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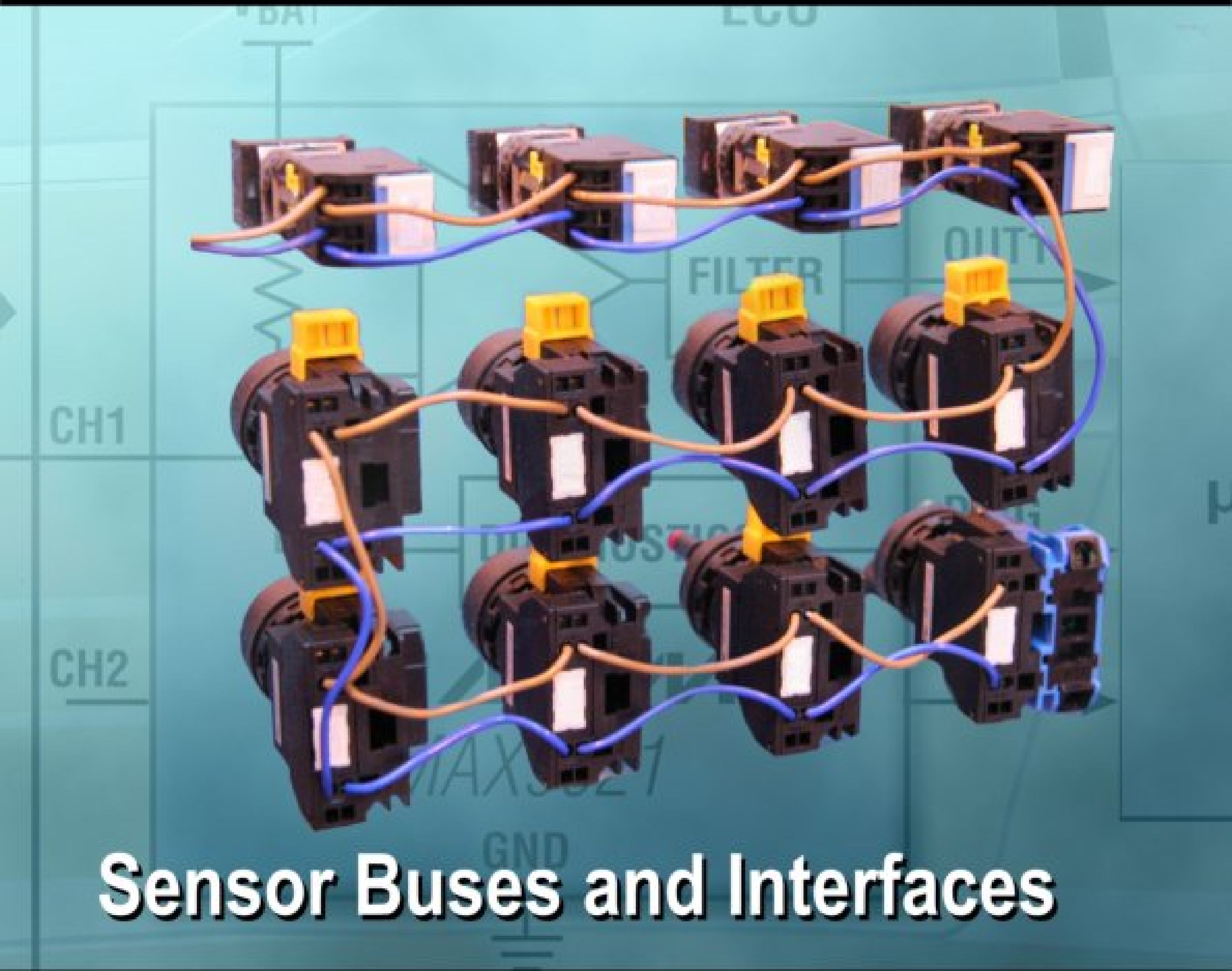

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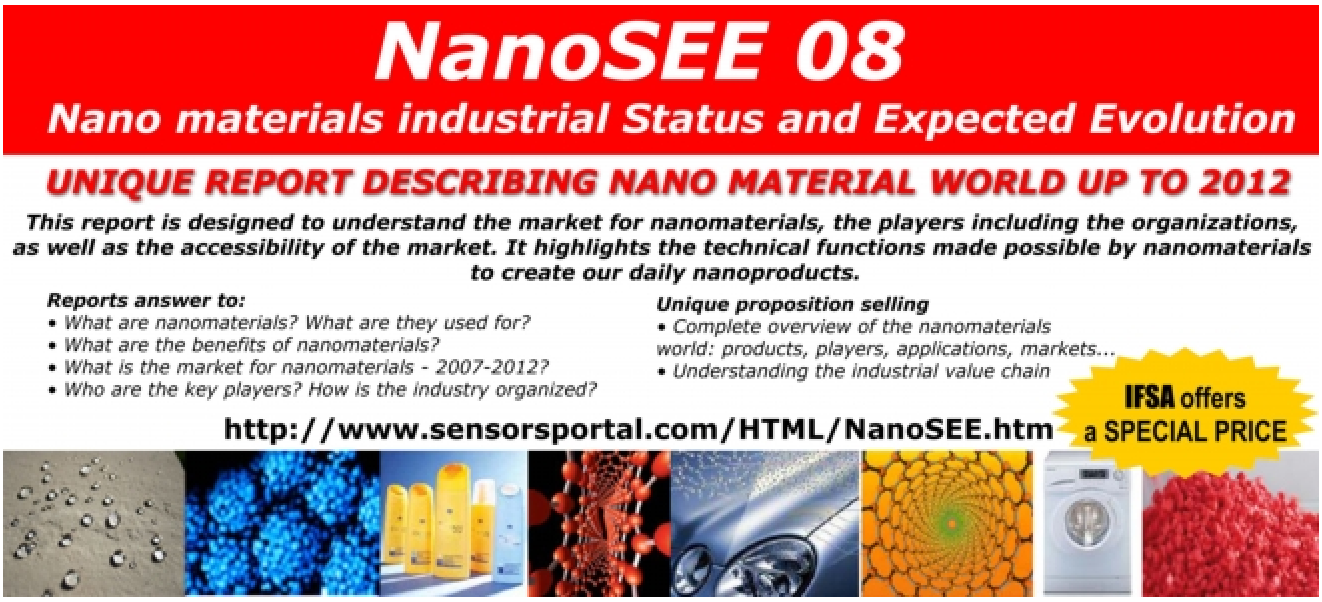
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Approximations in Calculating Stray Capacitance of Printed Spiral Inductors

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Abstract: Jia, Heuer, Hillmann, and Meyendorf recently reported some simulations of the stray capacitance of two-dimensional spiral coils of the kind often used in eddy-current sensors. In this Letter, some amendments to the analysis are suggested, together with some approximations that permit more efficient computation. *Copyright © 2010 IFSA.*

Keywords: Eddy current sensor, Matrix methods, Sparse matrix, Spiral coil, Stray capacitance

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1. Introduction

A recent paper by Jia, Heuer, Hillmann, and Meyendorf [1] presented a method of calculating the stray capacitance of a two-dimensional spiral coil. The motivation behind that work was to simulate the properties of a particular design of eddy-current sensor, but in general the method could be applicable to any design of printed spiral inductor, sense coil, or micro-actuator solenoid [2]. Such coils are also often used in RFICs, VHF and UHF amplifiers, and many other applications where conventional coil construction is an unnecessary complication if a small-value inductance is needed.

The method consists of an approximation whereby the gradual radius change with polar angle in a true spiral coil is modelled as a set of concentric circles, each having the same parameters as one turn of the spiral. With trivial modification, the method is in principle applicable to printed coils of square or rectangular (or other polygon) basic shape, in which case the base calculation of capacitance as a function of circle parameters are replaced by similar calculations as a function of square, rectangle, or polygon parameters.

Having modelled the spiral as a set of successive circular electrodes, the capacitances between all pairs of electrodes was then evaluated using a finite-element package (ANSYS). The overall stray capacitance was then evaluated essentially as the Thévenin equivalent of the resultant network; matrix methods permit some simplification of the required algebra. Jia, Heuer, Hillmann, and Meyendorf [1] were able to find the behaviour of the capacitance as a function of several parameters, such as number of turns, printed track width, printed track thickness, the inside diameter of the spiral or smallest circle in the replacement network, the spiral pitch, and the substrate thickness.

In the present paper, some amendments to the previous analysis are presented, together with approximations that improve the efficiency of the method.

2. Details of Model

The details of the method are illustrated in Fig. 1, modified from the equivalent diagram (Fig. 4) in Ref. [1]. Each node represents a single turn of the original spiral coil, and each capacitance has a value dependent upon the coil fabrication parameters. The overall capacitance is obtained by evaluating the combined effect of all the capacitors in the network. The main differences between the present Fig. 1 and Fig. 4 from Ref. [1] are the elimination of an unnecessary subscript in the node voltage symbols here, and more logical labelling of capacitances between V_0 and each device node. Also note that for the model as developed in Ref. [1], busbar V_0 cannot represent ground as the calculation requires that the current reaching terminal A is the same as that leaving terminal B, which is not necessarily the case if V_0 is the system ground. Assigning $V_0 = 0$ is purely an analytical convenience and does not imply that V_0 is the system ground, since only the *differences* of voltage are important in this calculation. If V_0 is in fact a ground plane (as is sometimes the case for a printed inductor on a circuit board) then the stray capacitance cannot be represented as a single component.

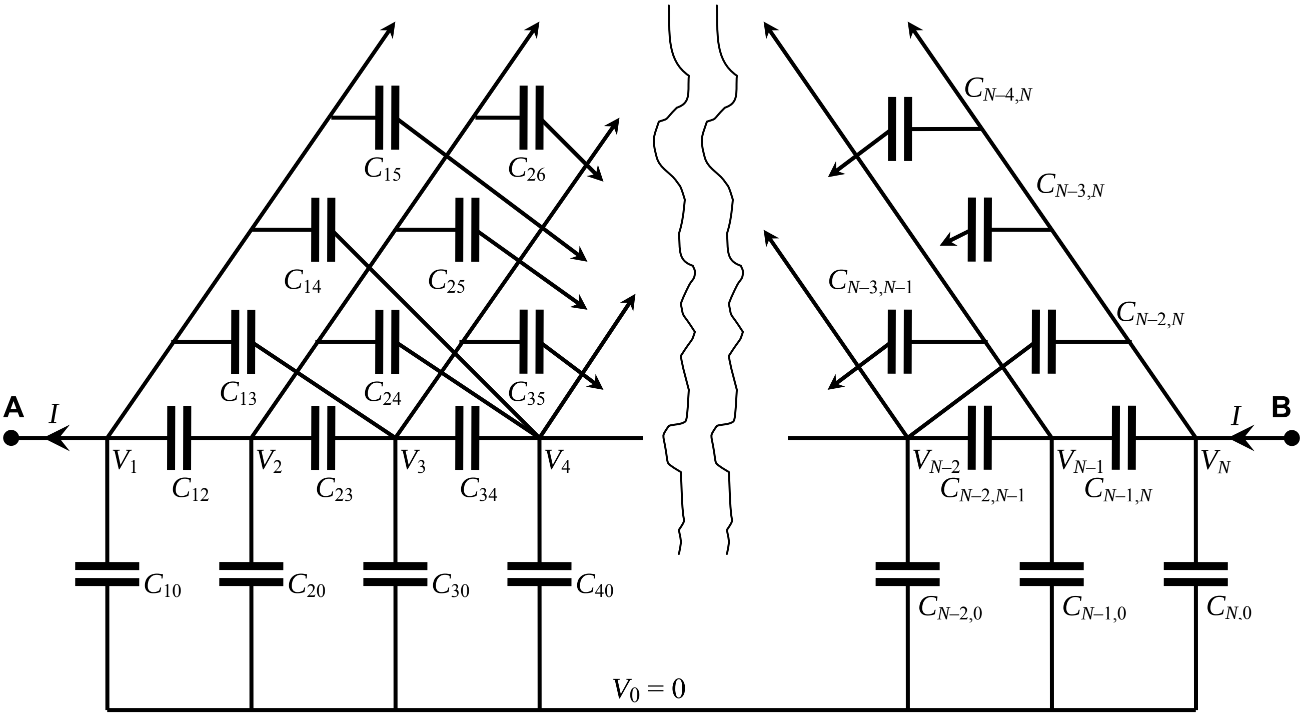

Fig. 1. Lumped capacitance network model of a printed spiral coil (modified from Fig. 4 of Ref. [1]).

The effect of any one particular capacitance is given by the equation

$$Y_{pq}(V_p - V_q) = I_{pq} \tag{1}$$

where I_{pq} is the current through capacitor C_{pq} directed from node p to node q, and

$$Y_{pq} = Y_{qp} = j\omega C_{pq} = j\omega C_{qp} \tag{2}$$

is the complex admittance of this capacitor (and the square root of (–1) = j appears to have been omitted from the definition of Y_{pq} in Ref. [1]). Therefore, since the net current flowing into each node must be zero,

$$\sum_{q=0}^{q=N} j\omega C_{pq}(V_p - V_q) = \begin{cases} -I \ (\text{for } p = 1) \\ 0 \ (p \neq 1,\ p \neq N) \\ I \ (\text{for } p = N) \end{cases} \tag{3}$$

or, in matrix form:

$$j\omega \begin{bmatrix} (C_{10}+C_{12}+\cdots+C_{1N}) & -C_{12} & \cdots\cdots & -C_{1N} \\ -C_{21} & (C_{20}+C_{21}+\cdots+C_{2N}) & \cdots\cdots & -C_{2N} \\ -C_{31} & -C_{32} & \cdots\cdots & -C_{3N} \\ \vdots & \vdots & \cdots\cdots & \vdots \\ \vdots & \vdots & \cdots\cdots & \vdots \\ -C_{N1} & -C_{N2} & \cdots\cdots & (C_{N0}+C_{N1}+\cdots+C_{N,N-1}) \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ \vdots \\ \vdots \\ V_N \end{bmatrix} = \begin{bmatrix} -I \\ 0 \\ 0 \\ \vdots \\ \vdots \\ +I \end{bmatrix}, \tag{4}$$

or, since the capacitance values are independent of the subscript order, the matrix is symmetrical:

$$j\omega \begin{bmatrix} (C_{10}+C_{12}+\cdots+C_{1N}) & -C_{12} & \cdots\cdots & -C_{1N} \\ -C_{12} & (C_{20}+C_{12}+\cdots+C_{2N}) & \cdots\cdots & -C_{2N} \\ -C_{13} & -C_{23} & \cdots\cdots & -C_{3N} \\ \vdots & \vdots & \cdots\cdots & \vdots \\ \vdots & \vdots & \cdots\cdots & \vdots \\ -C_{1N} & -C_{2N} & \cdots\cdots & (C_{N0}+C_{1N}+\cdots+C_{N-1,N}) \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ \vdots \\ \vdots \\ V_N \end{bmatrix} = \begin{bmatrix} -I \\ 0 \\ 0 \\ \vdots \\ \vdots \\ +I \end{bmatrix}. \tag{5}$$

At this point, note that the equivalent equation in Ref. [1] is their Eqn. (1) where the off-diagonal matrix elements have their negative sign omitted apparently in error. Assuming a non-singular matrix, the node voltages may be found formally by matrix inversion:

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ \vdots \\ \vdots \\ V_N \end{bmatrix} = \begin{bmatrix} (C_{10}+C_{12}+\cdots+C_{1N}) & -C_{12} & \cdots\cdots & -C_{1N} \\ -C_{12} & (C_{20}+C_{12}+\cdots+C_{2N}) & \cdots\cdots & -C_{2N} \\ -C_{13} & -C_{23} & \cdots\cdots & -C_{3N} \\ \vdots & \vdots & \cdots\cdots & \vdots \\ \vdots & \vdots & \cdots\cdots & \vdots \\ -C_{1N} & -C_{2N} & \cdots\cdots & (C_{N0}+C_{1N}+\cdots+C_{N-1,N}) \end{bmatrix}^{-1} \begin{bmatrix} -I/(j\omega) \\ 0 \\ 0 \\ \vdots \\ \vdots \\ +I/(j\omega) \end{bmatrix}, \tag{6}$$

or, in symbolic form,

$$\mathbf{V} = \mathbf{C}^{-1}\mathbf{S}, \tag{7}$$

where **V** and **C** are the voltage vector and capacitance matrix respectively, and **S** is the column vector defined by

$$\mathbf{S}^{\mathrm{T}} = [-I/(j\omega)\ 0\ 0\ \cdots\ \cdots\ +I/(j\omega)] \tag{8}$$

(where $^{\mathrm{T}}$ indicates transpose). Given an external current I, the equivalent capacitance C formed by the network is defined by

$$C(V_N - V_1) = I/(j\omega), \tag{9}$$

equivalent to Eqn. (3) of Ref. [1] except that the factor ($j\omega$) is omitted there. Because the column vector **S** is sparse (i.e., it contains only two non-zero elements), only the four corner elements of the matrix inverse $\mathbf{C}^{-1}$ need to be evaluated to find V_N and V_1. Furthermore, since the matrix **C** is symmetrical about its leading diagonal, then its inverse $\mathbf{C}^{-1}$ will also be symmetrical[*], so that only three elements of the inverse actually need to be calculated as two corner elements are identical:

$$V_N - V_1 = \left[(\mathbf{C}^{-1})_{11} + (\mathbf{C}^{-1})_{NN} - 2(\mathbf{C}^{-1})_{1N}\right]\frac{I}{j\omega}, \tag{10}$$

or,

$$C = \frac{1}{(\mathbf{C}^{-1})_{11} + (\mathbf{C}^{-1})_{NN} - 2(\mathbf{C}^{-1})_{1N}} \tag{11}$$

(exact, within this model). In addition, for a large number of coil turns the leading diagonal elements of **C** will be much larger in magnitude than the off-diagonal terms, so that some approximations may be made. First, it is noted that the inverse of any square matrix is the transpose of the matrix of the determinants formed by the cofactors divided by the determinant of the entire original matrix **C** [3]. Next, it is clear from the numerical results [1] that the values of C_{pq} for $q = 0$ or for $|p - q| = 1$ are much larger than for $|p - q| > 1$ and $q \neq 0$. This means that all the matrix elements on the leading diagonal of **C** are significant, the elements on the diagonals immediately above and below the leading diagonal are less significant, but the remaining elements of **C** may be ignored to a good approximation. The most efficient evaluation of the three required corner elements of $\mathbf{C}^{-1}$ then depends upon the degree of precision needed. In the simplest approximation, all but the leading diagonal elements of **C** may be ignored (essentially setting them to zero). In this case, the determinant of **C** is approximately equal to the product of all its leading diagonal elements, and

---

[*] For any non-singular matrix **M**, by definition $\mathbf{M}^{-1}\mathbf{M} = \mathbf{I}$, where **I** is the identity matrix, so therefore $\mathbf{M}^{\mathrm{T}}(\mathbf{M}^{-1})^{\mathrm{T}} = \mathbf{I}$ and so $[(\mathbf{M}^{\mathrm{T}})^{-1}\mathbf{M}^{\mathrm{T}}](\mathbf{M}^{-1})^{\mathrm{T}} = (\mathbf{M}^{\mathrm{T}})^{-1}\mathbf{I} = (\mathbf{M}^{\mathrm{T}})^{-1} = (\mathbf{M}^{-1})^{\mathrm{T}}$. It follows that if $\mathbf{M} = \mathbf{M}^{\mathrm{T}}$ (a symmetrical matrix) then $\mathbf{M}^{-1} = (\mathbf{M}^{-1})^{\mathrm{T}}$, and the inverse is also symmetrical.

$$\begin{aligned} V_N - V_1 &\approx [(C_{10}+C_{12})(C_{20}+C_{12}+C_{23})(\cdots)(\cdots)(C_{N-1,0}+C_{N-2,N-1}+C_{N-1,N}) \\ &\quad --(C_{20}+C_{12}+C_{23})(\cdots)(\cdots)(C_{N-1,0}+C_{N-2,N-1}+C_{N-1,N})(C_{N0}+C_{N-1,N})]\frac{I}{j\omega\det(\mathbf{C})} \\ &\approx \left[\frac{1}{C_{N0}+C_{N-1,N}}+\frac{1}{C_{10}+C_{12}}\right]\frac{I}{j\omega}, \end{aligned} \tag{12}$$

so that in this approximation

$$C \approx \frac{(C_{N0}+C_{N-1,N})(C_{10}+C_{12})}{C_{10}+C_{12}+C_{N0}+C_{N-1,N}}. \tag{13}$$

This result may be readily interpreted as being equivalent to the parallel pair C_{N0} and $C_{N-1,N}$ in series with the parallel pair C_{10} and C_{12}. Including off-diagonal elements of $\mathbf{C}$ will, of course, give a more complicated result.

3. Numerical Calculations

Graphs of most of the required individual capacitance values are available from Jia, Heuer, Hillmann, and Meyendorf [1] for the following parameter values: number of turns = 10, conducting trace width = 50 µm, conducting trace thickness = 50 µm, spiral inner diameter = 4000 µm, substrate thickness = 100 µm, relative permittivity = 1. Rather than repeating their detailed ANSYS calculations, these graphs were digitized to produce values of C_{p0}, C_{1p}, and $C_{p-1,p}$, for $1 \le p \le N = 10$, as a function of pitch distance. Other capacitance values were estimated as equal to analogous available values. As an example, these values were then used in a spreadsheet to obtain a graph of overall lumped capacitance for these values of pitch distance. The results are shown in Fig. 2. "Exact C" uses Eqn. (11); "Approx C" uses Eqn. (13); "Incorrect matrix" uses Eqn. (11) but all negative terms in $\mathbf{C}$ are written as positive in error; "Zero off 3 main diagonals" uses a matrix in which all elements apart from the leading diagonal and the immediate diagonal elements each side are approximated as zero; and, "Incl only NN" includes only nearest-neighbour capacitances and all others are set to zero.

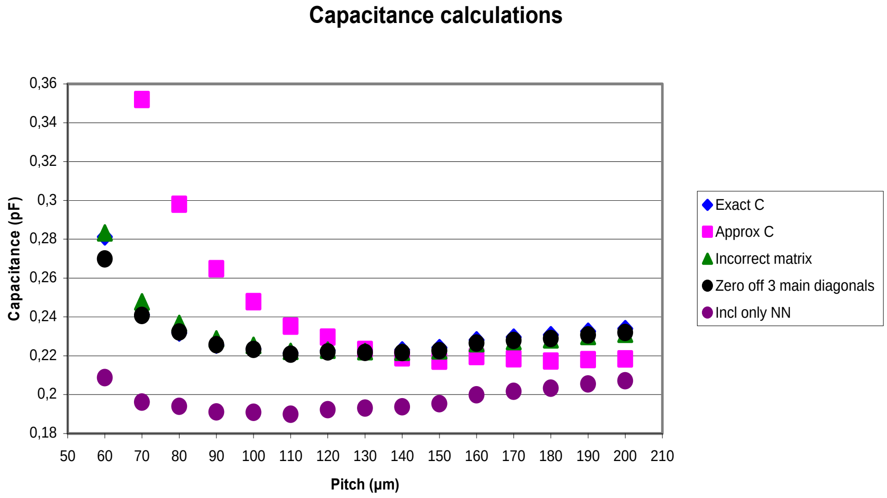

Fig. 2. Results of applying different approximations in calculating the overall lumped capacitance.

Small discrepancies between these results and those of Fig. 5(e) of Ref. [1] are due to the digitization process, so the correct comparison is as shown in the present Fig. 2. There is only a very small error introduced if all capacitance values apart from the leading diagonal and the nearest-neighbour interactions are reduced to zero, and this may provide an efficient time-saving in practice with a large number of coil turns since evaluating the inverse of a large matrix of real values is not a fast process. Reducing all nearest-neighbour interactions to zero gives a distinctly poorer approximation. The incorrect calculation with positive instead of negative off-diagonal elements gives a significant error, particularly at low pitch distances (where the non-nearest-neighbour interactions will be most significant). The approximation of Eqn. (13) would be expected to be more accurate and efficient for a large number of turns with small nearest-neighbour interactions (i.e., large distances between adjacent tracks of small width).

4. Conclusions

The previous report by Jia, Heuer, Hillmann, and Meyendorf [1] presented a method of calculating the stray capacitance of a printed spiral coil for applications as eddy-current sensors, inductors, sense coils, or micro-solenoids, and in RFICs, VHF and UHF amplifiers, and other applications. Their results have been amended analytically and some further analytical approximations have been presented. A considerable computational saving may be made by setting all non-nearest-neighbour interactions to zero. An even simpler calculation is possible, avoiding matrix inversion, although this yields less accurate results and so would be favoured in the case of a large number of coil turns, corresponding to a very large capacitance matrix, for which matrix inversion becomes very inefficient.

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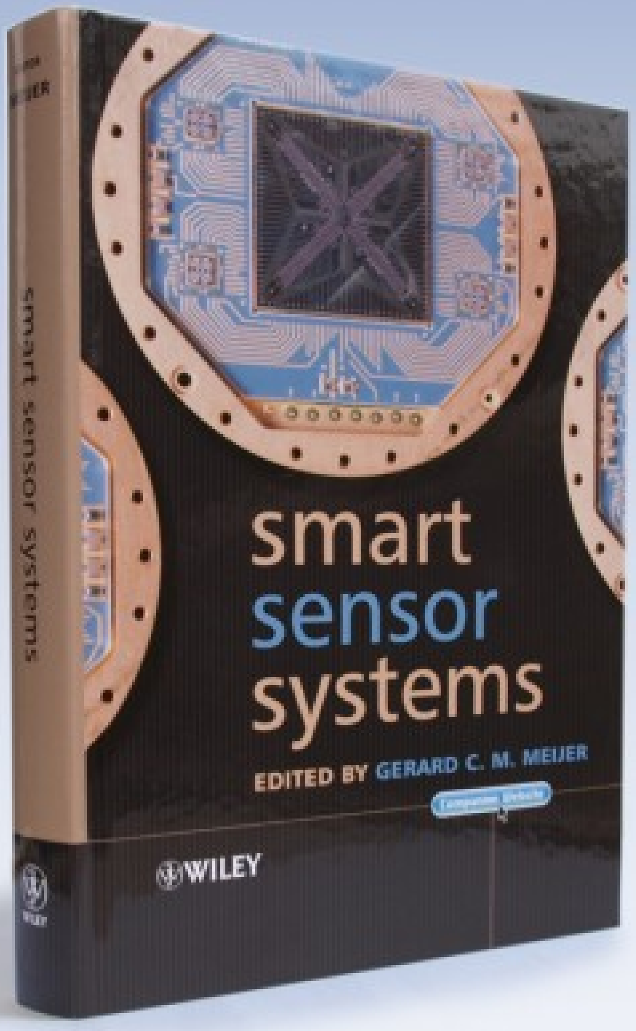

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