

# RFID TAGs Coil's Dimensional Parameters Optimization As Excitable Linear Bifurcation System

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## 1. Introduction

In this article, Very Crucial subject discussed in RFID TAG's Coil design. RFID Equivalent circuits of a Label can be represent as Parallel circuit of Capacitance (Cpl), Resistance (Rpl), and Inductance (Lpc). The Label measurement principal is as follow: Label positioned in defined distance to measurement coil, Low current or voltage source, Measuring of  $|Z|$  and Teta of measurement coil, Resonance frequency  $f_{ro}$  at Teta = 0, Calculation of unloaded quality factor  $Q_0$  out of measured bandwidth  $B_0$ . The Coil design procedure is based on three important steps. The first is Preparations: Definition of limits and estimations, Calculation of parameters. The second is Matrix Run 1: Definition of matrix, Equations and Calculations, Sample production, evaluation of samples, and Re calculation of parameters. The third is Matrix Run 2: Definition coil parameters, samples production, evaluation of samples, and decision on best parameters. Any RFID Coil design include definition of Limits and estimations, Maximum dimensions of coil (Maximum overall length, width), definition of the minimum gap between tracks and track thickness. It is very important to emphasis that basic Label IC (NXP I CODE for example), equivalent circuit is Capacitor (Cic) and Resistor (Ric) in parallel. The additional coil traces give the complete RFID equivalent circuit (Capacitor, Resistor, and inductor in parallel). The RFID equivalent circuit can be represent as a differential equation which depending on variable parameter. The investigation of RFID's differential equation based on bifurcation theory, the study of possible changes in the structure of the orbits of a differential equation depending on variable parameters. The article first illustrate certain observations and analyze local bifurcations of an appropriate arbitrary scalar differential equation. Since the implicit function theorem is the main ingredient used in these generalizations, include a precise statement of this theorem. Additional analyze the bifurcations of a RFID's differential equation on the circle. Bifurcation behavior of specific differential equations can be encapsulated in certain pictures called bifurcation diagrams. All of that for optimization of RFID TAG's dimensional parameters optimization – to get the best performance.

## 2. RFID TAG equivalent circuit

RFID TAG can be represent as a parallel Equivalent Circuit of Capacitor and Resistor in parallel. For example see below NXP/PHILIPS ICODE IC Parallel equivalent circuit.

Source: Radio Frequency Identification Fundamentals and Applications, Design Methods and Solutions, Book edited by: Cristina Turcu, ISBN 978-953-7619-72-5, pp. 324, February 2010, INTECH, Croatia, downloaded from SCIYO.COM

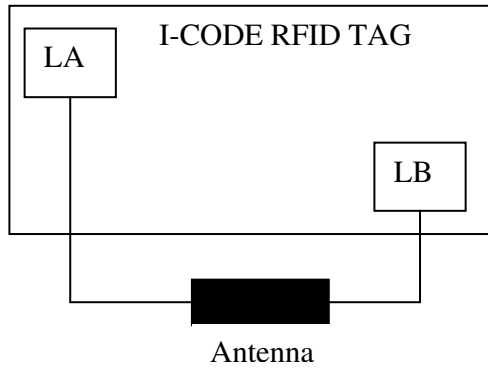


Fig. 1.

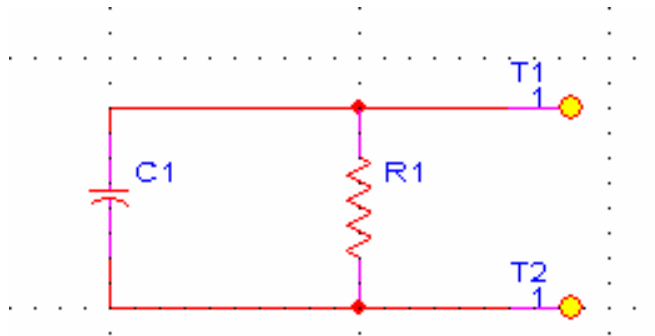


Fig. 2.

The RFID TAG Antenna can be represents as Parallel inductor to the basic RFID Equivalent Circuit. The simplified complete equivalent circuit of the label is as below:

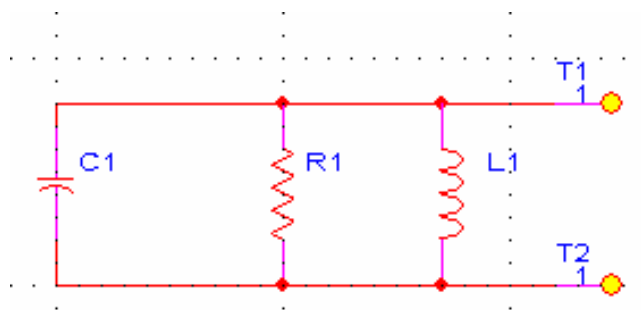


Fig. 3.

$$C1 = Cic + Ccon + Cc, R1 = (Ric * Rpc)/(Ric + Rpc) .$$

$$Vl1 = L * \frac{dI1}{dt}, Ic1 = C * \frac{dVc}{dt}$$

$$\begin{aligned}
 I1 &= \frac{1}{L1} * \int_0^{t1} V1 * dt \\
 \sum_{i=1}^{i=3} li &= 0, \frac{V}{R1} + C1 * \frac{dV}{dt} + \frac{1}{L1} * \int_{t=0}^{t=t1} V * dt = 0 \\
 \frac{1}{R1} * \frac{dV}{dt} + C1 * \frac{d^2V}{dt^2} + \frac{1}{L1} * V &= 0
 \end{aligned}$$

we get differential equation of RFID TAG sys which describe the evolution of the sys in continues time.  $V = V(t)$ .

Now I define the following Variable setting definitions:

$$V2 = \frac{dV1}{dt} = \frac{dV}{dt}, V1 = V$$

And get the dynamic equation system:

$$\frac{dV1}{dt} = V2$$

$$\frac{dV2}{dt} = -\frac{1}{C1 * R1} * V2 - \frac{1}{C1 * L1} * V1$$

The system shape is as Non linear system equations:

$$\frac{dV1}{dt} = f1(V1, V2, \dots, Vn), \frac{dV2}{dt} = f2(V1, V2, \dots, Vn)$$

The V1 and V2 variables are the phase space dimension two.

Now Lets Move to three variables system - which the time (t) is the third variable,  $V3 = t$ .

$$\frac{dV1}{dt} = V2, \frac{dV2}{dt} = -\frac{1}{C1 * L1} * V1 - \frac{1}{C1 * R1} * V2, \frac{dV3}{dt} = 1$$

Now we get the RFID's coil dimensional parameters:

$$d = 2 * (t + w) / \Pi, Aavg = a0 - Nc * (g + w), Bavg = b0 - Nc * (g + w)$$

$a0, b0$  - Overall dimensions of the coil.

$Aavg, Bavg$  - Average dimensions of the coil.

$t$  - Track thickness,  $w$  - Track width,  $g$  - Gap between tracks.

$Nc$  - Number of turns,  $d$  - Equivalent diameter of the track.

Average coil area;  $-Ac = Aavg * Bavg$ . Integrating all those parameters give the equations for inductance calculation:

$$X1 = Aavg * \ln \left( \frac{2 * Aavg * Bavg}{d * (Aavg + \sqrt{Aavg^2 + Bavg^2})} \right)$$

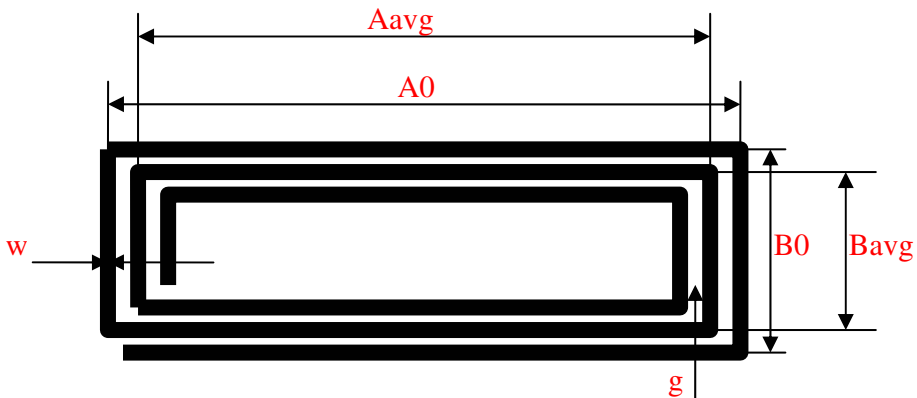


Fig. 4.

$$X2 = Bavg * \ln \left( \frac{2 * Aavg * Bavg}{d * (Bavg + \sqrt{Aavg^2 + Bavg^2})} \right)$$

$$X3 = 2 * \left[ Aavg + Bavg - \sqrt{Aavg^2 + Bavg^2} \right]$$

$X4 = (Aavg + Bavg) / 4$  , The RFID's coil calculation inductance expression is

$$Lcalc = \left[ \frac{\mu0}{\pi} * [X1 + X2 - X3 + X4] * Nc^p \right]$$

,  $L1 = Lcalc$

Definition of limits, Estimations: Track thickness t, Al and Cu coils (t > 30um). The printed coils as high as possible. Estimation of turn exponent p is needed for inductance calculation.

Coil manufacturing technology	P
Wired	1.8 - 1.9
Etched	1.75 - 1.85
Printed	1.7 - 1.8

Table 1.

Now I integrate the Lcalc value inside the differential equations which characterize the RFID system with the Coil inductance.

$$\frac{dV1}{dt} = 0 * V1 + 1 * V2 + 0 * V3$$

$$\frac{dV2}{dt} = - \frac{1}{C1 * \left[ \frac{\mu0}{\pi} * [X1 + X2 - X3 + X4] * Nc^p \right]} * V1 - \frac{1}{C1 * R1} * V2 + 0 * V3$$

$$\frac{dV3}{dt} = 0 * V1 + 0 * V2 + 0 * V3 + 1$$

The above differential equations can be represent as Matrix formulation:

$$\begin{bmatrix} \frac{dV1}{dt} \\ \frac{dV2}{dt} \\ \frac{dV3}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & -\frac{1}{C1 * R1} & 0 \\ C1 * \left[ \frac{\mu0}{\pi} * [X1 + X2 - X3 + X4] * Nc^p \right] & 0 & 0 \end{bmatrix} * \begin{bmatrix} V1 \\ V2 \\ V3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

### 3. RFID TAG as a dynamic system

The above representation can be represent as dynamical system. Lets first represent it as f(x), x formulation.

$$\begin{bmatrix} \frac{dX1}{dt} \\ \frac{dX2}{dt} \\ \frac{dX3}{dt} \end{bmatrix} = \begin{bmatrix} \frac{dV1}{dt} \\ \frac{dV2}{dt} \\ \frac{dV3}{dt} \end{bmatrix}, \quad \begin{bmatrix} X1 \\ X2 \\ X3 \end{bmatrix} = \begin{bmatrix} V1 \\ V2 \\ V3 \end{bmatrix}$$

Get the following three dimensional linear system: The X1 .. X4 inside matrix elements are not related to Variable X1 in the vector column ! later we return to the original representation by by substitute Xi by Vi.

$$\begin{bmatrix} \frac{dX1}{dt} \\ \frac{dX2}{dt} \\ \frac{dX3}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & -\frac{1}{C1 * R1} & 0 \\ C1 * \left[ \frac{\mu0}{\pi} * [X1 + X2 - X3 + X4] * Nc^p \right] & 0 & 0 \end{bmatrix} * \begin{bmatrix} X1 \\ X2 \\ X3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

The notation of a dynamical system is the mathematical formalization of general scientific concept of a deterministic process, in our case RFID equivalent circuit evolution with time. The future and past states of RFID systems can be predicted to a certain extent by knowing their present state and the laws governing their evolution. Provided these laws do not change in time, the behavior of such a system could be considered as completely defined by its initial state. Thus, the notion of a dynamical system includes a set of its possible states (state space) and a law of the evolution of the state in time. All possible states of the RFID system can be characterized by the points of some set X. This set is called the state space of the system. Actually, the specification of a point x belong to X must be sufficient not only to describe the current "position" of the system but also to determine its evolution. Often, the state space is called a phase space, following d tradition from classical mechanics. The following linear system is the right representation:

$$\begin{aligned}\frac{dX_1}{dt} &= f_1(x_1, x_2, x_3) \\ \frac{dX_2}{dt} &= f_2(x_1, x_2, x_3) \\ \frac{dX_3}{dt} &= f_3(x_1, x_2, x_3) + k\end{aligned}$$

The above three equations can be investigate as two pair of simultaneous differential equations of the form:

$$\begin{aligned}\frac{dX_1}{dt} &= f_1(x_1, x_2) \\ \frac{dX_2}{dt} &= f_2(x_1, x_2)\end{aligned}$$

$$f_1(x_1, x_2, x_3) = f_1(x_1, x_2), f_2(x_1, x_2, x_3) = f_2(x_1, x_2)$$

$I$  – Open..Interval.....  $\in \mathbb{R}$

$x_i : I \rightarrow \mathbb{R}; t \rightarrow x_i(t), \forall i = 1, 2$

be... $\mathbb{C}^1$ ..function..of..a..real..variable..t.

$f_i : \mathbb{R}^2 \rightarrow \mathbb{R}; \dots(x_1, x_2) \rightarrow f_i(x_1, x_2) \dots \forall i = 1, 2$

It will be convenient to use Boldface letters to denote vector quantities. For instance, if we let:

$$X = (x_1, x_2), \frac{dX}{dt} = \left( \frac{dx_1}{dt}, \frac{dx_2}{dt} \right), \text{and}, f = (f_1, f_2)$$

$$\text{then} \rightarrow \frac{dX}{dt} = f(X)$$

Norm...on... $\mathbb{R}^2$ ...function

$$\|\cdot\| : \mathbb{R}^2 \rightarrow \mathbb{R}; X \rightarrow \|X\|$$

Consequently, all of the qualitative results concerning differential equations will be independent of the choice of norm. Quantitative results, on the other hand, will of course depend on the norm. Since the function  $f$  is independent of  $t$ , on any line parallel to the  $t$  axis the segments of the direction field all have the same slope. Therefore, it is natural to consider the projections of the direction field and the trajectories of equation  $dX/dt=f(x)$  onto the  $(x_1, x_2)$  plane. To each point  $x$  on the  $(x_1, x_2)$  plane, when  $f(x)$  is defined, Association the vector  $f(x)=(f_1(x), f_2(x))$  which should be thought of as being based on  $x$ . Assign to the point  $x$  the directed line segment from  $x$  to  $x + f(x)$ . Now lets go back to 2 x 2 matrix representation of the system respect to two variables  $V_1$  and  $V_2$ .

$$\begin{bmatrix} \frac{dV_1}{dt} \\ \frac{dV_2}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ C_1 * \left[ \frac{\mu_0}{\pi} * [X_1 + X_2 - X_3 + X_4] * N C^p \right] & -\frac{1}{C_1 * R_1} \end{bmatrix} * \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

and denote the matrix's elements as functions K1 and K2 of Coil overall parameters.

$$K1 = K1(a0, b0, w, g, d, N_c, t, p, C1, R1) = \left\{ -\frac{1}{C1 * \left[ \frac{\mu 0}{\pi} * [X1 + X2 - X3 + X4] * N C^p \right]} \right\}$$

$$K2 = K2(a0, b0, w, g, d, N_c, t, p, C1, R1) = \left\{ -\frac{1}{C1 * R1} \right\}$$

Denote the RFID Matrix systems with those K1, K2 parameter function gives:

$$\begin{bmatrix} \frac{dV1}{dt} \\ \frac{dV2}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ K1 & K2 \end{bmatrix} * \begin{bmatrix} V1 \\ V2 \end{bmatrix}$$

Now consideration of trajectories of the form:  $V(t) = e^{\lambda * t} * S$

Where  $S \ll 0$  is some fixed vector to be determined, and  $\lambda$  is a growth rate, also to be determined. If such solution exist, they correspond to exponential motion along the line spanned by the vector S. To find the condition on S and  $\lambda$ , we substitute  $V(t) = e^{\lambda * t} * S$  into

$$\dot{V} = A * V$$

$$A = \begin{bmatrix} 0 & 1 \\ K1 & K2 \end{bmatrix}$$

and obtain  $\lambda * e^{\lambda * t} * S = e^{\lambda * t} * A * S$  and cancellation the nonzero scalar factor  $e^{\lambda * t}$  yields to  $\lambda * S = A * S$  which state that the desired straight line solutions exist if S is an eigenvector of A with corresponding eigenvalue  $\lambda$  and the solution is eigensolution. The eigenvalues of a matrix A are given by the characteristic equation  $\det(A - \lambda * I) = 0$  when I is the identity matrix  $I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ , we get

$$\Delta = \det(A) = 0 - K1 = -K1$$

$$\tau = \text{trace}(A) = 0 + K2 = K2$$

$$\lambda^2 - \tau * \lambda + \Delta = 0$$

$$\lambda^2 - K2 * \lambda - K1 = 0$$

$$\lambda_{1,2} = \frac{1}{2} * K2 \pm \frac{1}{2} * \sqrt{K2^2 + 4 * K1}$$

The above  $\lambda_{1,2}$  is a quadratic solution.

The typical solution is for the eigenvalues to be distinct  $\lambda 1 \neq \lambda 2$ . In this case, a theorem of linear algebra states that the corresponding eigenvectors S1 and S2 are linear independent, and hence span the entire plane. Any initial condition V0 can be written as a linear combination of eigenvectors,  $V0 = C1 * S1 + C2 * S2$ . Then the general solution for V(t) it is simply

$$V(t) = C1 * e^{\lambda_1 t} * S1 + C2 * e^{\lambda_2 t} * S2 .$$

By insertion quadratic solutions into the last V(t) equation we get

$$V(t) = C1 * e^{\left[\frac{1}{2} * K2 + \frac{1}{2} * \sqrt{K2^2 + 4 * K1}\right] * t} * S1 + C2 * e^{\left[\frac{1}{2} * K2 - \frac{1}{2} * \sqrt{K2^2 + 4 * K1}\right] * t} * S2$$

Now I use the theorem that state, if a coefficient matrix A has at least one eigenvalue with zero real part, then the planar linear system  $\dot{V} = A * V$  is topologically equivalent to precisely one of the following five linear systems with the indicated coefficient matrices, in our case only two options from five can fit;

$$\begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \rightarrow \text{two..zero..eigenvalues..but..one..eigenvector}$$

$$\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \rightarrow \text{two..purely..imaginary..eigenvalues}$$

Lets implement each case option to our RFID sys

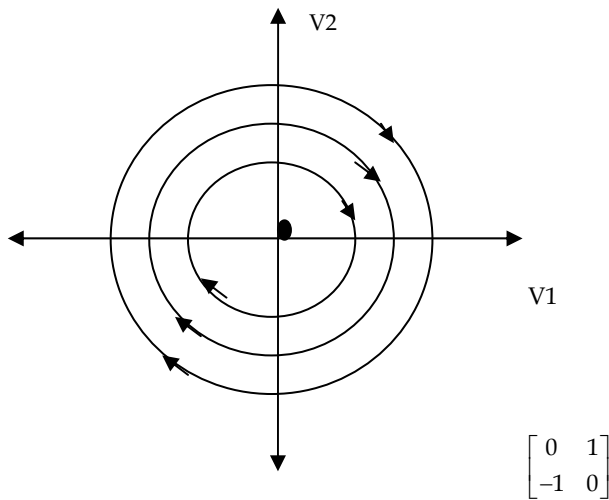


Fig. 5.

To fulfill the above behavior  $K2 = 0$  and  $K1 = -1$ , In our case

$$K2 \rightarrow 0, \forall \left\{ -\frac{1}{C1 * R1} \right\} \rightarrow 0, \forall C1, R1 \rightarrow \infty$$

$$K1 = -1, \forall \left\{ -\frac{1}{C1 * \left[ \frac{\mu 0}{\pi} * [X1 + X2 - X3 + X4] * Nc^p \right]} \right\} = -1$$

$$[X1 + X2 - X3 + X4] = \frac{\pi}{C1 * \mu 0 * Nc^p}$$



From above K1 condition we get RFID overall relationship.

$$[X1 + X2 - X3 + X4] = \frac{\pi}{C1 * \mu0 * Nc^p}$$

then

$$\left[ \begin{aligned} &Aavg * \ln \left( \frac{2 * Aavg * Bavg}{d * (Aavg + \sqrt{Aavg^2 + Bavg^2})} \right) + Bavg * \ln \left( \frac{2 * Aavg * Bavg}{d * (Bavg + \sqrt{Aavg^2 + Bavg^2})} \right) \\ &-2 * \left[ Aavg + Bavg - \sqrt{Aavg^2 + Bavg^2} \right] + (Aavg + Bavg) / 4 = \frac{\pi}{C1 * \mu0 * Nc^p} \end{aligned} \right]$$

In case the A matrix is  $\begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$

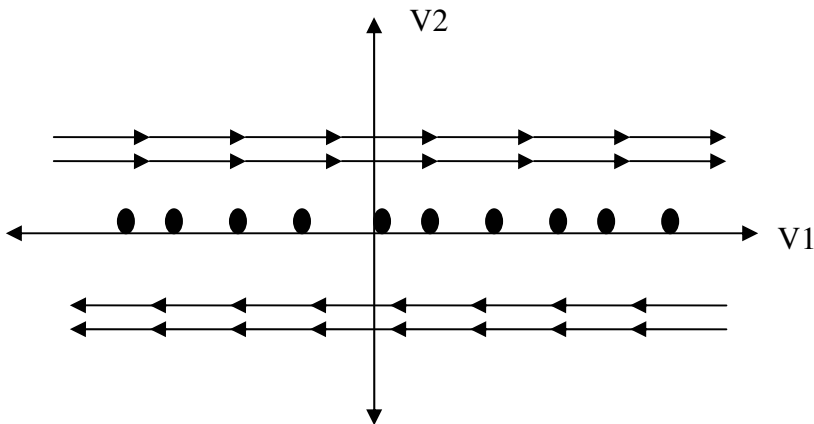


Fig. 6.

to fulfill those A matrix conditions , the following K1, K2 condition must exist:

$$K2 \rightarrow 0, \forall \left\{ -\frac{1}{C1 * R1} \right\} \rightarrow 0, \forall C1, R1 \rightarrow \infty$$

$$K1 = 0, \forall \left\{ -\frac{1}{C1 * \left[ \frac{\mu0}{\pi} * [X1 + X2 - X3 + X4] * Nc^p \right]} \right\} = 0$$

$$C1 * \left[ \frac{\mu0}{\pi} * [X1 + X2 - X3 + X4] * Nc^p \right] \rightarrow \infty$$

#### 4. RFID TAG behavior based on eigensolutions and eigenvalues characterization

Sketch a typical phase portrait for the case

$$\lambda_2 < \lambda_1 < 0$$

$$\frac{1}{2} * K_2 - \frac{1}{2} * \sqrt{K_2^2 + 4 * K_1} < \frac{1}{2} * K_2 + \frac{1}{2} * \sqrt{K_2^2 + 4 * K_1} < 0$$

$$\lambda_1 < 0 \dots \rightarrow \dots - K_2 > \sqrt{K_2^2 + 4 * K_1}$$

$$-\left\{ \frac{1}{C_1 * R_1} \right\} > \sqrt{\left\{ \frac{1}{C_1 * R_1} \right\}^2 + 4 * \left\{ -\frac{1}{C_1 * \left[ \frac{\mu_0}{\pi} * [X_1 + X_2 - X_3 + X_4] * N_c^p \right]} \right\}}$$

$$\frac{1}{C_1 * R_1} > \sqrt{\left\{ \frac{1}{C_1 * R_1} \right\}^2 - \left\{ \frac{4}{C_1 * \left[ \frac{\mu_0}{\pi} * [X_1 + X_2 - X_3 + X_4] * N_c^p \right]} \right\}}$$

$$\lambda_2 < \lambda_1$$

$$\frac{1}{2} * K_2 - \frac{1}{2} * \sqrt{K_2^2 + 4 * K_1} < \frac{1}{2} * K_2 + \frac{1}{2} * \sqrt{K_2^2 + 4 * K_1}$$

$$0 < \sqrt{K_2^2 + 4 * K_1} \dots \rightarrow \dots K_2^2 + 4 * K_1 > 0 \dots \rightarrow \dots K_2^2 > -4 * K_1$$

$$\left\{ \frac{1}{C_1 * R_1} \right\}^2 > -4 * \left\{ -\frac{1}{C_1 * \left[ \frac{\mu_0}{\pi} * [X_1 + X_2 - X_3 + X_4] * N_c^p \right]} \right\}$$

$$\left\{ \frac{1}{C_1 * R_1} \right\}^2 > \frac{4}{C_1 * \left[ \frac{\mu_0}{\pi} * [X_1 + X_2 - X_3 + X_4] * N_c^p \right]}$$

Then both eigensolutions decay exponentially. The fixed point is a stable node, except eigenvectors are not mutually perpendicular, in general. Trajectories typically approach the origin tangent to the slow eigendirection, defined as the direction spanned by the eigenvector with the smaller  $|\lambda|$ . In backward time  $t \rightarrow \infty$  the trajectories become parallel to the fast eigendirection.

if we reverse all the arrows in the above figure, we obtain a typical phase portrait for an unstable node. Now I investigate the case when eigenvalues are complex number. If the eigenvalues are complex, the fixed point is either a center or a spiral. The origin is surrounded by a family of closed orbits. Note that centers are neutrally stable, since nearby trajectories are neither attracted to nor repelled from the fixed point. A spiral would occur if the RFID sys were lightly damped. Then the trajectory would just fail to close, because the RFID sys loses a bit of energy on each cycle. To justify these statements, recall that the eigenvalues are

$$\lambda_{1,2} = \frac{1}{2} * K_2 \pm \frac{1}{2} * \sqrt{K_2^2 + 4 * K_1}$$

$$K_2^2 + 4 * K_1 < 0$$

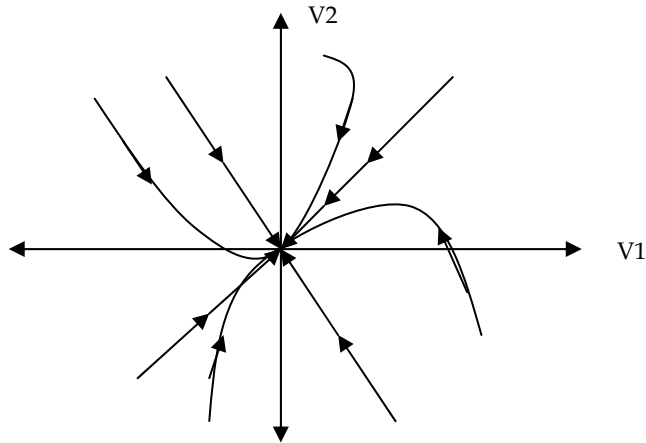


Fig. 7.

To simplify the notation, lets write the eigenvalues as

$$\lambda_{1,2} = \alpha \pm i\omega, \alpha = \frac{1}{2} * K2, \omega = -\frac{1}{2} * \sqrt{K2^2 + 4 * K1}$$

$$\omega \neq 0 \dots \exists V(t) = C1 * e^{\left[\frac{1}{2} * K2 + \frac{1}{2} * \sqrt{K2^2 + 4 * K1}\right] * t} * S1 + C2 * e^{\left[\frac{1}{2} * K2 - \frac{1}{2} * \sqrt{K2^2 + 4 * K1}\right] * t} * S2$$

C's, S's...complex,...since,...λ's...complex

$$V(t) = C1 * e^{\alpha * t} * S1 + C2 * e^{-\alpha * t} * S2$$

Euler's formula...  $\rightarrow \dots e^{i\omega * t} = \cos[\omega * t] + i * \sin[\omega * t]$

Hence V(t) is a combination of terms involving

$$e^{\alpha * t} * \cos[\omega * t], e^{\alpha * t} * \sin[\omega * t]$$

Such terms represent exponentially decaying oscillations if  $\alpha = \text{Re}(\lambda) < 0$

And growing if  $\alpha > 0$ . The corresponding fixed points are stable and unstable spirals, respectively. If the eigenvalues are pure imaginary  $\alpha = 0$ , then all the solutions are

periodic with period  $T = \frac{2 * \pi}{\omega}$ . The oscillators have fixed amplitude and the fixed point is center. For both centers and spirals, its easy to determine whether the rotation is clockwise or counterclockwise.

$$\alpha = \frac{1}{2} * K2 = \left\{ -\frac{1}{2 * C1 * R1} \right\}$$

$$\text{Decaying..oscillators..}\forall \dots \alpha < 0 \rightarrow \left\{ -\frac{1}{2 * C1 * R1} \right\} < 0 \rightarrow \frac{1}{2 * C1 * R1} > 0$$

$$\text{Growing..oscillators..}\forall \dots \alpha > 0 \rightarrow \left\{ -\frac{1}{2 * C1 * R1} \right\} > 0 \rightarrow \frac{1}{2 * C1 * R1} < 0$$

C1, R1 > 0 always then only the first behavior, decaying oscillator can exist in our RFID system.

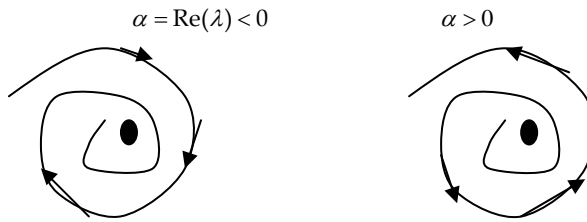


Fig. 8.

In all analysis until now, we have been assuming that the eigenvalues are distinct. What happens if the eigenvalues are equal? Suppose eigenvalues are equal  $\lambda_1 = \lambda_2 = \lambda$  then there are two possibilities: either there are two independent eigenvectors corresponding to  $\lambda$ , or there's only one. If there are two independent eigenvectors, then they span the plane and so every vector is an eigenvector with this same eigenvalue  $\lambda$ . To see this, let's write an arbitrary vector  $X_0$  as a linear combination of the two eigenvectors:  $X_0 = C_1 * S_1 + C_2 * S_2$ . Then

$$A * X_0 = A * (C_1 * S_1 + C_2 * S_2) = C_1 * \lambda * S_1 + C_2 * \lambda * S_2 = \lambda * X_0$$

$X_0$  is also an eigenvector with eigenvalue  $\lambda$ . Since the multiplication by  $A$  simply stretches every vector by a factor  $\lambda$ , the matrix must be a multiple of the identity:

$A = \begin{bmatrix} \lambda & 0 \\ 0 & \lambda \end{bmatrix}$  then if  $\lambda \neq 0$ , all trajectories are straight lines through the origin

$X(t) = e^{\lambda t} * X_0$  and the fixed point is a star node. On the other hand, if  $\lambda = 0$  the whole plane is filled with fixed points.

Let's now sketch the above options with RFID Overall parameters restriction.

$\lambda_1 = \lambda_2 = \lambda \neq 0$  then

$$\begin{aligned} \frac{1}{2} * K_2 + \frac{1}{2} * \sqrt{K_2^2 + 4 * K_1} &= \frac{1}{2} * K_2 - \frac{1}{2} * \sqrt{K_2^2 + 4 * K_1} \\ \sqrt{K_2^2 + 4 * K_1} &= 0 \rightarrow K_2^2 + 4 * K_1 = 0 \rightarrow K_2^2 = -4 * K_1 \\ \frac{\mu^0}{\pi} * [X_1 + X_2 - X_3 + X_4] * N_c^p &= C_1 * 4 * R_1^2 \end{aligned}$$

Now let's summarize the classification of fixed points in RFID system based on all investigation I did. It is easy to show the type and stability of all the different fixed points on a single diagram.

$$\tau^2 - 4 * \Delta = K_2^2 + 4 * K_1 = 0, \rightarrow K_2 = 2 * \sqrt{-K_1}$$

$$\tau = \text{trace}(A) = K_2, \Delta = \det(A) = -K_1$$

$$\lambda^2 - K_2 * \lambda - K_1 = 0, \lambda_{1,2} = \frac{1}{2} * \left[ \tau \pm \sqrt{\tau^2 - 4 * \Delta} \right]$$

$$\tau = \lambda_1 + \lambda_2 = K_2, \Delta = \lambda_1 * \lambda_2 = -K_1$$

$$\text{Characteristic equation...} (\lambda - \lambda_1) * (\lambda - \lambda_2) = \lambda^2 - \tau * \lambda + \Delta = 0$$

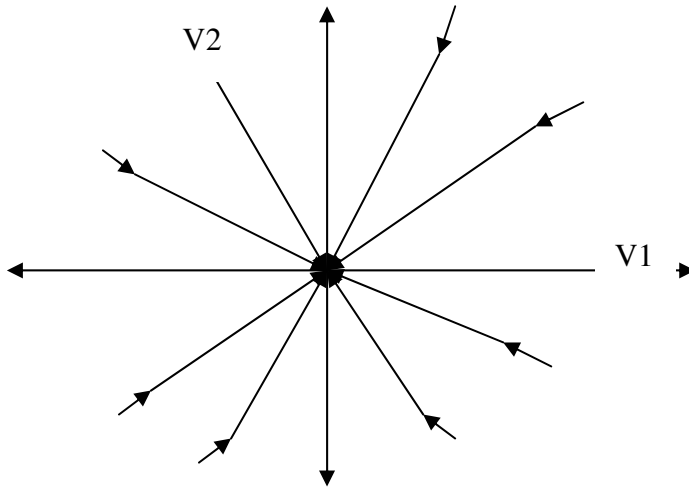


Fig. 9.

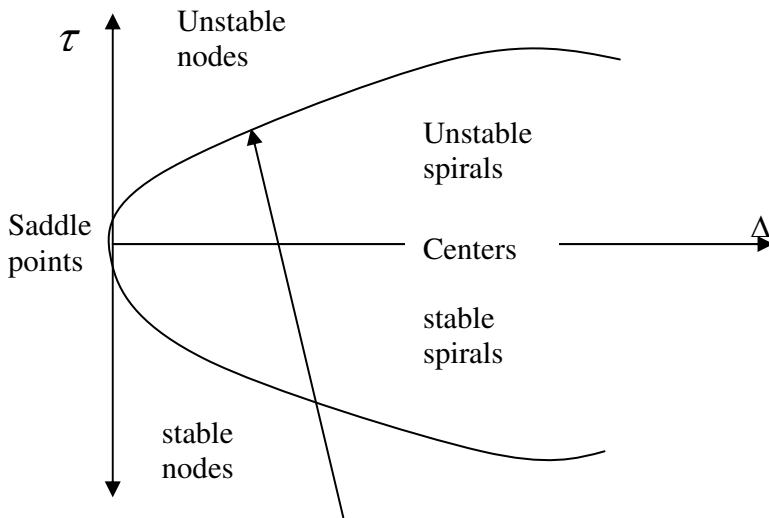


Fig. 10.

$\Delta < 0 \dots (K1 > 0)$	$\Delta > 0 \dots (K1 < 0)$	$\Delta = 0 \dots (K1 = 0)$
The eigenvalues are real and have opposite sign hence the fixed point is a saddle point,	The eigenvalues are either real with the same sign (nodes), or complex conjugate (spiral & centers).	At least one of the eigenvalues is zero. Then the origin is not an isolated fixed point. There is either a whole line of a fixed points, or a plane of fixed point

Table 2.

Nodes satisfy  $\tau^2 - 4*\Delta > 0$  and spirals satisfy  $\tau^2 - 4*\Delta < 0$ . The parabola  $\tau^2 - 4*\Delta = 0$  is the borderline between nodes and spirals. Star nodes and degenerate nodes live on this parabola. The stability of the nodes and spirals is determined by  $\tau$  value. When  $\tau < 0$ , both eigenvalues have negative real parts, so the fixed point is stable. Unstable spirals and nodes have  $\tau > 0$ . Neutrally stable centers live on the borderline  $\tau = 0$ , where eigenvalues are purely imaginary.

### 5. RFID system phase plan

For our RFID system the general form of a vector field on the phase plan is

$$\dot{V}_1 = f_1(V_1, V_2)$$

$$\dot{V}_2 = f_2(V_1, V_2)$$

Where  $V_1$  is the voltage on RFID system ( $V$ ) and  $V_2$  is the derivative of that voltage respect with time ( $dV/dt$ ). The  $f_1$  and  $f_2$  are given functions and this system can be written more compactly in vector notation as:

$$\frac{dV}{dt} = f(V)$$

Where  $V=(V_1, V_2)$  and  $f(V)=(f_1(V), f_2(V))$ . Here  $V$  represents a point in the phase plane (RFID voltage at time  $t$ ), and  $dV/dt$  is the voltage change in time at that point. By flowing the vector field, a phase point traces out a solution  $V(t)$ , corresponding to a trajectory winding through the phase plan.

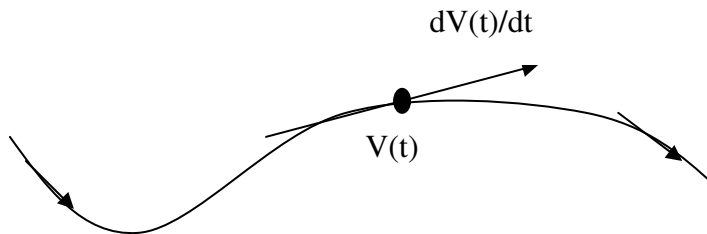


Fig. 11.

Furthermore, the entire phase plane is filled with trajectories, since each point can play the role of an initial condition. The most salient features of phase portrait are:

1. Fixed points satisfy  $f(V^*)=0$ , and correspond to steady states or equilibria of the system.
2. The closed orbits, these correspond to periodic solutions, i.e. solutions for which  $V(t+T) = V(t)$  for all  $t$  values, and  $T>0$ .
3. The stability or instability of the fixed points and closed orbits. Some fixed points are unstable, because nearby trajectories tend to move away from them, where the closed orbit is stable.

Now lets sketch the numerical computation of RFID phase portraits. Using Runge - Kutta method, which in vector form is the following:

$$\begin{aligned}
 V_{n+1} &= V_n + \frac{1}{6} * (\zeta_1 + 2 * \zeta_2 + 2 * \zeta_3 + \zeta_4) \\
 \zeta_1 &= f(V_n) * \Delta t \\
 \zeta_2 &= f(V_n + \frac{1}{2} * \zeta_1) * \Delta t \\
 \zeta_3 &= f(V_n + \frac{1}{2} * \zeta_2) * \Delta t \\
 \zeta_4 &= f(V_n + \zeta_3) * \Delta t \\
 \Delta t &= 0.1 \dots (\text{stepsize})
 \end{aligned}$$

The step 0.1 usually provides sufficient accuracy for our RFID system. When plotting the phase portrait, there is a grid of representative vectors in the vector field. The arrowheads and different lengths of the vectors tend to clutter such pictures. A plot of the direction field is clearer, short line segments are used to indicate the local direction of flow. Existence and Uniqueness of RFID system: We consider in our system the initial state  $dV/dt=f(V)$  and  $V(0)=V_0$  which is the initial RFID voltage before investigation the system dynamic change with time. Suppose that  $f$  is continuous and that all partial derivatives

$$\frac{\partial f_i}{\partial V_j}, i, j = 1, 2, \dots, n$$

Are continuous for  $V$  in some open connected set  $D \subset \mathbb{R}^n$ . Then for  $V_0 \in D$ , the initial value problem has a solution  $V(t)$  on some time interval about  $t=0$ , and the solution is unique. Existence and uniqueness of solutions are guaranteed if  $f$  is continuously differentiable. We will assume that all our vector fields are smooth enough to ensure the existence and uniqueness of solutions, starting from any point in the RFID phase space. The existence and uniqueness theorem has an important corollary, different trajectories never intersect. If two trajectories did intersect, then there would be two solutions starting from the same point (the crossing point) and would violate the uniqueness part of the theorem. Trajectories cant move in two directions at once in our RFID system. Because trajectories cant intersect, phase portraits always have a well groomed look to them. Otherwise they might degenerate into a snarl of criss crossed curves and the existence and uniqueness theorem prevents this from happening. In our RFID two dimensional phase spaces, these results have especially strong topological consequences. For example, suppose there is a closed orbit behavior

in the RFID phase plan. Then any trajectory starting inside the closed orbit is trapped in there forever. If there are fixed points inside that closed orbit, then of course the trajectory might eventually approach one of them. For vector fields on the plane, the Poincare-Bendixson theorem states that if a trajectory is confined to a closed, bounded region and there are no fixed points in the region, then trajectory must eventually approach a closed orbit. Now Lets suppose that  $V1^*$  and  $V2^*$  is fixed point  $(V1^*, V2^*)$  then we get

$$\begin{aligned}
 f_1(V1^*, V2^*) &= 0 \\
 f_2(V1^*, V2^*) &= 0
 \end{aligned}$$

Lets.....

$$\xi_1 = V1 - V1^*$$

$$\xi_2 = V2 - V2^*$$

$\xi_1, \xi_2$  - denote the components of a small disturbance from the fixed point. To see whether the disturbance grows or decays, we need to derive differential equations for  $\xi_1, \xi_2$ . Lets do the  $\xi_1$  equation first.

$$\begin{aligned} \dot{\xi}_1 &= \dot{V}_1 = f1(V1^* + \xi_1, V2^* + \xi_2) = \\ &f1(V1^*, V2^*) + \xi_1 * \frac{\partial f1}{\partial V1} + \xi_2 * \frac{\partial f1}{\partial V2} + O(\xi_1^2, \xi_2^2, \xi_1 * \xi_2) \\ \forall \dots f1(V1^*, V2^*) &= 0 \dots \text{Fixed..point..condition} \\ f1 &= V2, f2 = V1 * K1 + V2 * K2 \\ \frac{\partial f1}{\partial V1} &= 0, \frac{\partial f1}{\partial V2} = 1 \end{aligned}$$

Similarly we can write:

$$\begin{aligned} \dot{\xi}_2 &= \dot{V}_2 = f2(V1^* + \xi_1, V2^* + \xi_2) = \\ &f2(V1^*, V2^*) + \xi_1 * \frac{\partial f2}{\partial V1} + \xi_2 * \frac{\partial f2}{\partial V2} + O(\xi_1^2, \xi_2^2, \xi_1 * \xi_2) \\ \forall \dots f2(V1^*, V2^*) &= 0 \dots \text{Fixed..point..condition} \\ f1 &= V2, f2 = V1 * K1 + V2 * K2 \\ \frac{\partial f2}{\partial V1} &= K1, \frac{\partial f2}{\partial V2} = K2 \end{aligned}$$

Hence the disturbance  $\xi_1, \xi_2$  evolve according to

$$\begin{aligned} &\xi_1, \xi_2 \\ \begin{bmatrix} \dot{\xi}_1 \\ \dot{\xi}_2 \end{bmatrix} &= \begin{bmatrix} \frac{\partial f1}{\partial V1} & \frac{\partial f1}{\partial V2} \\ \frac{\partial f2}{\partial V1} & \frac{\partial f2}{\partial V2} \end{bmatrix} * \begin{bmatrix} \xi_1 \\ \xi_2 \end{bmatrix} + \text{Quadratic..terms} \end{aligned}$$

Matrix

$$A = \begin{bmatrix} \frac{\partial f1}{\partial V1} & \frac{\partial f1}{\partial V2} \\ \frac{\partial f2}{\partial V1} & \frac{\partial f2}{\partial V2} \end{bmatrix}_{(V1^*, V2^*)}$$



Linearized..system

$$\begin{bmatrix} \dot{\xi}_1 \\ \dot{\xi}_2 \end{bmatrix} = \begin{bmatrix} \frac{\partial f1}{\partial V1} & \frac{\partial f1}{\partial V2} \\ \frac{\partial f2}{\partial V1} & \frac{\partial f2}{\partial V2} \end{bmatrix} * \begin{bmatrix} \xi_1 \\ \xi_2 \end{bmatrix}$$

As we move from one dimensional to two dimensional systems, still fixed points can be created or destroyed or destabilized as parameters are varied – in our system RFID global TAG parameters. We can describe the ways in which oscillations can be turned on or off. The exact meaning of bifurcation is: if the phase portrait changes its topological structure as a parameter is varied, we say that a bifurcation has occurred. Examples include changes in the number or stability of fixed points, close orbits, or saddle connections as a parameter is varied.

### 6. RFID TAG with losses as a dynamic system

RFID TAG system is not an ideal and pure solution. There are some Losses which need to be under consideration. The RFID TAG losses can be represent first by the equivalent circuit. The main components of RFID TAG simple equivalent circuit are Capacitor in Parallel to Resistor and additional Parallel inductance (Antenna Unit). The RFID equivalent circuit Under Losses consideration is as describe below:

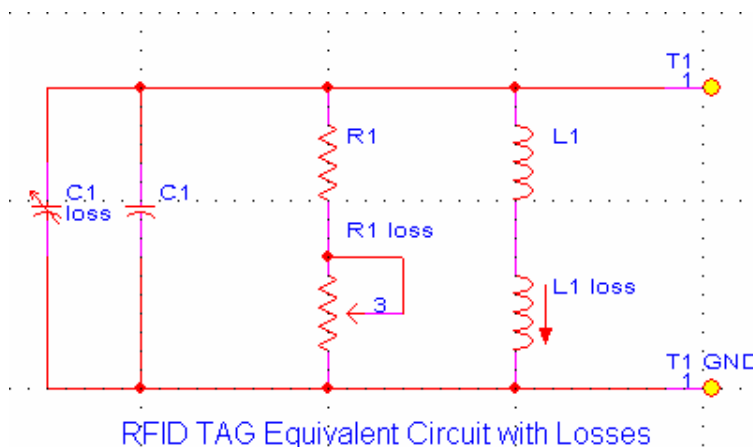


Fig. 12.

C1loss, R1loss and L1loss need to be tuned until we get the desire and optimum dynamic behavior of RFID system. Now, Lets investigate the RFID TAG system under those losses. The C1, R1, L1 (Lcalc) move value displacement due to those losses: C1 >> C1+C1loss, R1 >> R1+R1loss, L1 >> L1+L1loss. We consider in all analysis that L1 is Lcalc and depend in many parameters.

$$L_{calc} = L_{calc}(X1, X2, X3, X4, N_c^p) = \left[ \frac{\mu_0}{\pi} * [X1 + X2 - X3 + X4] * N_c^p \right]$$

$$X1 \rightarrow X1 + X1_{loss}, X2 \rightarrow X2 + X2_{loss}$$

$$X3 \rightarrow X3 + X3_{loss}, X4 \rightarrow X4 + X4_{loss}$$

$$\text{then....}L_{calc} \rightarrow L_{calc} + L_{calc_{loss}}$$

*Lets..go..back..to..each..RFID..Coil..Parameter..and..his..loss..value*

$$d \rightarrow d + d_{loss}, \dots A_{avg} \rightarrow A_{avg} + A_{avg_{loss}}, \dots B_{avg} \rightarrow B_{avg} + B_{avg_{loss}}$$

$$a_0 \rightarrow a_0 + a_{0_{loss}}, \dots b_0 \rightarrow b_0 + b_{0_{loss}}, \dots t \rightarrow t + t_{loss}, w \rightarrow w + w_{loss}$$

$$g \rightarrow g + g_{loss}$$

Now Lets sketch the  $X1 \dots X4$  graphs depend on  $A_{avg}$  and  $B_{avg}$ :

$X1 = X1(A_{avg}, B_{avg})$ ,  $X2 = X2(A_{avg}, B_{avg})$ ,  $X3 = X3(A_{avg}, B_{avg})$ ,

$X4 = X4(A_{avg}, B_{avg})$ .

$$X1 = A_{avg} * \ln \left( \frac{2 * A_{avg} * B_{avg}}{d * (A_{avg} + \sqrt{A_{avg}^2 + B_{avg}^2})} \right) = X1(A_{avg}, B_{avg}), \text{ 3D sketch}$$

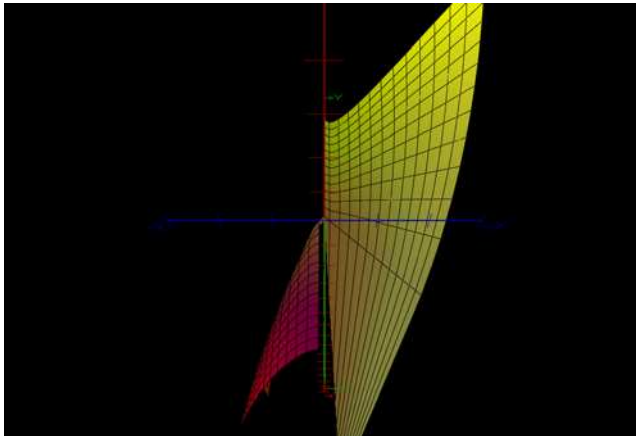


Fig. 13.

$$X2 = B_{avg} * \ln \left( \frac{2 * A_{avg} * B_{avg}}{d * (B_{avg} + \sqrt{A_{avg}^2 + B_{avg}^2})} \right) = X2(A_{avg}, B_{avg}), \text{ 3D sketch}$$

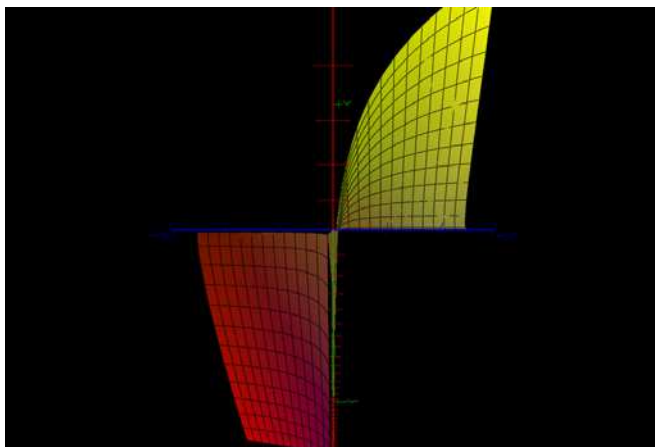


Fig. 14.

$$X3 = 2 * \left[ Aavg + Bavg - \sqrt{Aavg^2 + Bavg^2} \right] = X3(Aavg, Bavg), 3D \text{ sketch}$$

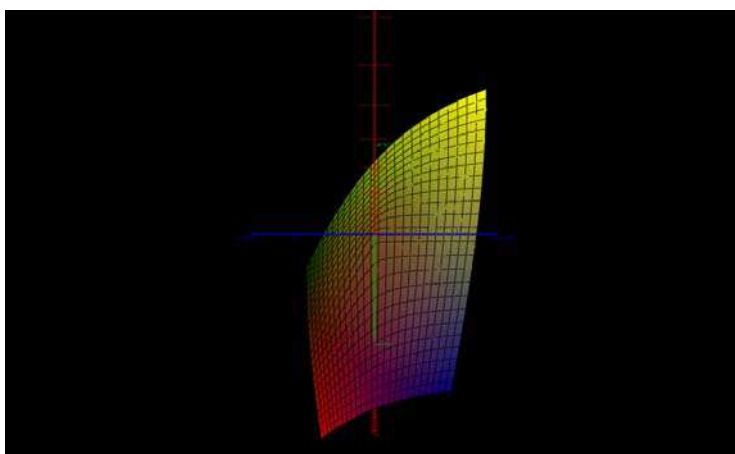


Fig. 15.

$$X4 = (Aavg + Bavg) / 4 = X4(Aavg, Bavg), 3D \text{ sketch}$$

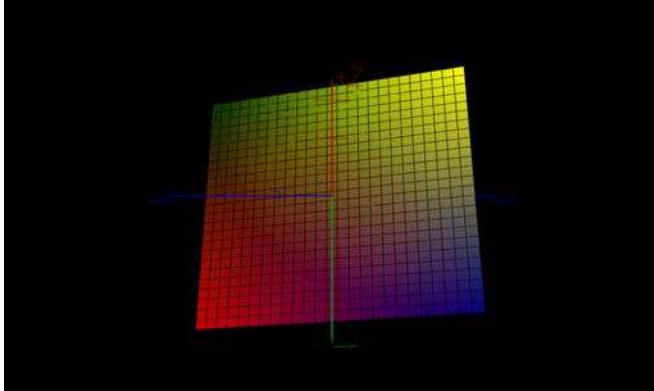


Fig. 16.

All  $X_1, \dots, X_4$  draw in one 3D coordinate system

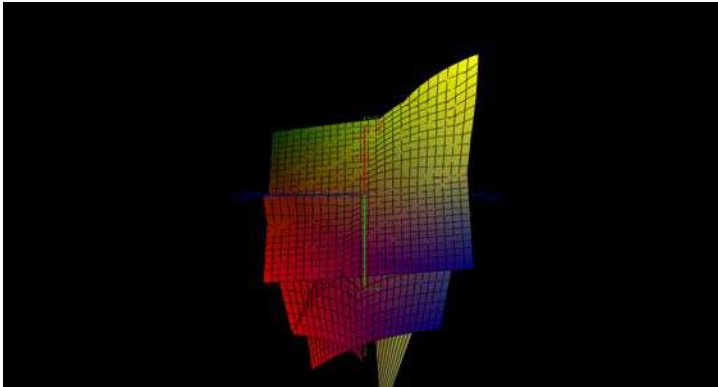


Fig. 17.

Now lets sketch 3D diagram of  $L_{calc} = L_{calc}(A_{avg}, B_{avg})$

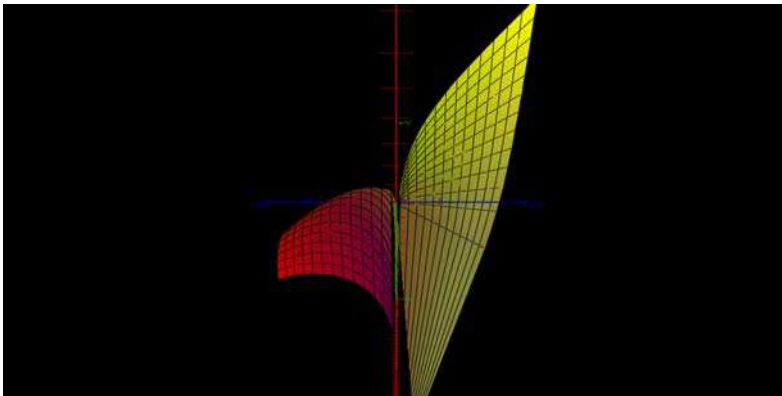


Fig. 18.

$$K1 = K1(a0, b0, w, g, d, N_c, t, p, C1, R1) = \left\{ -\frac{1}{C1 * \left[ \frac{\mu 0}{\pi} * [X1 + X2 - X3 + X4] * N C^p \right]} \right\}$$

K1 = K1(Aavg, Bavg) 3D Sketch graph:

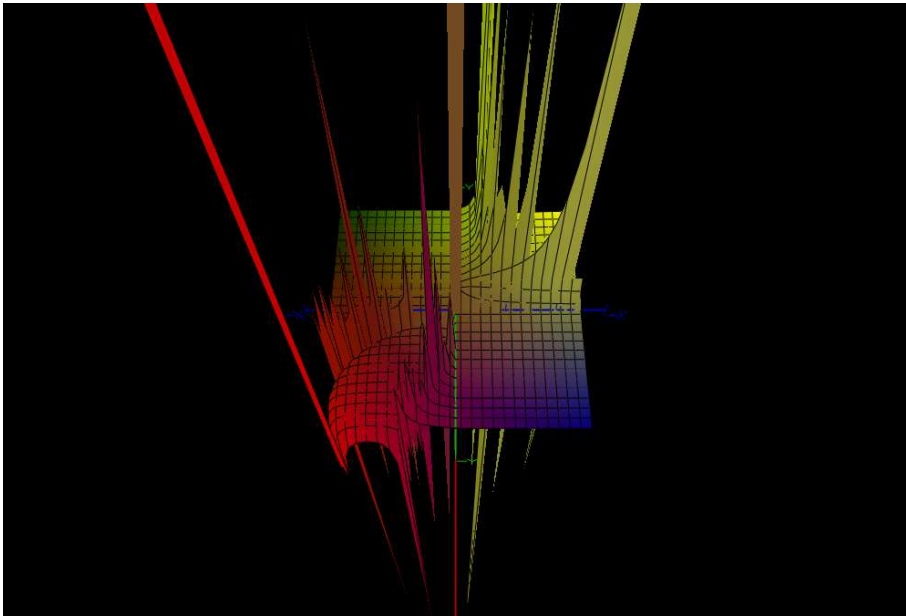


Fig. 19.

K1 is a critical function in all RFID Bifurcation system. Calculation of Aavgloss, Bavgloss and dloss gives:

$$\begin{aligned} Aavg &\rightarrow Aavg + Aavgloss = \\ a0 + a0loss - (Nc + Ncloss) * (g + gloss + w + wloss) &= \\ a0 + a0loss - Nc * g - Nc * gloss - Nc * w - Nc * wloss &= \\ -Ncloss * g - Ncloss * gloss - Ncloss * w - Ncloss * wloss &= \\ a0 - Nc * (g + w) + a0loss - Nc * (gloss + wloss) &= \\ -Ncloss * (g + gloss + w + wloss) = Aavg + a0loss - Nc * (gloss + wloss) &= \\ -Ncloss * (g + gloss + w + wloss).....then &= \\ Aavgloss = a0loss - (Nc + Ncloss) * (gloss + wloss) - Ncloss * (g + w) &= \\ \text{and..in..the..same..way..get..Bavgloss..value..Bavg} \rightarrow Bavg + Bavgloss &= \\ Bavgloss = b0loss - (Nc + Ncloss) * (gloss + wloss) - Ncloss * (g + w) &= \\ d \rightarrow d + dloss = 2 * (t + tloss + w + wloss) / \pi = d + \frac{2 * (tloss + wloss)}{\pi} &= \\ dloss = \frac{2 * (tloss + wloss)}{\pi} &= \end{aligned}$$

Lets now describe the  $X1, \dots, X4$ , Lcalc internal function parameter under Losses.

$$X1 \rightarrow X1 + X1_{loss} =$$

$$[A_{avg} + A_{avgloss}] * \ln \left[ \frac{2 * (A_{avg} + A_{avgloss})(B_{avg} + B_{avgloss})}{(d + d_{loss}) * [A_{avg} + A_{avgloss} + \sqrt{(A_{avg} + A_{avgloss})^2 + (B_{avg} + B_{avgloss})^2}]} \right] =$$

$$X1 + \ln \left[ \frac{\left\{ \frac{2 * (A_{avg} + A_{avgloss})(B_{avg} + B_{avgloss})}{(d + d_{loss}) * [A_{avg} + A_{avgloss} + \sqrt{(A_{avg} + A_{avgloss})^2 + (B_{avg} + B_{avgloss})^2}] \right\}^{[A_{avg} + A_{avgloss}]}}{d * \left[ \frac{A_{avg} + \sqrt{A_{avg}^2 + B_{avg}^2}}{2 * A_{avg} * B_{avg}} \right]^{A_{avg}}} \right]$$

$$X1_{loss} = \ln \left[ \frac{\left\{ \frac{2 * (A_{avg} + A_{avgloss})(B_{avg} + B_{avgloss})}{(d + d_{loss}) * [A_{avg} + A_{avgloss} + \sqrt{(A_{avg} + A_{avgloss})^2 + (B_{avg} + B_{avgloss})^2}] \right\}^{[A_{avg} + A_{avgloss}]}}{d * \left[ \frac{A_{avg} + \sqrt{A_{avg}^2 + B_{avg}^2}}{2 * A_{avg} * B_{avg}} \right]^{A_{avg}}} \right]$$

$$X2 \rightarrow X2 + X2_{loss} =$$

$$[B_{avg} + B_{avgloss}] * \ln \left[ \frac{2 * (A_{avg} + A_{avgloss})(B_{avg} + B_{avgloss})}{(d + d_{loss}) * [B_{avg} + B_{avgloss} + \sqrt{(A_{avg} + A_{avgloss})^2 + (B_{avg} + B_{avgloss})^2}]} \right] =$$

$$X2 + \ln \left[ \frac{\left\{ \frac{2 * (A_{avg} + A_{avgloss})(B_{avg} + B_{avgloss})}{(d + d_{loss}) * [B_{avg} + B_{avgloss} + \sqrt{(A_{avg} + A_{avgloss})^2 + (B_{avg} + B_{avgloss})^2}] \right\}^{[B_{avg} + B_{avgloss}]}}{d * \left[ \frac{B_{avg} + \sqrt{A_{avg}^2 + B_{avg}^2}}{2 * A_{avg} * B_{avg}} \right]^{B_{avg}}} \right]$$

$$X2_{loss} = \ln \left[ \frac{\left\{ \frac{2 * (A_{avg} + A_{avgloss})(B_{avg} + B_{avgloss})}{(d + d_{loss}) * [B_{avg} + B_{avgloss} + \sqrt{(A_{avg} + A_{avgloss})^2 + (B_{avg} + B_{avgloss})^2}] \right\}^{[B_{avg} + B_{avgloss}]}}{d * \left[ \frac{B_{avg} + \sqrt{A_{avg}^2 + B_{avg}^2}}{2 * A_{avg} * B_{avg}} \right]^{B_{avg}}} \right]$$

$$\begin{aligned}
 X3 &\rightarrow X3 + X3loss = \\
 2 * [Aavg + Aavgloss + Bavg + Bavgloss - \sqrt{(Aavg + Aavgloss)^2 + (Bavg + Bavgloss)^2}] &= \\
 2 * \left[ \begin{aligned} &Aavg + Bavg + (Aavgloss + Bavgloss) - \sqrt{(Aavg + Aavgloss)^2 + (Bavg + Bavgloss)^2} + \\ &\sqrt{Aavg^2 + Bavg^2} - \sqrt{Aavg^2 + Bavg^2} \end{aligned} \right] &= \\
 2 * \left[ \begin{aligned} &Aavg + Bavg - \sqrt{Aavg^2 + Bavg^2} \end{aligned} \right] + 2 * \left[ \begin{aligned} &(Aavgloss + Bavgloss) - \sqrt{(Aavg + Aavgloss)^2 + (Bavg + Bavgloss)^2} + \\ &\sqrt{Aavg^2 + Bavg^2} \end{aligned} \right] &= \\
 X3 + 2 * \left[ \begin{aligned} &(Aavgloss + Bavgloss) - \sqrt{(Aavg + Aavgloss)^2 + (Bavg + Bavgloss)^2} + \\ &\sqrt{Aavg^2 + Bavg^2} \end{aligned} \right] &= \\
 X3loss = 2 * \left[ \begin{aligned} &(Aavgloss + Bavgloss) - \sqrt{(Aavg + Aavgloss)^2 + (Bavg + Bavgloss)^2} + \\ &\sqrt{Aavg^2 + Bavg^2} \end{aligned} \right] &= \\
 X4 \rightarrow X4 + X4loss = [Aavg + Aavgloss + Bavg + Bavgloss] / 4 = \frac{Aavg + Bavg}{4} + \frac{Aavgloss + Bavgloss}{4} &= \\
 X4loss = \frac{Aavgloss + Bavgloss}{4} &=
 \end{aligned}$$

**7. Summery**

RFID TAG system can be represent as Parallel Resistor, Capacitor, and Inductance circuit. Linear bifurcation system explain RFID TAG system behavior for any initial condition V(t) and dV(t)/dt. RFID's Coil is a very critical element in RFID TAG functionality. Optimization can be achieved by Coil's parameters inspection and System bifurcation controlled by them. Spiral, Circles, and other RFID phase system behaviors can be optimize for better RFID TAG performance and actual functionality. RFID TAG losses also controlled for best performance and maximum efficiency.

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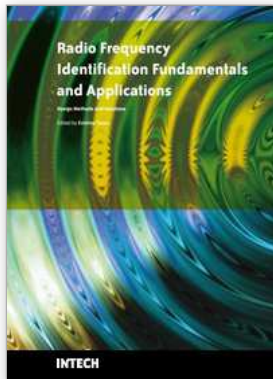
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## **Radio Frequency Identification Fundamentals and Applications Design Methods and Solutions**

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This book, entitled Radio Frequency Identification Fundamentals and Applications, Bringing Research to Practice, bridges the gap between theory and practice and brings together a variety of research results and practical solutions in the field of RFID. The book is a rich collection of articles written by people from all over the world: teachers, researchers, engineers, and technical people with strong background in the RFID area. Developed as a source of information on RFID technology, the book addresses a wide audience including designers for RFID systems, researchers, students and anyone who would like to learn about this field. At this point I would like to express my thanks to all scientists who were kind enough to contribute to the success of this project by presenting numerous technical studies and research results. However, we couldn't have published this book without the effort of InTech team. I wish to extend my most sincere gratitude to InTech publishing house for continuing to publish new, interesting and valuable books for all of us.

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