Frequency Response Modeling of Inductive Position Sensor with Finite Element Tools

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Abstract: The paper presents here an inductive position sensor which is based on a horizontally moveable/sliding type of thin rectangular or rhombus-shaped copper (activator element) plate and a row of planar coils, printed directly on the PCB. The frequency domain model of the presented inductive sensor has been developed using the Comsol multiphysics tool to estimate the change in inductance values of planar coils due to eddy current effects in the copper activator element at different horizontal positions. The proposed inductive sensor has been already implemented in the automatic gear shifter modules of leading German cars.

Keywords: Inductive position sensor, Planar coil, Eddy current effect, Activator element, Frequency domain modeling

1. Introduction

The position sensors find several applications in the automotive sector. Automatic gear shifter, seat position adjustment and accelerator-pedal position modules etc. are some common examples of position sensing in automotive electronics. Because of extreme weather condition, such as dust, humidity, moisture, vibration, pressure, fluctuation of day/night temperature and wide operating temperature range (-40°C to +90°C) confronted by automotive electronics position sensing based on resistive or capacitive principles are inappropriate in many occasions. Instead, a non-contact type of inductive position sensor has several advantages in such applications. With this objective in mind, a frequency domain model of a planar inductive coil has been developed to estimate the change of coil's inductance corresponding to the horizontal moving distance of the copper activator element over the planar coil. Inductive position sensor has been presented briefly in the Section 2. Comsol Multiphysics has been applied here as Finite Element tools for such modeling and therefore, the corresponding mathematical framework /model of a planar inductive position sensor have been described in Section 3. Section 4 describes the batch sweep and frequency domain modeling results from Comsol multiphysics tools. Section 5 concludes with brief remarks.

2. Inductive Position Sensor

Figure-1 shows below the schematic view of an inductive position sensor, in which the inductive coils are planar type and the Rhombus shaped activator element is made up of thin copper plate.

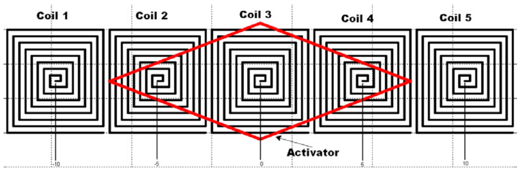

Figure 1: Inductive Position Sensor

Planar coils are fabricated directly on the PCB in the form of a row of flat coils so that three coils' inductances (e.g., coil 2, coil 3 and coil 4) are influenced by the eddy current damping effect due to sliding activator element as shown in Figure-1. Due to the limited space on the PCB often such coils have smaller size and less number of turns, e.g. 8-9 turns. Again, a small size of coil and less number of turns will produce a small amount of inductance which may be insufficient for a reliable position sensing. Therefore, inductive position sensing method often uses the multi-layer planar coils with a sliding copper, brass or aluminum metal plate as an activator element [1] approximately 0.2 to 0.3 mm over the coils, wherein the transducer generates a coil voltage/inductance that changes along with moving distance under the eddy current damping effects at higher frequencies. Planar coils of different geometrical shapes (square, rectangular, trapezoidal, circular or even elliptical) together with a rectangular or rhombus or even hexagonal shaped copper activator form actually the basis of a non-contact type of inductive position sensors which can be used in the automatic gear shifter module for sensing the P (park), N (neutral), R (reverse), D (drive) and S (sport) modes with M+ (manual gas/acceleration +) and M- (manual gas/acceleration -) etc. for instance.

3. Use of COMSOL Multiphysics

The presented non-contact type of inductive position sensor can be viewed as leaky and loosely coupled primary and secondary windings of a transformer model. This is due to the fact that the behavior of the planar coil of the inductive position sensor is similar to the primary coil of the transformer and the sliding copper plate resemblances very much with the shorted secondary coil of the transformer. Instead of a high permeable ferromagnetic core of the transformer inductive position sensor described here uses the air as core material. Owing to the use of air as core material in the inductive position sensor the coupling factor between the primary coil and shorted secondary is very much smaller than the normal transformer and thereby leakage of magnetic flux is very high in this type of inductive sensor. The schematic circuit model of an ideal transformer with a loaded (Z_L) secondary coil is shown in Fig. 2 below.

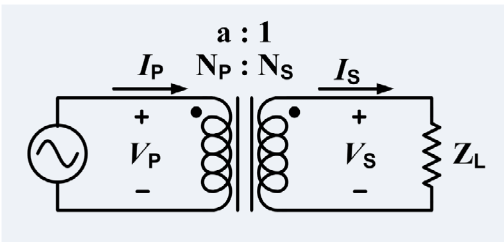

Figure 2: Equivalent transformer model

In Fig. 2, V_p and I_p represent respectively the applied primary input voltage and the corresponding current flowing into the primary coil, and in contrast V_s and I_s represent respectively the induced secondary voltage and current flowing through the loaded secondary coil. Referring to Fig. 2 above, the mathematical model of the (non-ideal) transformer can be written roughly as follows:

$$\begin{aligned} V_p &= I_p R_p + L_p \cdot dI_p/dt - M \cdot dI_s/dt, \\ M \cdot dI_p/dt &= I_s(R_s + Z_L) + L_s \cdot dI_s/dt \end{aligned} \quad \ldots \quad (1a)$$

and $$M = K_{coupl}\sqrt{L_p L_s} \quad ..... \quad (1b)$$

where R_p and R_s (not shown in Fig. 2) represent respectively the resistance of the primary coil and secondary coil. Similarly, L_p and L_s (not shown in Fig. 2) represent respectively the inductance of primary coil and secondary coil of the transformer and Z_L is the load in the secondary side. M = mutual inductance between primary and secondary coil and mathematically, M is represented by the product of coupling factor (K_{coupl}) and square root of the product of L_p and L_s. The mutual inductance term in the primary circuit represents the load due to secondary. It has negative sign because it insists the AC supply source (voltage) to produce more current in response to increasing load (small value of Z_L) in the secondary side. The mutual inductance term in the secondary represents the coupling from the primary and acts as the voltage source that drives the secondary circuit [2]. The relations given in equation (2) hold further for an *ideal transformer*.

$$\begin{aligned} &V_p/V_s = I_s/I_p = Np/Ns = a \\ &and \quad \sqrt{L_p/L_s} = a \end{aligned} \quad .... \quad (2)$$

For an *ideal transformer* with *shorted secondary* the load $Z_L = 0$ and primary coil resistance (R_p) and the secondary coil resistance (R_s) are also approximated as zero Ohm. Therefore, from equation (2) one can find the secondary current in terms of primary current and turns ratio as follows:

$$I_s = aI_p\,, \quad V_p = (L_p - aM)dI_p/dt \;.... \quad (3)$$

Furthermore, from equations (1a) and (3) one can derive the followings:

$$aM = K_{coupl}L_p, V_p = (1 - K_{coupl})L_p\, dI_p/dt \ldots (4)$$

From the equation (4) one can see that for a moderate coupling between the primary and secondary windings the primary coil inductance L_p is reduced by a factor of (1-K_{coupl}). In reality the coupling factor is always less than 1 *i.e.*,

K_{coupl} < 1. The aforementioned principle is used in the inductive position sensor as described below. When the copper activator element is brought very close to the planar coil the coupling factor (K_{coupl}) increases from 0 to some moderate value (e.g., 0.5 to 0.6) and thereby, the inductance of planar coil is reduced approximately by 40% to 50% of its nominal value. When the activator element moves away further from the concerned planar coil the coupling factor is reduced to zero value and therefore, inductance value of the planar coil goes back to its nominal value. The change of planar coil's inductance value is suitably converted to corresponding voltage signal and location of sliding activator element is estimated.

The aforementioned physical phenomenon can also be explained alternatively as follows. When an alternating current flows into the planar coil it produces a varying magnetic flux in the surrounding air core. The varying magnetic field impinging on the shorted secondary winding (copper activator element) induces further a varying voltage and current as per Faraday's law [2]. The induced current in the copper activator element, termed as eddy current, further opposes the varying magnetic flux generation as per Lenz's law and thus also opposing the current flow into the planar coil by giving rise to the lower coil inductance value. Higher the frequency of primary current, larger is the eddy current effect in the sliding copper plate. This, in turn, reduces the coil inductance of the inductive sensor. Model of both a single-layer/multilayer (Figure-1) planar coil, along with a sliding Cu-activator of Rhombus shape, operating at 10 MHz frequency has been developed to simulate such effects. The change of coil inductance values with sliding activator's distance over the planar coil form the basis of presented inductive sensor.

The above phenomenon has been modeled and simulated with the help of Comsol multiphysics frequency domain tool. The model building was performed with the following steps as shown in Figure- 3 under Geometry 1. After the 3D Geometry construction of planar coil and Rhombus shape activator element copper material was assigned to both the planar coil and activator element and both these models were placed in an air-filled big sphere. The diameter of sphere was greater than 2 times of Xoff (mm). The move 1 step was necessary in model building, as the activator element moves left and right horizontally above the planar coil.

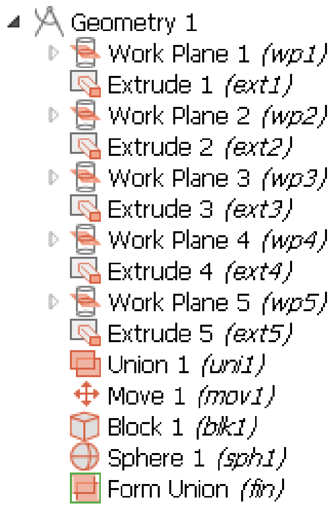

Figure 3. Geometry building steps of planar coil with activator element in Model Builder.

ACDC Magnetic fields (mf) was selected under add Physics. After the mesh generation of Geometry model Batch Sweep study was performed in frequency domain. In the Batch Sweep study the user defined Xoff parameter was set to 7 mm and 9 mm respectively for a single layer and double layer planar coils' simulation respectively, whereas user defined both Yoff and Zoff parameters were set to 0.

4. Results

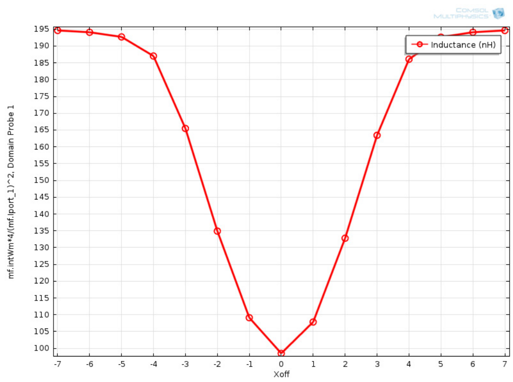

Figure 4. Cu-activator's X-off position (mm) vs. Inductance (nH) graph for a single layer planar coil.

Figure 4 and Figure 5 show the frequency domain (batch-sweep) simulation results of a 3D model of an inductive position sensor (both planar coil and a Rhombus shape copper activator element) obtained from Comsol multiphysics tool at f = 10 MHz frequency. Figure 4 depicts the horizontal distance (Xoff position in mm) of the copper activator element versus coil inductance (nH) graph. It can be observed from Figure 4 that for a single layer planar coil the coil inductance (L-coil) changes from 195 nH to 100 nH and then again to 195 nH when the Cu-activator slides from horizontal position Xoff = -7 mm to Xoff = 0 mm and then further to Xoff = +7 mm respectively maintaining a fixed vertical distance (Z_dist = 0.3 mm) between the planar coil and the activator element. Note that for a constant vertical distance of 0.3 mm, coil's inductance change due to sliding activator in the present simulation is approximately 49%.

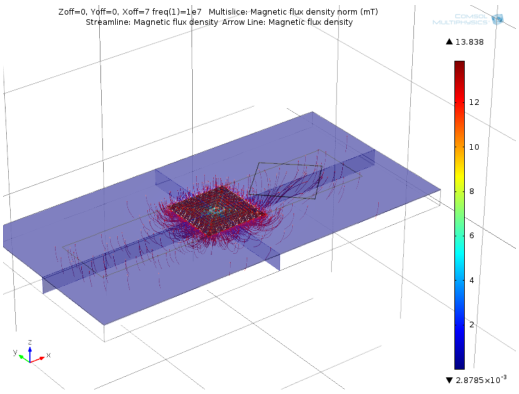

Figure 5. Flux density norm (mT) for a single layer planar coil.

Figure 5 shows the magnetic flux density norm (B_{norm} in mT) at f = 10 MHz frequency which can attain 13.84 mT when the activator element is at Xoff = +7 mm from the center of the planar coil. Figure 5 also shows the magnetic flux density arrow line. Further experimental simulations were performed with a double layer planar coil also at f = 10 MHz frequency (Figure 6, Figure 7 and Figure 8). Figure 6 shows the screen shot of batch sweep and frequency domain simulation of double layer planar coil and Figure 7 shows the zoomed view of magnetic flux density norm for the double layer planar coil with magnetic flux arrow volume.

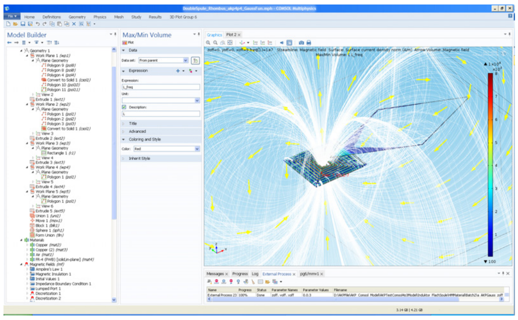

Figure 6. Screen shot of Flux density norm (mT) for a double layer planar coil.

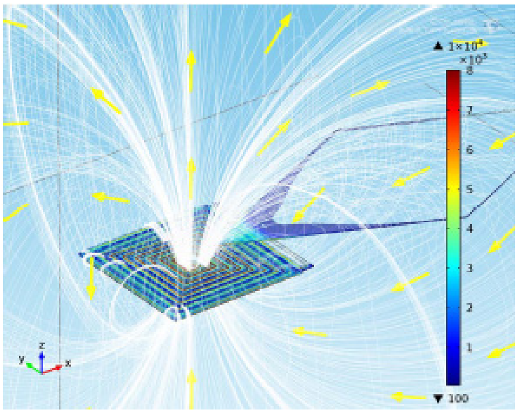

Figure 7. Zoomed view of flux density norm (mT) for a double layer coil.

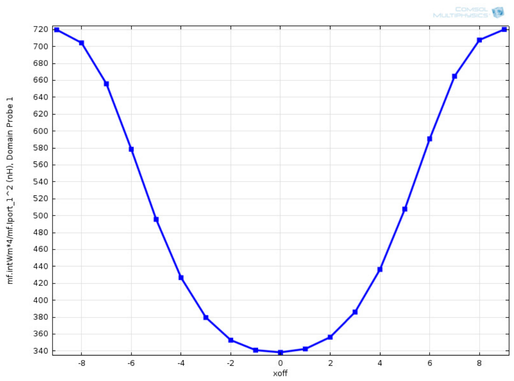

Figure 8. Cu-activator's X-off position (mm) vs. Inductance (nH) curve for a double layer coil.

Figure 8 shows the inductance (nH) graph of a planar coil for different horizontal distances (Xoff position in mm) of copper activator element from the center of a double layer planar coil. It can be observed from Figure 8 that for a double layer planar coil the coil inductance (L-coil) changes from 720 nH to 340 nH and then again to 720 nH when the Cu-activator slides from horizontal position Xoff = -9 mm to Xoff = 0 mm and then further to Xoff = +9 mm respectively. The shape of this curve is similar to the copper activator element's horizontal distance (Xoff position in mm) versus coil inductance (nH) curve for a single layer planar coil as shown in Figure 4. Similar to single layer planar coil in this case also a fixed vertical distance (Z_dist = 0.3 mm) between the double layer planar coil and the activator element is maintained. Note that for the double layer planar coil the coil inductance changes by approximately 53%. The Xoff-position versus coil inductance curves in Figure 8 and Figure 4 both look like an inverted Gaussian function.

5. Conclusions

An inductive position sensor was modeled using Comsol Multiphysics frequency domain (batch-sweep) tool, where the planar coil's inductance changes due to eddy current formation in the sliding Cu-activator element at high frequency. The inductance (nH) curve (X_{off} position (mm) versus coil's inductance graph) looks like an inverted Gaussian function. The coil inductance will be further reduced at Xoff = 0 mm horizontal position if the vertical distance (Z_dist) between the center of activator and center of top layer (for multi-layer coil) of planar coil is made equal to 0.2 mm or even lower. This is due to the fact that with smaller vertical distance (Z_dist) coupling factor (K_{coupl}) between the planar coil (primary winding) and activator (shorted secondary winding) increases further in equation (4). The sensitivity of the inductive sensor was also investigated at different frequencies with the presented model. It was observed that sensor efficiency and sensitivity are highly dependent on the shape/geometry, size and physical dimensions of both planar-coil and Cu-activator element besides the vertical Z-distance between the planar coil and Cu-activator element. All such fine effects were simulated with Comsol multiphysics tool for design optimization of inductive position sensor. The simulation results were used in the development of an automatic gear shifter module of a leading German car.

6. References

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