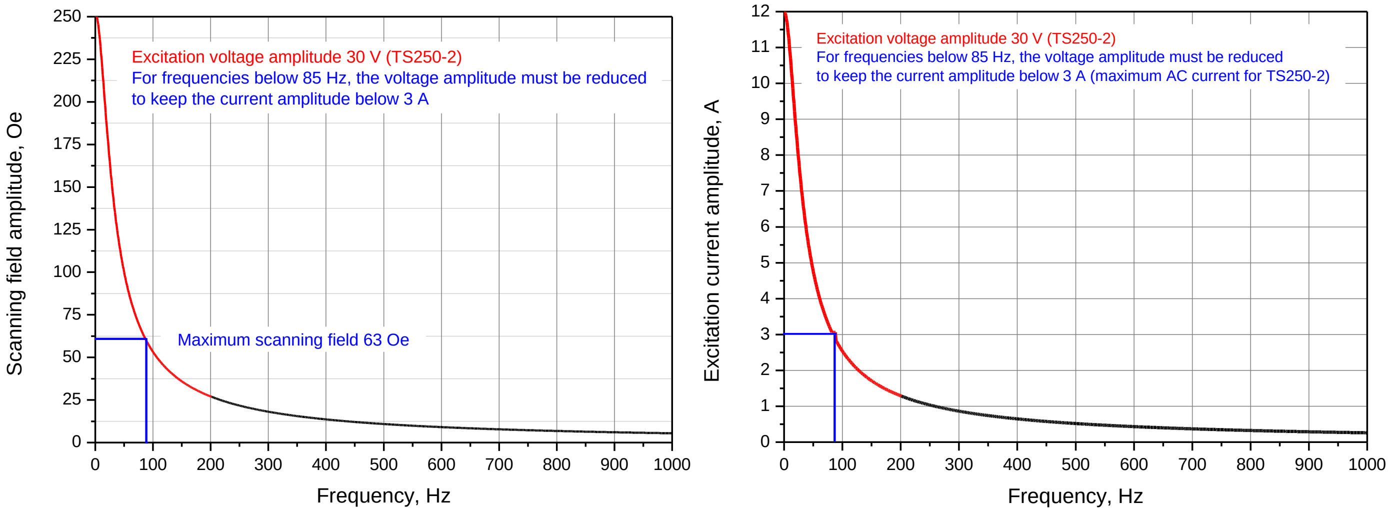

Fig. 5. Frequency performance of the small Helmholtz coil (shown in Fig. 1).

At the same time, we must obtain a detectable voltage at the pickup coils. The coil geometrical parameters are dictated by the size of the Helmholtz coil. We chose the following dimensions for the pickup coils:

- Diameter – 10 mm
- Length – 30 mm

For reasons of the field uniformity inside the Helmholtz coil, the width of the assembly of two pickup coils must not exceed 40 mm. We tried two pickup coil designs with the wire windings made of AWG-38 and AWG-40 (https://en.wikipedia.org/wiki/American_wire_gauge):

- Wire diameter together with the enamel coating – 0.109788 mm (copper wire AWG-38)
- Number of layers – 30
- Turns in each layer – 273
- Total number or turns – 8190
- Total diameter (30 layers) – 17 mm

- Wire diameter together with the enamel coating – 0.087059 mm (copper wire AWG-40)
- Number of layers – 40
- Turns in each layer – 344
- Total number or turns – 13760
- Total diameter (40 layers) – 17 mm

The pickup voltage amplitudes vs. frequency calculated for the two coil designs with the wire windings made of AWG-38 and AWG-40 are shown in Fig. 6. Both designs are acceptable, but we should prefer the wire winding made of AWG-40 because it provides a larger voltage output.

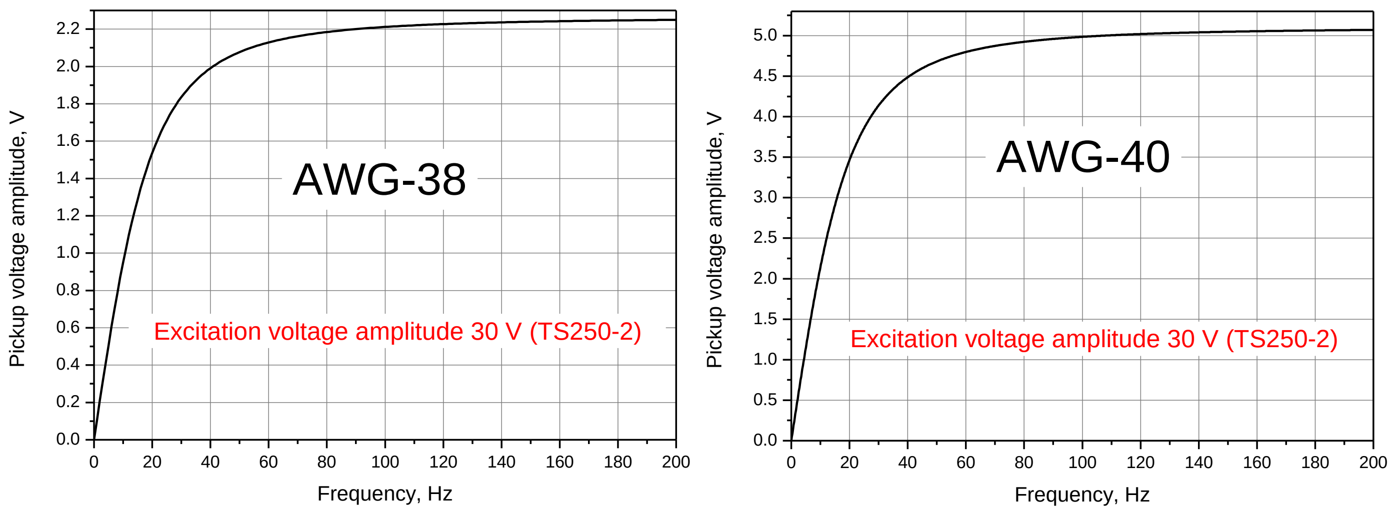

Fig. 6. Pickup voltage amplitudes vs. frequency calculated for the two coil designs with the wire windings made of AWG-38 and AWG-40.

To use the inductive excitation method (Fig. 3) for higher frequencies, we will need a lighter Helmholtz coil. Ideally, with two Helmholtz coils ("small" and "large") we should cover both low and high frequency BH loops. For the coils we currently have, there will be a gap in the excitation frequencies.

Large Helmholtz coil – resonance excitation and high frequency BH-loops

For the resonance excitation scheme shown in Fig. 4, we can use the large Helmholtz coil (currently used for MI measurements). The amplitude of the excitation voltage must be reduced to $V_0 = 25$ V to guarantee $I = V_0 / R = 25/8.38 \approx 3$ A – maximum current amplitude for the waveform amplifier TS250-2. The coil inductance is 320 mH.

Let us start the design looking at the frequency dependence of the voltage amplitude V_C across the capacitor shown in Fig. 7. From this graph we can see that V_C may reach 50 kV. So, a high voltage (HV) capacitor will be required for the LC resonance circuit. Potential suppliers of the HV capacitors:

- http://www.avx.com/products/ceramic-capacitors/high-voltage/hdhe-type/
- http://www.vishay.com/capacitors/ceramic/high-voltage/
- http://www.kemet.com/High-Volt-MLCC
- http://www.calramic.com/CalRamic-capacitors-products.html

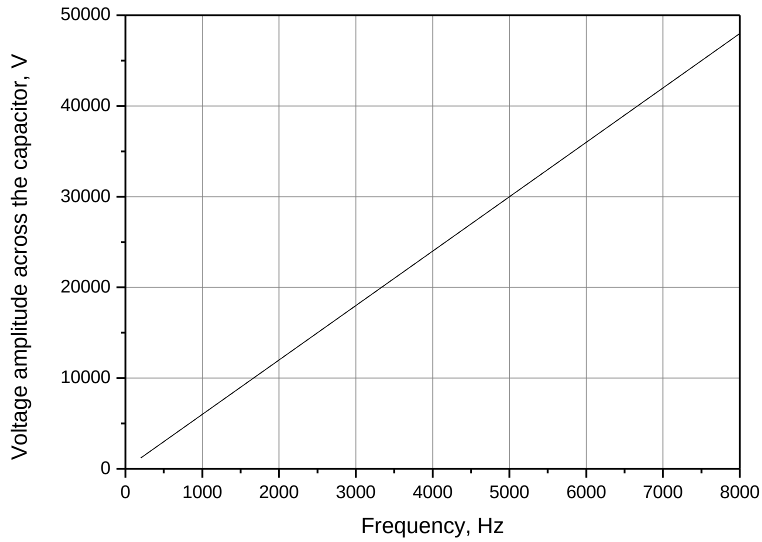

Fig. 7. The voltage amplitude across the capacitor calculated for $V_0 = 25$ V.

The maximum capacitance of a high voltage capacitor with acceptable dimensions we could find is 45 nF. This capacitor has the voltage rate just 3 kV. Therefore, V_0 must be further reduced, at least three times less, if we want to measure within 1-2 kHz. As a result, the scanning field amplitude will be also reduced. Further reducing the frequency would be unreasonable because the voltage rate decreases when the capacitance increases. So, with our current Helmholtz coils (“small” and “large”) it would be impossible to fill the gap between the low frequency (below 200 Hz) and high frequency (kHz) BH-loop measurements. A lighter coil than our “small” one will be required to extend the low frequency BH-loop measurements with the inductive excitation scheme in Fig. 3.

In Fig. 8, we show the performance of the excitation and pickup coils calculated for $V_0 = 9$ V and the following pickup coil parameters:

- Diameter – 10 mm
- Length – 30 mm
- Wire diameter together with the enamel coating – 0.109788 mm (copper wire AWG-38)
- Number of layers – 6
- Turns in each layer – 273
- Total number or turns – 1638
- Total diameter (6 layers) – 11 mm

The amplitude of the scanning magnetic field will be around 39 Oe: $H[\mathrm{Oe}] = a[\mathrm{OeA}^{-1}]V_0 / R$ with $a = 35.95$ Oe/A, $V_0 = 9$ V, and $R = 8.38$ Ω. Increasing the resonance frequency and decreasing the capacitance (< 45 nF), we can gradually increase the scanning field amplitude because the voltage rate of the capacitor will also increase. The frequency scale must be divided into narrow sectors, for each one an individual pickup coil must be designed. The design we are demonstrating in this section is for $f_{res} \approx 1350$ Hz, $L = 320$ mH, $R = 8.38$ Ω, and $C = 45$ nF. Starting from a sufficiently high frequency, it would be reasonable to return to the small Helmholtz coil to reduce the voltage V_C across the capacitor according to (16). However, such high frequencies are probably not of interest for our conductive ferromagnetic wires.

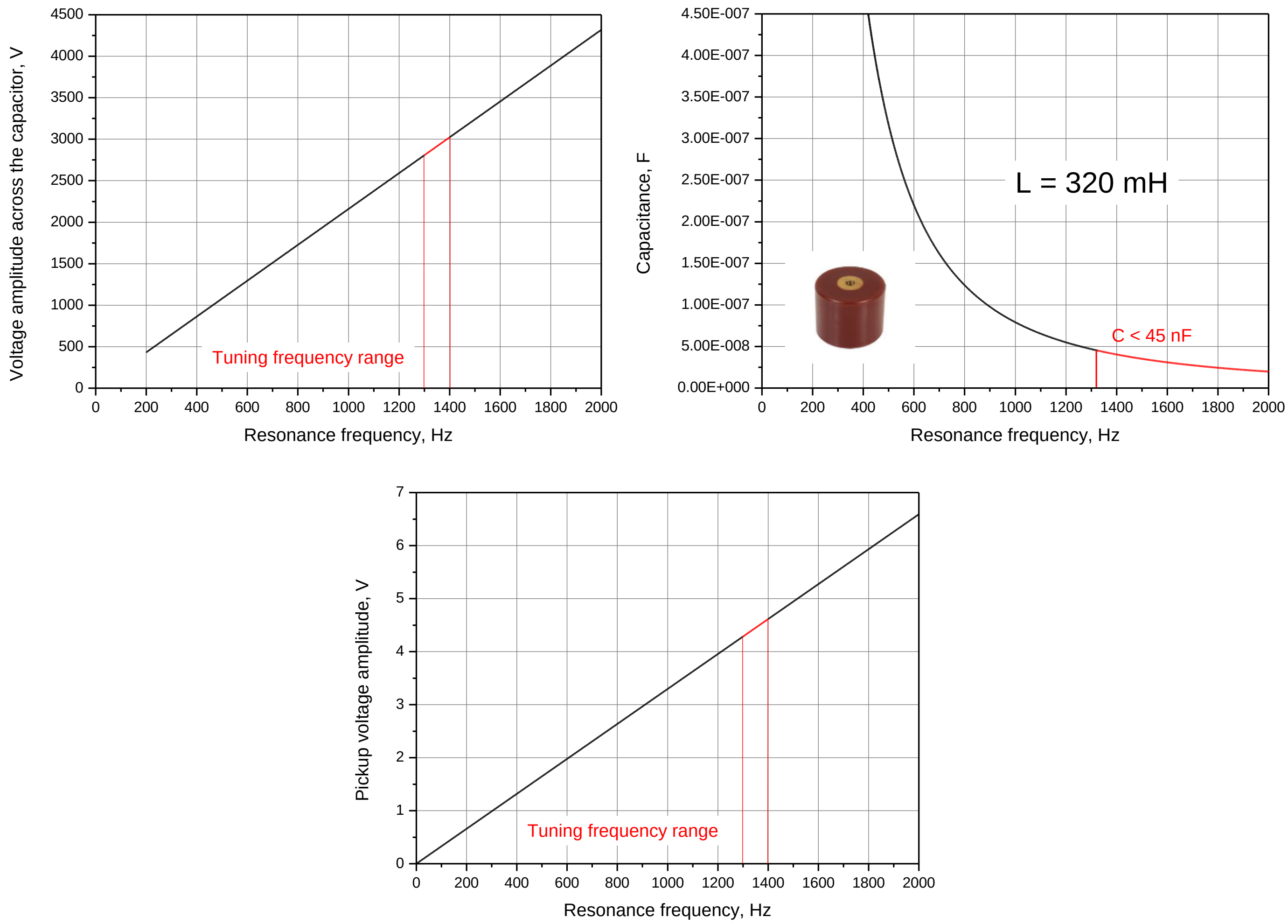

Fig. 8. Performance of the excitation and pickup coils for the selected resonance excitation near 1350 Hz.

Selecting NI devices

The signal acquisition scheme with is shown in Fig. 9. We have chosen NI 9215 analog input module: 4 differential analog inputs (virtual ground), ±10 V, 16 Bit, 100 kS/s per channel, screw-terminals, simultaneous sampling of all input channels. The voltages from the excitation and pickup coils will be sampled simultaneously – three channels in total. The fourth channel will be reserved. The sampling rate 100 kS/s is more than enough for our applications where the excitation frequencies will not exceed several kHz. The output voltage amplitudes must not exceed 5 V. The module NI 9215 will be inserted into the 1-slot chassis NI cDAQ 9181 with the Ethernet connection shown in Fig. 10.

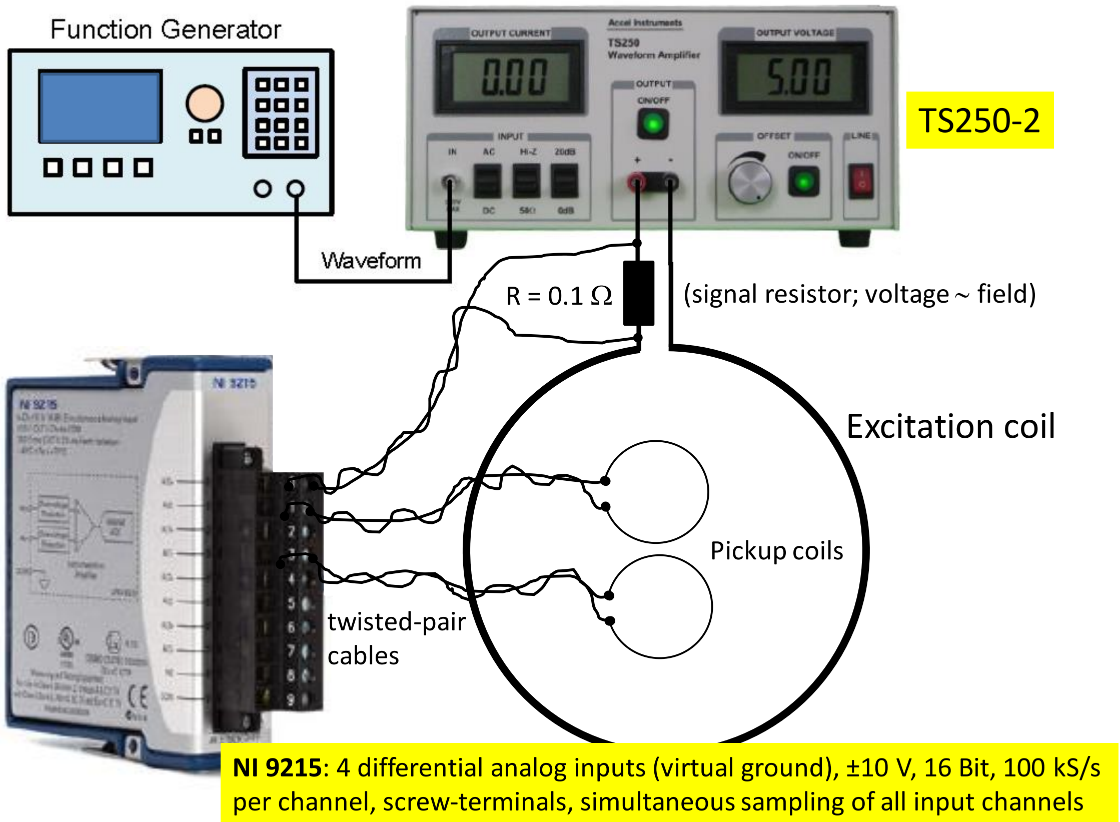

Fig. 9. Signal acquisition scheme.

Fig. 10. 1-slot chassis NI cDAQ 9181.