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AN677

Designing a Base Station Coil for the HCS410

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OVERVIEW

This application note describes the Excel spreadsheet to design base station coils. The spreadsheet file name is basestaxls.

The basic approach used is to choose the driver circuit driving voltage and current. These two values are used to calculate the total resistance that the series resistor-inductor-capacitor (RLC) circuit should have. Secondly, the resonating capacitor rated voltage is chosen. The coil inductance and resonating capacitor value can then be calculated.

For a given coil inductance and coil resistance, choosing the coil average diameter and coil winding aspect ratio determines the coil dimensions, number of turns and wire diameter.

The magnetic field strength can be calculated at any given distance given the coil average diameter, number of turns and coil current.

FEATURES

The spreadsheet is split into three worksheets. The first worksheet concerns the HCS410 Evaluation Kit coil driver circuit. Based on the HCS410 Evaluation Kit power supply and coil driver electrical characteristics, the coil inductance, total coil losses at operating temperature and resonant capacitor can be calculated.

The second worksheet uses the coil inductance and total coil losses from the first worksheet with added inputs such as coil diameter to calculate an optimum coil. Coil dimensions, optimum number of turns and wire diameter is provided.

The third worksheet uses the root mean square (RMS) coil current, number of turns and coil diameter from the first two worksheets to calculate the magnetic field at a given axial distance away from the coil.

INTRODUCTION

Overview of Inductive Communication

Communication between a KEELOQ® transponder and a base station occurs via magnetic coupling between the transponder coil and base station coil.

The base station coil forms part of a series RLC circuit. The base station communicates to the transponder by switching the 125kHz signal to the series RLC circuit on and off. Thus, the base station magnetic field is switched on and off.

The transponder coil is connected in parallel with a resonating capacitor (125kHz) and a KEELOQ HCS410 transponder integrated circuit. When the transponder is brought into the base station magnetic field, it magnetically couples with this field and draws energy from it. This loading effect can be observed as a decrease in voltage across the base station resonating capacitor. The KEELOQ transponder communicates to the base station by “shorting out” its parallel LC circuit. This detunes the transponder and removes the load, which is observed as an increase in voltage across the base station resonating capacitor. The base station capacitor voltage is the input to the base station AM-demodulator circuit. The demodulator extracts the transponder data for further processing by the base station software.

Power Losses

- The dominant system power losses in the HCS410 Evaluation Kit are listed below
  - The power supply filter loss, which reduces the coil driver voltage.
  - The losses due to the field effect transistors (FETs) that supply current to the RLC circuit.
  - The coil resistance losses at DC.
  - The coil losses due to skin effect and proximity losses. These are approximated to be equal to the coil resistance at DC.

Using the worksheet

Color coding

Color	Meaning
Green	User input. The default values correspond to the HCS410 Evaluation Kit. If the HCS410 Evaluation Kit is used for a new coil design, changes are not required.
Red	Output
Gray	System defined

Units

The units in the worksheet have been made SI units. Below is a table with some of the most common conversions that the user may come across.

Conversion from:	Operation
Inches (in) to meters (m)	x .0254
Inches (in) to centimeters (cm)	x 2.54
Inches (in) to millimeters (m)	x 25.4
Centimeters (cm) to meters (m)	x 0.01
Millimeters (mm) to meters (m)	x 0.001
Farads (F) to nanofarads (nF)	x 1e-9
Henry (H) to microhenry (μH)	x 1e-6

WORKSHEET 1: HCS410 EVALUATION KIT BASE STATION COIL DRIVER

HCS410 Evaluation Kit Base Station Driver Design

FIGURE 1: EVALUATION KIT COIL DRIVER CIRCUIT

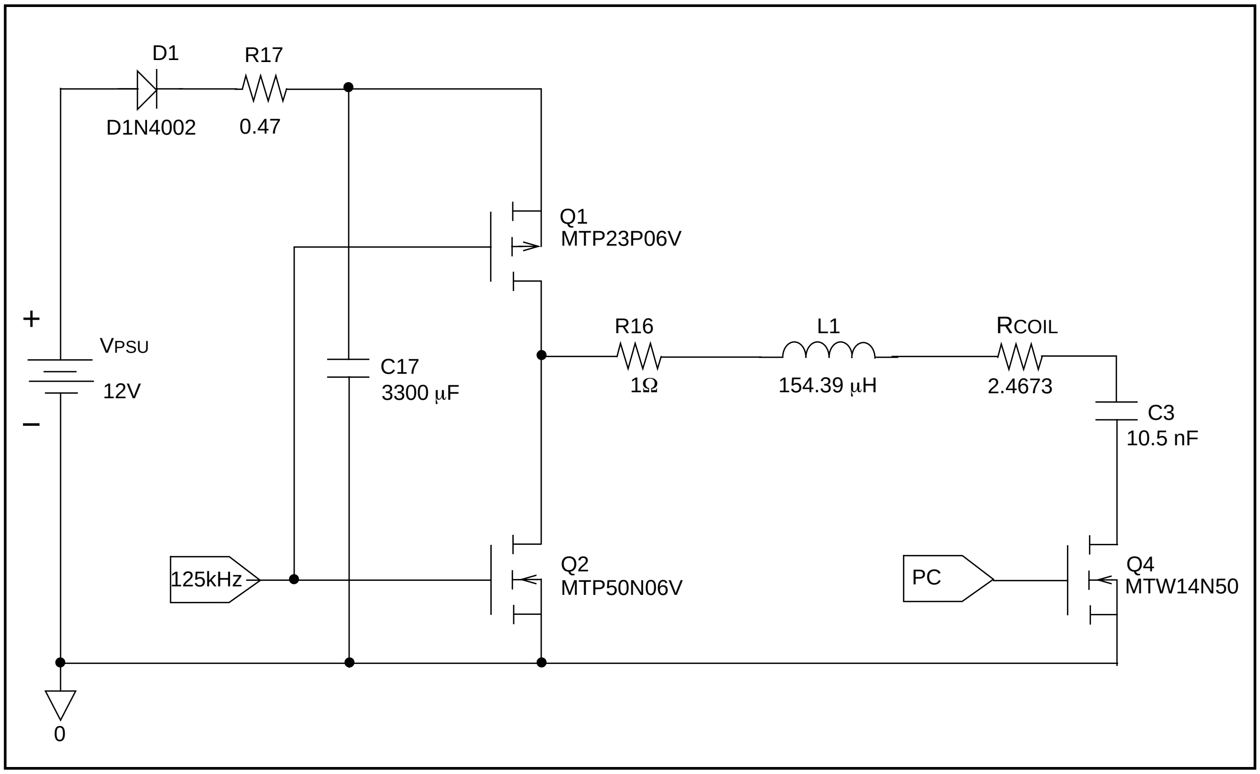


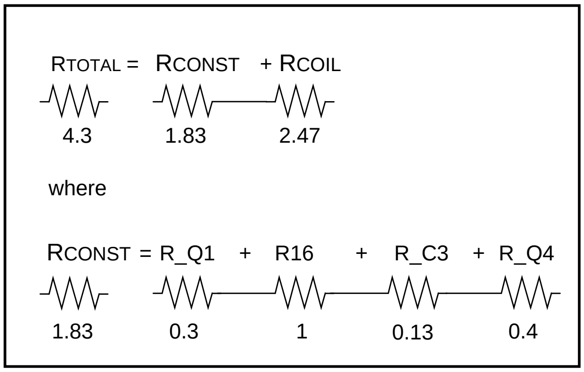
Figure 1 shows the final stage of the evaluation kit coil driver circuit. The input “125 kHz” is a 125 kHz square wave which drives Q1 and Q2 to generate a magnetic field. When this square wave is stopped, no magnetic field is generated. The signal “PC” preserves charge on the capacitor C3 when the field is switched off by disconnecting the capacitor from ground.

The magnetic field produced by a coil is directly proportional to coil current. The base station coil (L1) forms part of a series RLC circuit that resonates at 125kHz. At resonance, the series RLC circuit is a purely resistive load for the driver circuit. Thus the current (and field) is determined as driver voltage divided by RLC circuit resistance. The RLC circuit resistance consists of all the circuit losses and not just the DC resistance of the coil.

The driver square wave peak-to-peak voltage is proportional to the power supply voltage V_{PSU} minus the voltage drop across the blocking diode D1 and filter resistor R17.

The total RLC circuit resistance R_{TOTAL} is fixed by the ratio of driver square wave RMS voltage divided by RMS coil current.

FIGURE 2: RESISTANCE LOSSES



The resistance RTOTAL minus the driver circuit loss RCONST determines the total coil loss resistance RCOIL. The driver circuit loss resistance RCONST consists of the losses due to the FET (Q1 or Q2 and, Q4) "on" resistance, the series resistor R16 if used, and the loss due to the dissipation factor of resonating capacitor C3.

If the starting point for the design selects a power supply current which is too high or a power supply voltage which is too low, then a RTOTAL circuit resistance is required which will be lower than the driver circuit losses RCONST. This is not realizable and would require the coil loss resistance RCOIL to be negative.

For maximum operating distance, the aim of the coil driver is to have low losses. This means using FET's that have a low "on" resistance. Preserving charge in capacitor C3 when the field is switched off reduces the time for the field to build up to its maximum when enabled again. This removes the bandwidth limitation on the Q factor of the resonating circuit, given as Q=f/BW. The Q is now limited by the maximum voltage across the resonating capacitor C3, and is given by Q=VCAP/VRMS, where VRMS is the coil driver voltage applied to the RLC circuit.

Since the Q is limited by the voltage rating of the resonating capacitor V_C3, and the total RLC circuit resistance RTOTAL is known, the coil inductance L is calculated from

$$Q = \frac{V\_C3_{RMS}}{V_{RMS}} = \frac{\omega_r \times L}{R_{TOTAL}}$$

where the resonant frequency f_r is given by

$$f_r = \frac{\omega_r}{2\pi}$$

The coil inductance L and resonant frequency ω_r determine the resonating capacitor C from the equation

$$\omega_r^{\ 2} = \frac{1}{LC}$$

Data Required

TABLE 1: POWER SUPPLY PARAMETERS

Input	Units	Typical Value	Description
VPSU	[V]	12	Rated PSU voltage used with the base station. This should remain in the range of 8 Volts to 14 Volts if the HCS410 Evaluation Kit Base Station is to be used.
IPSU	[A]	0.5	Rated PSU current. This can be lowered and will lower the magnetic field strength if the design is current limited.

TABLE 2: COIL DRIVER CIRCUIT ELECTRICAL PARAMETERS

Input	Units	Typical Value	Description
f_r	[Hz]	125000	Coil operating frequency (resonance)
V_D1	[V]	0.625	Blocking diode forward voltage drop at IPSU
R17	[ohm]	0.47	Supply filter resistor value
R_Q1	[ohm]	0.3	Maximum "on" resistance of Q1 and Q2
R16	[ohm]	1	RLC series resistor
R_C3	[ohm]	0.128	Resonating capacitor dissipation resistance
R_Q4	[ohm]	0.4	Enhanced frequency circuit Q4 on resistance
V_C3	[V]	400	Resonating capacitor C3 rated maximum voltage

Intermediate Calculations

TABLE 3: COIL DRIVER CIRCUIT CALCULATED PARAMETERS

Output	Units	Typical Value	Description
VDRV	[V]	11.14	Driver square wave peak to peak voltage
VRMS	[V]	5.01	Driver square wave rms voltage
IRMS	[A]	1.11	RMS coil current
RTOTAL	[ohm]	4.51	Total resistance
Q		28.2	Quality factor of RLC circuit
ω_r	[rad/sec]	785398	Transmission frequency
RCONST	[ohm]	1.83	Evaluation circuit losses

Output Data

TABLE 4: RLC RESONATOR CIRCUIT VALUES

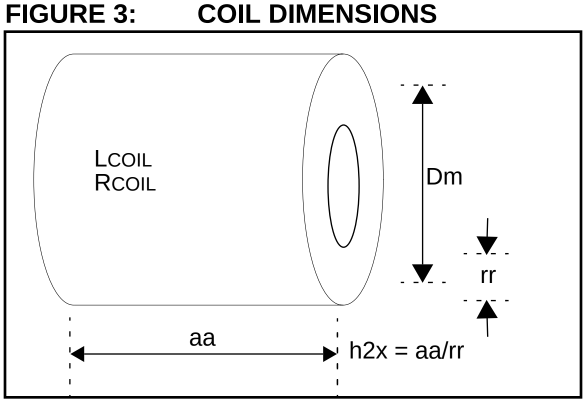
Output	Units	Typical Value	Description
CRES	[nF]	10	Resonating Capacitor
LCOIL	[µH]	162.11	Coil inductance
RCOIL	[ohm]	2.69	Total coil losses at temperature t

The inductance LCOIL and coil resistance RCOIL are used for inputs to the Coil Design worksheet.

WORKSHEET 2: COIL DESIGN ENGINE

Data Required

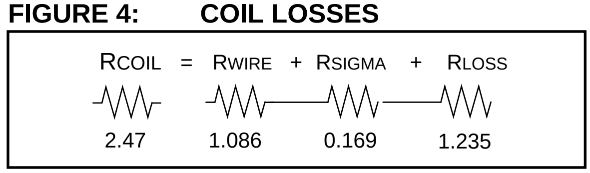
FIGURE 3: COIL DIMENSIONS



The input to the coil design specifies coil inductance LCOIL, coil loss resistance RCOIL, coil average diameter Dm, coil winding aspect ratio h2x, coil loss factor KLOSS, coil wire packing factor, electrical characteristics for the wire used, coil operating temperature and relative permeability for the coil if a core is used.

With large currents, the coil will get hot, as do the drivers. The coil temperature is proportional to the coil losses, which are due to the DC resistance of the wire at the operating temperature t, plus losses due to skin effect and proximity effect. The assumption made in this worksheet is that the losses due to skin effect and proximity effect RLOSS are equal to KLOSS X the DC resistance of the wire at room temperature (RWIRE) plus the increase in wire resistance RSIGMA due to temperature. Thus KLOSS is set to 1 in the worksheet.

FIGURE 4: COIL LOSSES



The default values in Table 5 assume annealed copper wire and an air core coil.

TABLE 5: COIL PARAMETERS

Input	Units	Typical Value	Description
L_{COIL}	[μH]	162.11	Coil inductance
R_{COIL}	[ohm]	2.69	Total coil losses at temperature t
Dm	[mm]	54	Coil average diameter
h2x		3	Coil aspect ratio (height/depth)
K_{LOSS}		1	Factor for skin effect and proximity losses. These losses are dissipated in the coil are assumed to be K_{LOSS} times the DC coil resistance at temperature t.
K		0.5	Space factor (packing). This compensates for copper area lost due to wire shape which is round and not square as well as wire insulation. If the coil is wound by hand, then the space factor of less than 0.5 may have to be chosen to compensate for wasted space.
ρ	[ohm-m]	1.72E-08	Coil wire resistivity at 20 degrees C. Resistivity for annealed copper wire is used. If the coil uses another type of wire, then the corresponding resistivity would have to be used.
sigma	[per deg C]	0.00393	Coil wire resistance temperature coefficient. The value used is for copper wire. This value is used to calculate the resistance increase due to the coil operating at a temperature different than 20 ^{o}C.
t	[deg C]	60	Coil operating temperature. This will vary according to the duty cycle, which is determined by the HCS410 Evaluation Kit firmware. The temperature rises with higher duty cycle.
μ_r		1	Relative permeability. It is assumed that the base station coil has an air core. This design does not consider ferrite cores.

Output Data

FIGURE 5: COIL SPECIFICATION

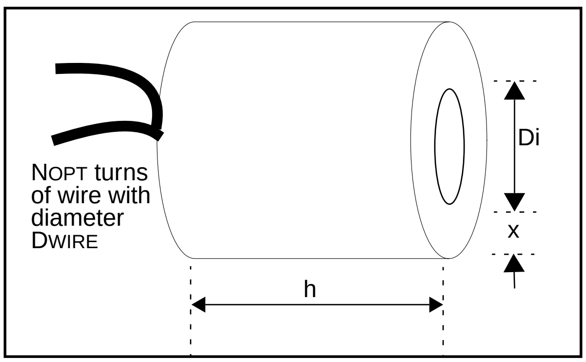


TABLE 6: OUTPUTS

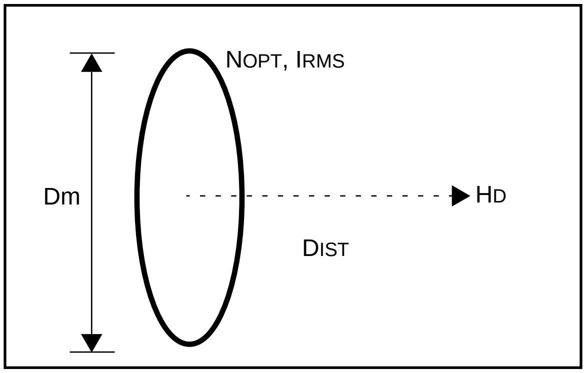
Output	Units	Typical Value	Description
R_{WIRE}	[ohm]	1.16	Coil DC resistance at room temperature
D_{WIRE}	[mm]	0.356	Wire diameter: choose closest to
N_{OPT}	turns	39.59	Optimum number of turns: choose closest to
D_I	[mm]	52.38	Coil inside diameter
h	[mm]	4.86	Coil axial height
x	[mm]	1.62	Coil winding depth

WORKSHEET 3: MAGNETIC FIELD PRODUCED BY A COIL

Data Required

For a base station coil shown below

FIGURE 6: MAGNETIC FIELD AT DISTANCE DIST



The magnetic field at distance DIST along the axis is given by

$$H_D = \frac{N_{OPT} \times I_{RMS} \times \left(\frac{D_m}{2}\right)^2}{2 \times \left[\left(\frac{D_m}{2}\right)^2 + (\text{Dist})^2\right]^{3/2}}$$

The values NOPT and Dm are used from the coil design on worksheet 2 and IRMS is used from worksheet 1. The input Dist can be entered to see what the magnetic field HD is at a certain distance. The value range is the estimated range at which the field would activate an Evaluation Kit long-range transponder

TABLE 7: TRANSPONDER DISTANCE FROM BASE STATION

Input	Units	Typical Value	Description
DIST	[cm]	0	Transponder axial distance from coil center

Output Data

TABLE 8: MAGNETIC FIELD STRENGTH

Output	Units	Typical Value	Description
HD	[A/m]	814.26	Magnetic field at distance Dist, in ampere turns per meter.
Range	[cm]	24.11	Evaluation Kit transponder, proximity activation range. This is the distance along the coil axis where the field is 1.123 ampere-turns per meter, which is the field, required to activate an Evaluation Kit transponder for RF talkback.

CONCLUSION

By using the formulas given in Appendix B, the equation for the field can be rewritten as shown in the following equation.

$$H_D = 5 \times 2^{3/4} \times \sqrt{5} \times \sqrt{127} \times \frac{\sqrt{V_{CAP}}}{\sqrt{\mu_r \times \omega_r}} \times \sqrt{\frac{V_{RMS}}{R_{TOTAL}}} \times \left(D_m \times \sqrt{\frac{3 \times D_m + 9 \times h + 10 \times x}{\left(D_m^2 + 4 \times \text{Dist}^2\right)^3}}\right)$$

It can be seen that the field is:

- proportional to the square root of the rated capacitor voltage VCAP,
- proportional to the square root of the current in the coil and,
- inversely proportional to the cube of the axial distance from the coil.
- The reason that increased frequency ω_r, or increased relative permeability μ_r decreases the field is because the number of turns has to be decreased to remain within VCAP specification.
- For a distance Dist, it can be shown that the magnetic field strength HD is a maximum when Dm (coil radius) is twice the distance Dist.

APPENDIX A: EXAMPLE CALCULATION

Problem

Design a coil that uses the HCS410 Evaluation Kit as base station, has a diameter of 120mm with square coil cross section, and draws 1A from the power supply.

Solution

Worksheet 1: Change the following from the default values in the worksheet.

IPSU=1amp, R16=0 ohms, as a series resistor is not needed.

The coil inductance required is 81 μH with resonating capacitor 20nF.

Worksheet 2: Change the following from the default values in the worksheet.

Dm=120, h2x=1 to get a square coil cross section.

The result for the coil is to use wire with a diameter of 0.48mm. From the table, AWG #24 is chosen which has a diameter of 0.51 mm. The number of turns is 17.

Worksheet 3:

The distance for a standard Evaluation Kit long-range transponder to be activated should be 39cm.

The values calculated give a good starting point for the coil design but are approximations, and the resonating capacitor will still have to be trimmed for resonance to occur. The model used for the losses is KLOSS is equal to 1. This loss factor may vary for different coils.

APPENDIX B: FORMULAS USED

This appendix gives the main formulas used in the worksheet. All values use metric units.

For a square wave with peak to peak voltage VDRV, driving an RLC circuit, the RMS value of this voltage VRMS is given by

$$V_{RMS} = V_{DRV} \times \frac{\sqrt{2}}{\pi}$$

The total resistance of the circuit is given by

$$R_{TOTAL} = \frac{V_{RMS}}{I_{RMS}}$$

For a frequency f in Hertz, the radians per second frequency is given by

$$\omega_r = 2\pi f$$

For a series RLC circuit with resistance RTOTAL, coil with inductance LCOIL and resonating capacitor with rated voltage V_CRES, the quality factor Q of the circuit is given by

$$Q = \frac{V\_C_{RES}}{V_{RMS} \times 2 \times \sqrt{2}} = \frac{\omega_r L_{COIL}}{R_{TOTAL}}$$

The resonating capacitor CRES value is given by

$$C_{res} = \frac{1}{\omega_r^2 \times L_{COIL}}$$

If NOPT turns of wire occupies a cross sectional area of x by h, with packing factor of K (ratio of copper area to total area), then the wire diameter DWIRE is

$$D_{WIRE} = 2 \times \sqrt{\frac{K \times x \times h}{\pi \times N_{OPT}}}$$

For a coil of average diameter DM, wound with NOPT turns of wire with diameter DWIRE and resistivity ρ, the resistance of the wire RWIRE is given by

$$R_{WIRE} = \frac{4 \times \rho \times D_m \times N_{OPT}}{D_{WIRE}^2}$$

For a coil of average diameter DM, with core which causes relative permeability UR, wound with NOPT turns of wire with axial height h and radial depth (inside radius to outside radius) x, the coil inductance in Henry is given by

$$L_{COIL} = \frac{\mu_r \times (D_m)^2}{127000 \times (3 \times D_m + 9 \times h + 10 \times x)} \times (N_{OPT})^2$$

For a coil of average diameter DM, wound with NOPT turns and carrying current IRMS, the magnetic field at axial distance DIST away is given by

$$H = \frac{N_{OPT} \times I_{RMS} \times \left(\frac{D_m}{2}\right)^2}{2\left[\left(\frac{D_m}{2}\right)^2 + (Dist)^2\right]^{3/2}}$$

APPENDIX C: REFERENCES

1. Babani, B.B., ed. 1974. *Coil Design and Construction Manual.* London: Bernards (publishers) Limited.
2. Nelkon, M., & Parker, P. ed. 1970. *Advanced Level Physics.* London: Heinemann Educational Books Ltd.

Note: Our design does not calculate self inter-winding capacitance of the inductor.

COMMENTS

The authors welcome feedback, comments, questions and errata via e-mail.

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GLOSSARY

Dissipation Factor: A measure of the losses of a capacitor. Dissipation factor varies with frequency and temperature.

Proximity Effect Losses: Losses are losses caused by adjacent conductors (proximity) generating eddy currents in each other.

Relative Permeability μr: The ratio of magnetic field in a material to the magnetic field if the material were replaced by vaccuum.

Skin Effect: This is the tendency for an alternating current to flow near the surface (skin) of a conductor as the frequency increases.

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