U2270B Antenna Design Hints

Table of Contents

General Information

The reader antenna is a series resonance circuit consisting of an inductor, a capacitor and a resistor (see figure 1).
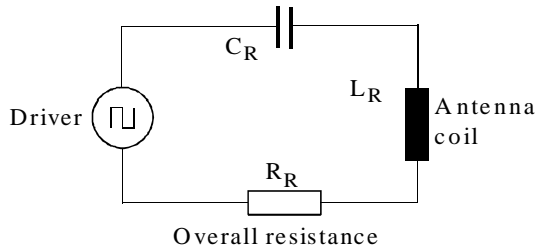

Figure 1. Equivalent circuit of the reader antenna

The antenna is characterized by its resonant frequency and its Q factor. The resonant frequency f_0 is the operating frequency of the ID system. This frequency is determined by the inductor and the capacitor of the antenna and can be calculated using the following formula:

$$f_0 = \frac{1}{2 \times \pi \times \sqrt{L_R \times C_R}}$$

This frequency is selected to $f_0 = 125$ kHz. The Q factor, Q_R, represents the bandwidth, B, of the antenna and also the ratio between the reader antenna voltage (U_R) and the sinusoidal content of the antenna's driver voltage (U_{DRV}).

$$B = \frac{f_0}{Q_R} \qquad\qquad U_R = U_{DRV} \times Q_R$$

The sinusoidal content of the antenna's driver voltage is determined by the peak-to-peak square-wave driver output signal (U_{DRVpp}) of the U2270B. Note that this value is twice the measured driver output voltage swing in the differential mode.

$$U_{DRV} = \frac{4}{\pi} \times U_{DRVpp}$$

A higher Q factor results in a higher reader-antenna voltage and therefore enhances the energy transfer to the transponder. The drawback of a higher Q factor is the reduced bandwidth of the antenna. A smaller bandwidth can reduce the induced data signal volt-age in accordance with the transponder's data rate.

In most automotive applications, the reader antenna is situated very close to the lock cylinder material. This material can have a major influence on the antenna coil inductance and on the Q factor of the coil. A higher Q factor results in a higher possible influence due to the lock cylinder material. If this is the case, the Q factor can vary with variations of the lock-cylinder material and with the mounting accuracy of the antenna coil. Therefore, the Q factor should not be set to a value of $Q_R > 15$.

A good compromise regarding this scenario is a Q factor of $Q_R = 12$. This value is proposed for all described applications and is also used in the TEMIC demo kit. Nevertheless, there are other non-automotive applications where other values could be preferred. If this is the case the Q factor should be kept within $Q_R = 5 - 15$.

The determination of the antenna inductivity is described in the following chapters. If that inductivity is determined, the Q factor can be calculated by using the following formula:

$$Q_R = \frac{2 \times \pi \times f_0 \times L_R}{R_R}$$

Note that R_R is the overall resulting series resistance. R_R includes the losses due to the lock-cylinder material, the copper losses of the coil and the external series resistor R_6. (see ID demo kit, page 6) An exact formula to determine R_6 cannot be given due to the unknown influence of the lock cylinder material. The Q factor can be changed by varying the series resistor R_6. A lower value for R_6 results in a higher Q factor for the antenna. A value of $R_6 = 100\ \Omega$ is recommended to start with. This value can now be decreased to achieve the desired Q factor. The antenna's Q factor can be monitored by the antenna voltage. When using the demoboard, this Q factor is achieved at an antenna voltage of $V_R = 130\ V_{PP}$.

Antenna Design Procedure

The resonant frequency of the reader antenna shows a certain tolerance due to the limited accuracy of the frequency-determining antenna components, the influence of the lock cylinder material, and the mounting accuracy of the coil. This chapter describes the design of the reader antenna under that condition in respect to the actual magnetic coupling situation.

The first step in designing the antenna is to increase the magnetic coupling factor, k, as much as possible. A good coupling factor enhances the energy transfer from the reader antenna to the transponder but also increases the signal voltage of the information that is sent back to the reader antenna by the transponder. This issue is very important as it can help to achieve a more cost-effective overall system design. This topic is described in detail in the chapter "Optimizing the Magnetic Coupling Factor".

With the value of k, determined in the chapter mentioned above, the transponder voltage and the modulated voltage at the reader coil can be calculated according to the TEMIC Application Note ANT019 (page 3). Due to deviations of the resonance frequency of the reader antenna and that of the transponder antenna, the data signal voltage at the reader coil may be decreased or could even disappear. This behavior is described in the TEMIC Application Note ANT019 pages 3 and 6-7.

Depending on the actual coupling factor k and the desired antenna tolerances, the appropriate strategy is selected to avoid negative consequences due to that effect. Depending on the selected strategy, the antenna is operated with a fixed frequency or with one of two frequencies which is selected by the decoding μC. In this case, an output port of the μC is required to control the appropriate alternative. The procedure of selecting the suitable strategy is described in the chapter "How to Meet the Actual Frequency Tolerance Situation". The determination of the inductivity of the reader antenna is also part of this chapter. A lower value for the inductivity allows higher tolerances for the resonant frequencies of the antennas, but also results in a higher supply current for the system.

If the reader antenna can be operated with a fixed frequency, the design is finished. If it is necessary to switch between two different frequencies, their values must be determined. This topic is described in the chapter " How to Meet the Actual Frequency Tolerance Situation". Table 1 summarizes the antenna design in a flow chart.

Table 1. Antenna design procedure

1. Setting the fixed conditions (Q_R=12, antenna driver in differential mode)		
2. Optimizing the magnetic coupling factor k. (from the chapter "Optimizing the Magnetic Coupling Factor")		
3. Selecting the strategy to meet the actual frequency tolerance situation		
3.1 Operating the antenna with a fixed frequency is possible	3.2 The antenna is operated with two alternating frequencies	3.3 The system cannot be operated under the actual antenna tolerance/ magnetic coupling factor condition
L_R is determined according to the chapter "How to Meet the Actual Frequency Tolerance" $C_R = \dfrac{1}{L_R \times (2 \times \pi \times f_0)^2}$	L_R and two different values for C_R are determined according to the chapter "How to Meet the Actual Frequency Tolerance"	The magnetic coupling factor must be increased or the antenna tolerance must be decreased for a secure design

Optimizing the Magnetic Coupling Factor

The coupling factor depends only on the mechanical dimensions of the coil arrangement (diameters, reading distance, coil orientation) and the magnetic materials close to the coil. The coupling factor does not depend on the inductance of the reader antenna or the transponder coil.

To improve the coupling factor, the transmission distance to be selected should be as small as possible. If the transponder cannot be placed in the axis of the reader coil, the magnetic field strength vector is not in parallel to the transponder coil axis. If this is the case, please check for the best transponder orientation.

If the reading distance is fixed due to mechanical constraints, the reader antenna coil diameter and also the magnetic coupling factor k can be optimized for that specific distance.

$$H = \frac{U_R}{4 \times \pi \times f_0 \times \sqrt{\pi \times \mu_0}} \times \frac{1}{\sqrt{L_R}} \times \left(\frac{r}{r^2 + d^2}\right)^{1.5}$$

H   Magnetic field strength

U_R Reader coil voltage

f_0 Operating frequency

μ_0 Magnetic field constant

$$\mu_0 = 1.257 \times 10^{-6} \frac{Vs}{Am}$$

L_R Reader coil inductance

r   Radius of the antenna coil

d   Reading distance

The formula on the left hand side provides the magnetic field strength on the transponder. The first part of the formula is fixed in all applications. The term in the middle indicates the dependence of the selected coil inductance, and the term on the right describes the dependence on the mechanical situation. As the magnetic coupling factor, k, depends on the mechanical dimensions of the coil arrangement, it is proportional to the term on the right. Figure 2 illustrates how the magnetic field strength and the coupling factor varies for a given fixed reading distance if the coil radius is changed. The diagram corresponds to the following conditions:

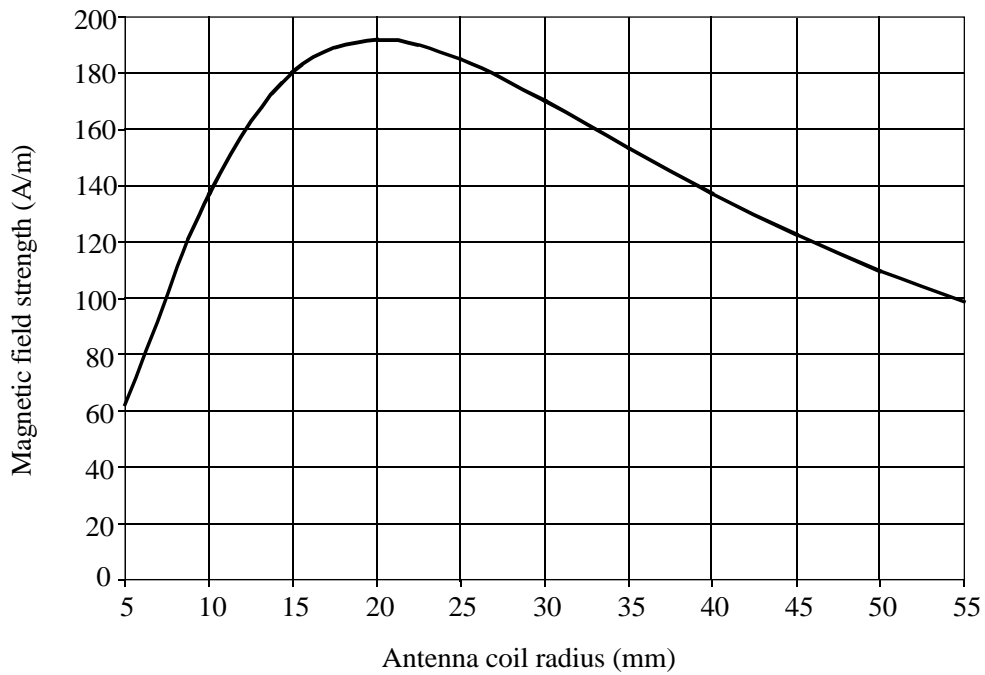|	
$U_R = 130 \, V_{SS}$	Reader coil voltage
$f_0 = 125 \, kHz$	Operating frequency
$L_R = 737 \, \mu H$	Reader coil inductance
$r = 5 - 55 \, mm$	Radius of the antenna coil (varied parameter)
$d = 20 \, mm$	Reading distance of the transponder

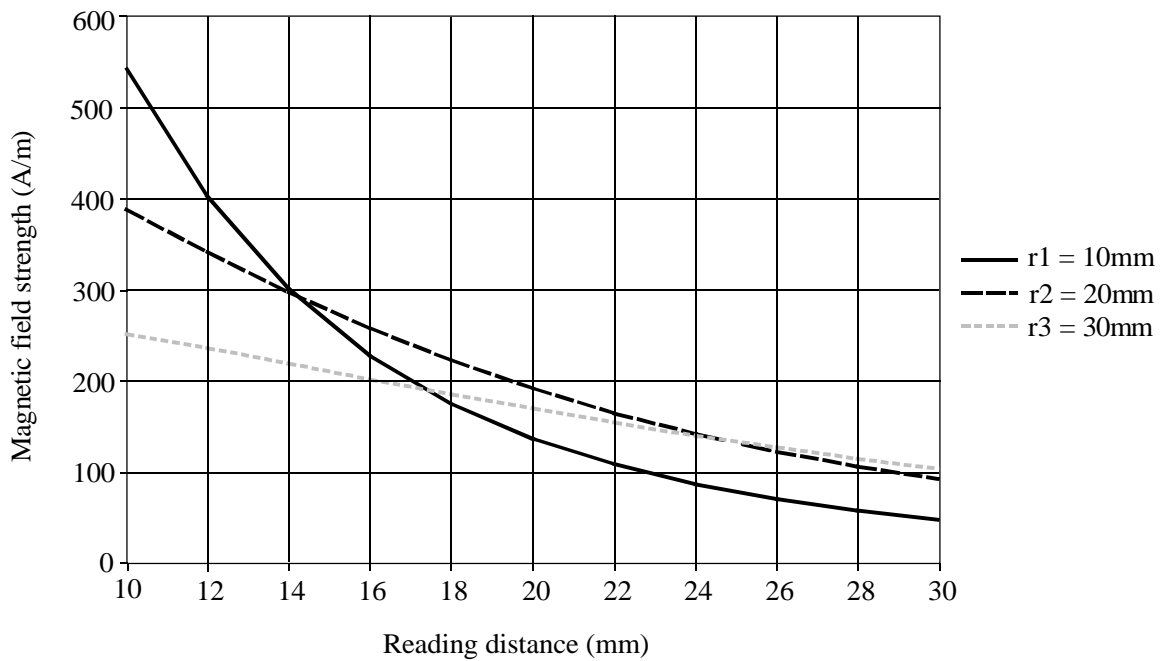Figure 2. The magnetic field strength via the coil radius of the reader antenna

Figure 3. The magnetic field strength via the reading distance for various radius

The maximum magnetic field strength for a given reading distance is achieved when the coil radius is equal to the reading distance. If this is the case, the magnetic field is $H_{max} = 192$ A/m for r = 20 mm.

Figure 3 shows the magnetic field strength via the reading distance for various coil radiuses. Coil 2 ($r_2 = 20$ mm) is optimized for a reading

distance of d = 20 mm. The corresponding parameters are:

$U_R = 130\ V_{SS}$ — Reader coil voltage

$f_0 = 125\ kHz$ — Operating frequency

$L_R = 737\ \mu H$ — Reader coil inductance

$r_1 = 10\ mm$ — Radiuses of the antenna coils

$r_2 = 20\ mm$

$r_3 = 30\ mm$

$d = 10 - 30\ mm$ — Reading distance of the transponder

$$H_n(d) = \frac{U_R}{4 \times \pi \times f_0 \times \sqrt{\pi \times \mu_0}} \times \frac{1}{\sqrt{L_R}} \times \left(\frac{r_n}{r_n^2 + d^2} \right)^{1.5}$$

Magnetic field strength at the transponder

Figure 3 shows that the coil with the smallest diameter displays the highest magnetic field strength at small distances, but the lowest value at a distance of d > 18 mm. The coil with the largest diameter shows the lowest decline vs. an increasing transmission distance but starts from a low value. Coil 2 has the best performance for d = 20 mm as the radius is determined as r = d.

Determination of the Magnetic Coupling Factor

In order to determine the coupling factor, TEMIC provides a test transponder coil (TTC) with the same characteristic as the antenna coil of a TEMIC plastic transponder. This TTC can be placed at the actual transponder location. The voltage across the TTC coil can then be measured while the actual reader antenna is being operated by a signal generator. The corresponding coupling factor can be determined by using the measured voltage U_T together with the coil inductivities and the reader antenna voltage. Figure 4 shows the setup for the measurement.
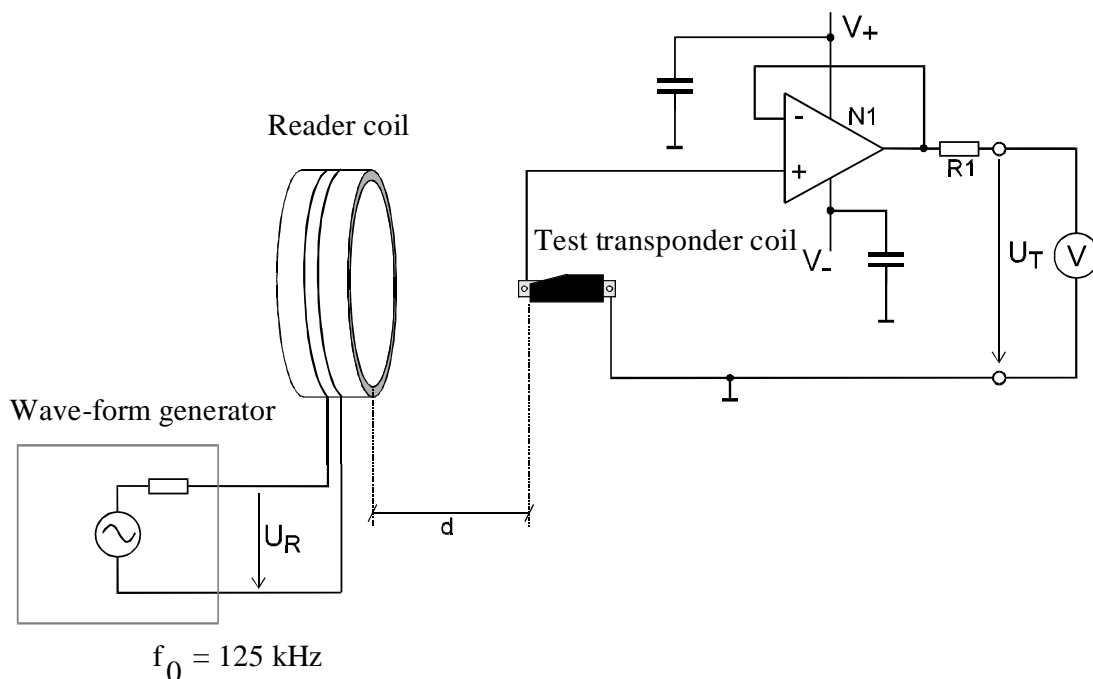

Figure 4. Circuit diagram to determine the magnetic coupling factor
(N1: TL081 or LF 356N, R1: 100 to 500 Ω)

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Figure 5 shows the electrical model of the TTC together with the connected measurement equipment. C_{Para} is the internal parasitic capacitance in parallel to the coil. C_{Cable} and C_{Probe} are the load capacitances of the connected measurement equipment. These capacitances have an influence on the measured voltage.
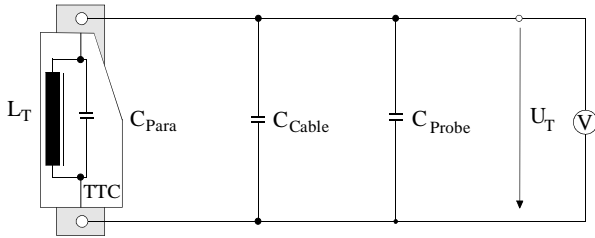

Figure 5. Electrical model of the TTC with the load capacitances of the probe (C_{Para} = 20 pF)

To compensate that effect, a correction factor A_k can be determined to achieve an accurate result. A_k can be calculated using the formula on the right hand side of the page, or can be read from the diagram shown in figure 6. If the input capacitance of the measurement equipment is (C_{Cable} + C_{Probe}) < 30 pF, the equipment can be directly connected to the TTC. In this case, the buffer OP amplifier is not needed.

$$A_k = 2 - \frac{1}{1 - \omega^2 \times C_{GES} \times L_T}$$

$$C_{GES} = C_{Para} + C_{Probe} + C_{Cable}$$

A_k Correction factor   (< 1)

ω $2 \times \pi \times 125$ kHz

L_T Transp. coil inductance (3.95 mH)

Using the formula below, the coupling factor k can now be calculated.

$$k = A_k \times \frac{U_T}{U_R} \times \sqrt{\frac{L_R}{L_T}}$$

A_k Correction factor

U_T Transponder coil voltage

U_R Reader coil voltage

k   Coupling factor

L_T Transponder coil inductance
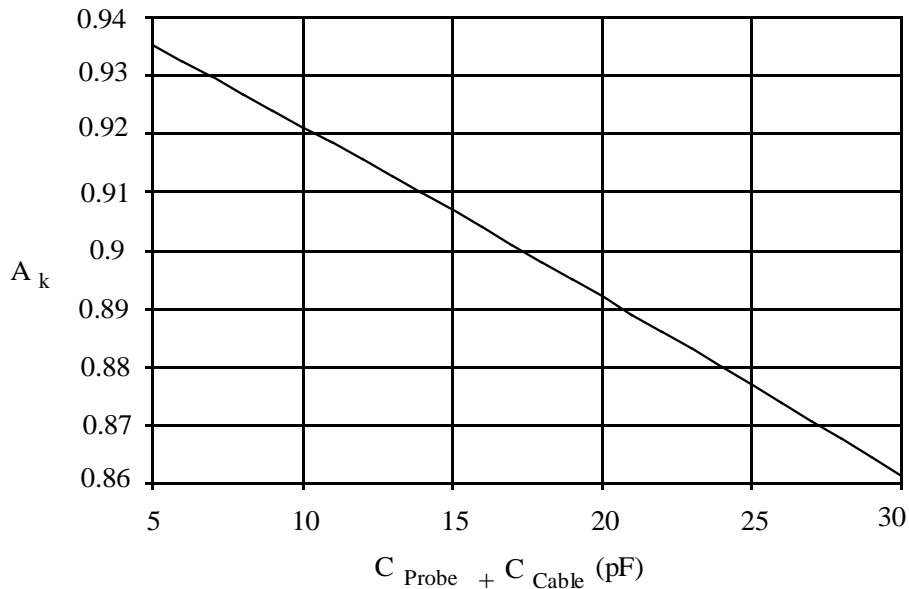
L_R Reader coil inductance

Figure 6. Diagram to determine the correction factor A_k

How to Meet the Actual Frequency Tolerance Situation

According to the chapter "Optimizing the Magnetic Coupling Factor", the magnetic coupling factor is now set to the highest possible value. One of two operation modes can be selected depending on that value and the resonant frequency tolerances of the transponder and the reader antenna.

Operation Mode 1

The reader antenna is operated with a fixed frequency of $f_{osc} = 125$ kHz. This mode is preferred due to the following reasons:

- Less external components
- An additional µC pin is not required
- Faster detection time

Operation Mode 2

The reader antenna is operated with two alternating frequencies. The differences to operation mode 1 are:

- Allows higher resonant frequency tolerances at the same magnetic coupling factor
- The decoding µC selects and controls the preferred operating frequency

Figure 7 and figure 8 help to decide whether to choose mode 1 or mode 2. This figure shows the maximum tolerable total antenna tolerances for different magnetic coupling factors k and for different inductivities L_R of the reader coil. The total antenna tolerance hereby is the sum of the reader antenna frequency tolerance and the transponder resonant frequency tolerance.
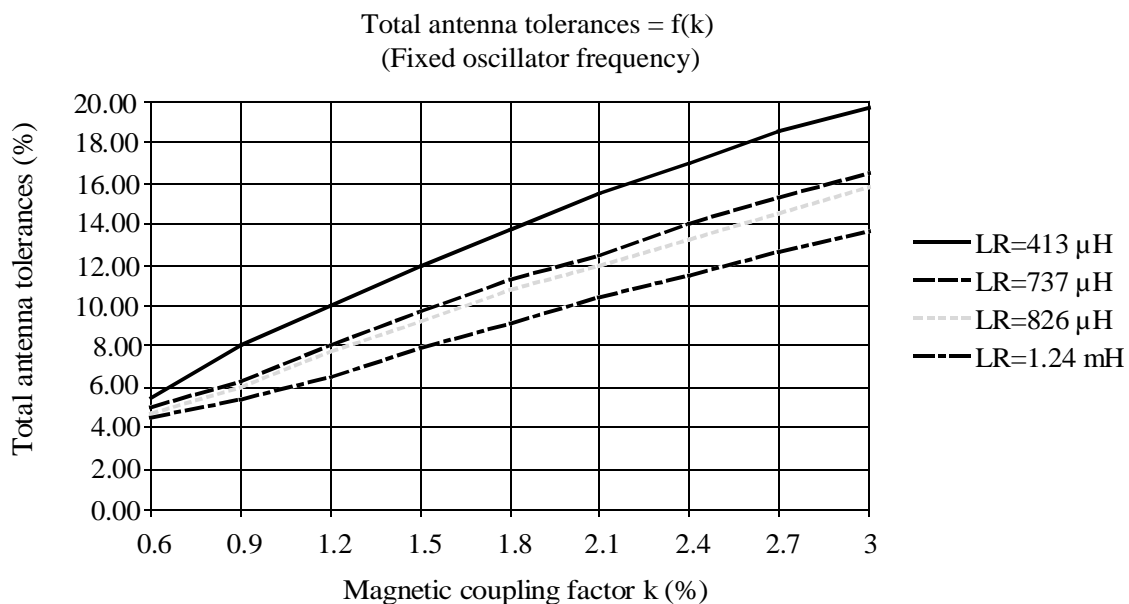
Total antenna tolerances = f(k)
(Fixed oscillator frequency)

Figure 7. Determination of L_R for the fixed frequency mode

Total antenna tolerances = f(k)
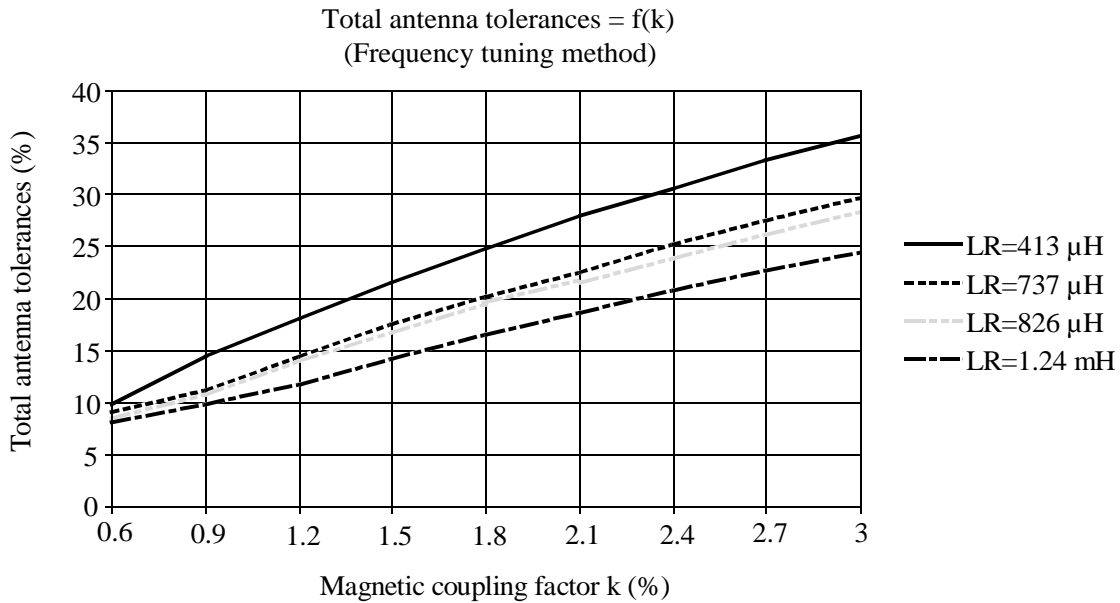(Frequency tuning method)

Figure 8. Diagram to determine L_R for altering operating frequencies

The plots in figure 7 and 8 indicate that the tolerable tolerances increase with a higher magnetic coupling factor and with a lower reader antenna coil inductivity. Note that a lower reader antenna inductivity results in a higher antenna current. The maximum antenna current is limited to $I_{Rpp} = 400$ mA due to the antenna driver current capability of the U2270B. If the reader antenna coil voltage is considered, the reader antenna inductance is not able to be decreased to values of $L_R < 413$ µH.

The total antenna tolerances together with the actual magnetic coupling factor define a specific point in both figures 7 and 8. Plots that are above that point correspond to antenna coil inductances that match the corresponding operation mode. Any inductivity between $L_R = 413$ µH and the inductivity indicated by that point can be used. Operation mode 1 is preferred if both modes can be used. If mode 1 is used, the antenna capacitance can be calculated using the formula:

$$C_R = \frac{1}{L_R \times (2 \times \pi \times f_0)^2} \qquad f_0 = 125 \text{ kHz}$$

If mode 2 is used, the reader antenna is operated with two alternating frequencies. The two frequencies and the corresponding capacitors (see figure 9) can be determined by using the maximum antenna frequency tolerances.

$$C_{R1} = \frac{1}{L_R \times (2 \times \pi \times f_1)^2}$$

$$f_1 = 125 \text{ kHz} - 0.44 \times \left(\left| Tol_R (\%) \right| + \left| Tol_T (\%) \right| \right)$$

$$C_{R2} = \frac{1}{L_R \times (2 \times \pi \times f_2)^2}$$

$$f_2 = 125 \text{ kHz} + 0.44 \times \left(\left| Tol_R (\%) \right| + \left| Tol_T (\%) \right| \right)$$

$Tol_R(\%)$ Frequency tolerance of the reader antenna in %

$Tol_T(\%)$ Frequency tolerance of the transponder antenna in %.

As the capacitors C_{R1} and C_{RP} act in parallel the switched capacitor C_{RP} can be determined as being:

$$C_{RP} = C_{R2} - C_{R1} \qquad \text{(see figure 9)}$$

If no coil inductance of $L_R \geq 413$ μH can be used in mode 1 or mode 2, the magnetic coupling factor must be increased or the reader antenna tolerance must be decreased to enable a successful design.

Note that the graphs in figure 7 and 8 are only valid for applications using the TEMIC reader IC U2270B together with any read-only TEMIC transponder. These graphs should not be used for any other component combinations because they were designed for TEMIC transponder applications only.
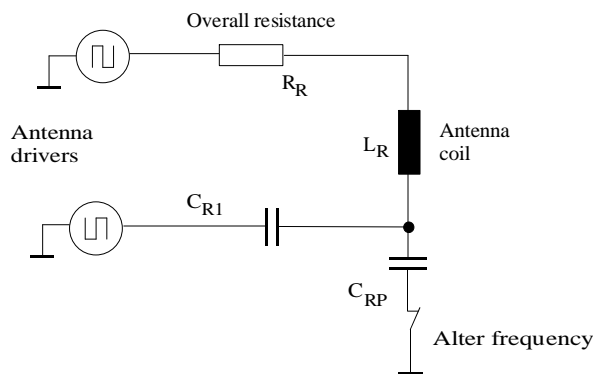

Figure 9. Equivalent circuit of the frequency altering reader antenna

Example

The TEMIC ID demonstration kit including the reader board, the reader antenna and the TEMIC read only plastic transponder is intended to assist the understanding of the ID system as it offers the possibility of verifying all physical parameters such as antenna voltage and coupling factor etc.

Moreover, the kit serves as a fictive antenna design example to illustrate the design procedure. The following assumptions and constraints apply for this design example:

Radius of the reader coil:	15 - 25 mm
Frequency tolerance of the reader coil:	± 3%
Frequency tolerance of the TEMIC plastic transponder	± 4%
Minimum reading distance	20 mm

The first step in designing the reader antenna is to increase the magnetic coupling factor as much as possible. In this example the radius of the reader antenna can be varied to maximize this factor for the minimum reading distance of d = 20 mm. According to the chapter "Optimizing the Magnetic Coupling Factor", the ideal antenna radius is calculated as being: r = d, resulting in a value r = 20 mm.

The next step is to determine the magnetic coupling factor using the TEMIC test transponder coil (TTC) as described in the chapter "Determination of the Magnetic Coupling Factor". Figure 10 shows results of the measurements versus the reading distance.

Here, a coupling factor of k = 1.2% can be extracted for the required transmission distance of d = 20 mm. In the next stage, the required operation mode is selected according to the chapter "How to Meet the Actual Frequency Tolerance Situation". The total antenna tolerance is the sum of the tolerances of reader and transponder antenna, summarizing to ± 7% in this example.

According to figure 7, it is possible to select the operation mode using a fixed frequency. Only the plot of the reader coil with $L_R = 1.24$ mH is below the point that is determined by k = 1.2% and the total antenna tolerance of ± 7%. Any reader coil inductance between $L_R \approx 850$ μH and $L_R = 413$ μH can be selected. In this example, $L_R = 737$ μH is chosen. By using the formula:

$$N \approx \sqrt{\frac{L_R}{r \times \pi \times \mu_0}}$$

L_R	Reader coil inductance
r	Radius of the reader coil
μ_0	Magnetic field constant:

$$\mu_0 = 1.257 \times 10^{-6} \frac{Vs}{Am}$$

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the required number of turns of the reader coil is determined as being N = 97. As this is only an approximation formula, please check via measurements. The capacitance of the reader antenna is determined by means of the following formula:

$$C_R = \frac{1}{(2 \times \pi \times f_0)^2 \times L_R}$$

C_R	Reader antenna capacitance
L_R	Reader coil inductance
f_0	Operating frequency

In this example the capacitance is calculated to be $C_R = 2.2$ nF.

Table 2 summarizes all relevant parameters together with the applicable formulas as a reference to measurements with the demoboard.

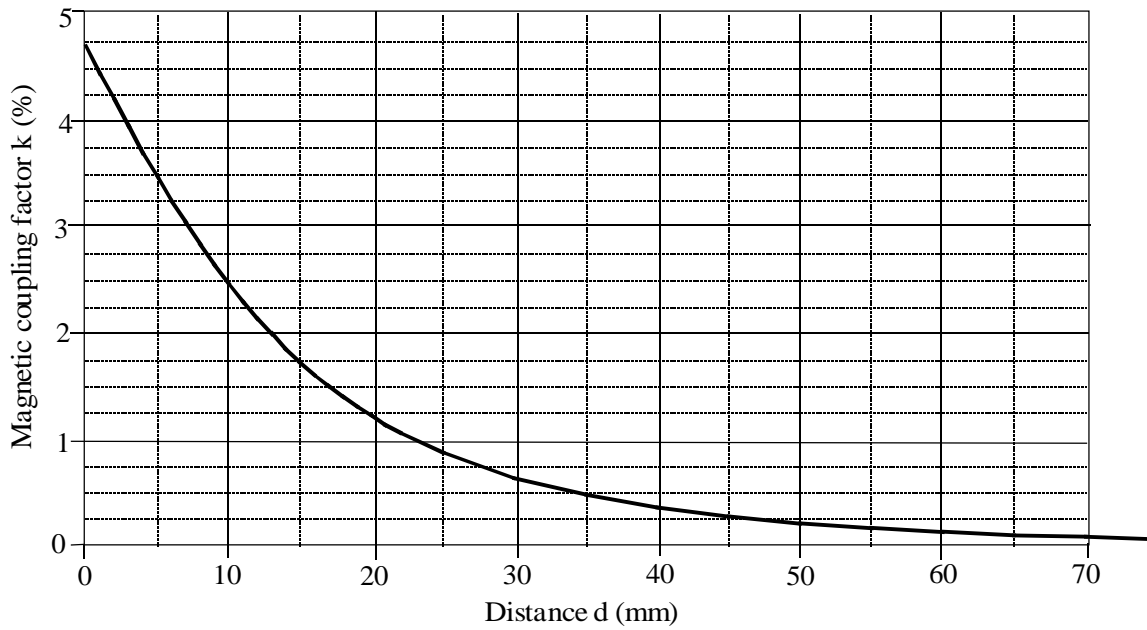Figure 10. Magnetic coupling factor vs. transmission distance

Table 2. Summary of relevant parameters

Parameter	Design Criteria	Value
Sinusoidal content of the antenna driver voltage	$U_{DRV} = \dfrac{4}{\pi} \times U_{DRV\,pp}$ $\left(U_{DRV\,pp} = 8.5 \text{ V in differential mode} \right)$	10.8 V (pp)
Q factor of the reader antenna (Q_R)	Fix for most automotive applications See the chapter "General Information"	12
Reader antenna voltage	$U_R = U_{DRV} \times Q_R$	130 V (pp)
Reader coil radius (r)	Optimized for maximum magnetic coupling factor	20 mm
Reader coil inductance (L_R)	Designed according to the chapter "How to Meet the Actual Frequency Tolerance Situation"	737 μH
Number of turns	$N \approx \sqrt{\dfrac{L_R}{r \times \pi \times \mu_0}}$	97
Reader antenna capacitance (f_0)	$C_R = \dfrac{1}{\left(2 \times \pi \times f_0\right)^2 \times L_R}$	2.2 nF
Operating frequency	Fixed frequency according to chapter "How to Meet the Actual frequency Tolerance Situation"	125 kHz
Reader coil current	$I_R = \dfrac{U_R}{2 \times \pi \times f_0 \times L_R}$	224 mA (pp)
Supply current	$I_s = \dfrac{I_R}{\pi}$	72 mA
Magnetic field strength at d = 20 mm and f_0 = 125 kHz	$H = \dfrac{U_R}{4 \times \pi \times f_0 \times \sqrt{\pi \times \mu_0}} \times \dfrac{1}{\sqrt{L_R}} \times \left(\dfrac{r}{r^2 + d^2}\right)^{1.5}$ $H = \dfrac{N \times I}{2 \times r \times \left(\dfrac{d^2}{r^2} + 1\right)^{1.5}}$	$192\dfrac{A}{m}$ (pp)