MICROCHIP

AN1239

Inductive Touch Sensor Design

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INTRODUCTION

This application note is intended to provide a technical overview of the sensor design of an inductive touch system. It will concentrate on the design of the sense inductor, target, spacer and fascia layer.

THEORY OF OPERATION

The physical principles behind inductive touch technology are based upon a few fundamental physical laws. However, the design of an inductive touch sensor does not require an in-depth understanding of those laws, so they will not be covered here. They are available in the appendix of this document for those that are interested.

SYSTEM AND COMPONENT DESCRIPTIONS

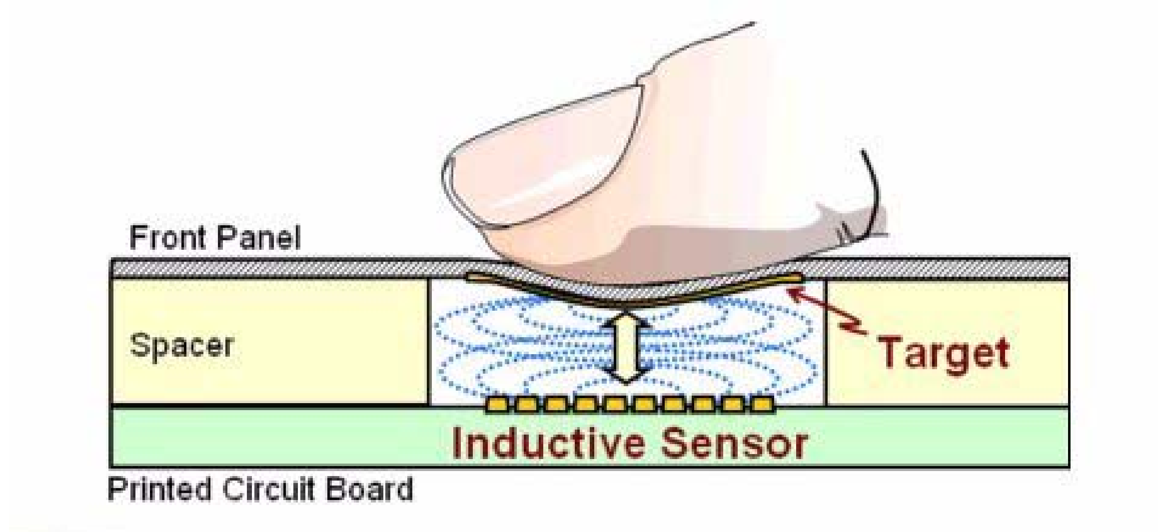
An inductive touch system uses the magnetic coupling between a solid metal target and an inductive sensing coil. If a user presses on the front panel, then the coupling between the target and sense coil will change due to the minute shift in the target's position, as shown in Figure 1.

To sense this change in the inductive sensing coil, an impedance converter and microcontroller are required. The microcontroller periodically polls the various sensors by measuring impedance of the sensing coil. If the impedance of the sense coil has changed, then the microcontroller determines if the shift in impedance is sufficient to qualify as a user's press.

The following sections will discuss the various elements of the design, but only the fascia, target and sensor coil will be discussed in depth. For information concerning the impedance converter, refer to *AN1237, "Inductive Touch Hardware Design"*.

In most configurations, the target is separated from the sensing coil by a forth element – a spacer layer. This element has two functions: the first is to provide a sufficient separation for the fascia and target to move freely during a user's press; the second is to position the target at an optimal distance from the sensor such that the deviation due to a press produces an optimal shift in impedance.

FIGURE 1: CROSS SECTION OF AN INDUCTIVE TOUCH SENSOR ASSEMBLY



Fascia

The fascia is typically the top layer of the sensor sandwich. It is the plastic panel or metal sheet that the user presses on and usually caries the labeling that identifies the button's location and function.

The fascia can also be the target if it is conductive, and can be sufficiently deformed by the user's press to cause the required minimum change in inductance (see **Mechanical Construction**). The material of the fascia can, in theory, be made from any material – so long as it elastically deforms under the range of expected pressures that will be applied by the user.

Common fascia constructions include plastic injection moldings, plastic sheet, sheet or formed metal. Other products can also be used by the user, provided they elastically deform under pressure.

While it is theoretically possible to use very stiff materials such as glass or ceramics, it is often impractical due to the difficulty in producing a fascia that can deform sufficiently under the applied (finger) pressure of the user. In inductive touch sensing applications, the practical thickness of glass is <0.5 mm for a nominal 25 mm diameter sensor.

Fascia materials can also be used as the target, to simplify the construction of the sensor sandwich, provided they have the appropriate conductivity and permeability. Materials of choice for a fascia/target, in order of preference for conductivity and permeability, are copper, aluminium, brass, stainless steel and mild steel.

There are two options in case the desired thickness of a one piece fascia/target layer is too stiff to produce a sufficient deformation for detection. One option is to use a separate thinner target with a more flexible fascia layer. The second option is to etch the target in the area above the sensor coil, reducing its thickness until the target is sufficiently flexible. Note that etching away the coil side of the target will increase the spacing between the coil and the target, so the thickness of the spacer layer may have to be reduced to maintain the proper spacing.

Concerning the effects of EMI, RFI and the capacitive effect of a user's touch onto a metal fascia, no change will be detected if it does not cause a physical deformation of the target over a sensor coil.

During normal operation all sensor coils are either directly grounded or grounded through one of the other coils in the system, limiting their susceptibility to noise. Further, placing a DC voltage, or grounding the metal fascia/target, will not effect the inductive touch sensor operation so, grounding the target/fascia is a reasonable and recommended precaution for limiting EMI/RFI/ESD effects on the system.

Targets

The target is a passive, electrically conductive or magnetically permeable layer which is arranged to displace or deform along the measurement axis relative to the coil. If a separate fascia layer is used, then the target is mechanically bonded to the fascia, so it will deform with pressure on the fascia.

While magnetically permeable materials such as ferrites can be used for the target, highly conductive materials are preferable, due to their good conductivity and lower cost.

In a typical application, the target is made from a copper lamination, but it could also be made from any other highly conductive materials such as aluminium, gold, silver or steel. Mild steel is less conductive and should only be considered as target material where the deformation is relatively large and/or the coil area is large.

Only a thin layer of conductive material is actually required for a target (typically <100 microns) and can be produced, for example, using 3 ounce copper cladding on a PCB substrate. Generally, the target should be the size and shape as the coil (although greater sensitivity can be achieved using a smaller coil, as described in Appendix B).

Electrical isolation is not generally required between individual targets, although this may assist sensor performance when sensors are located in close proximity. Deformation in one sensor area might carry across to neighboring sensors.

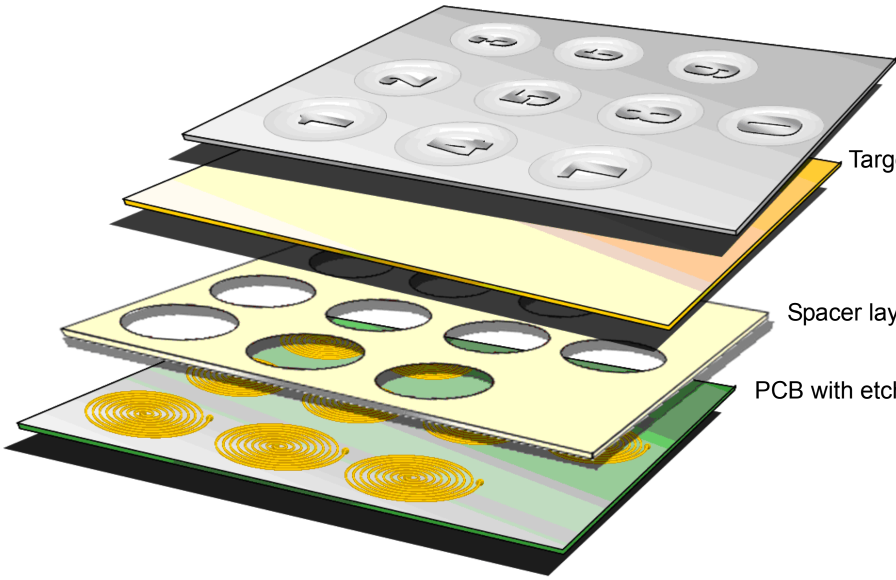
In some applications, a self-adhesive copper label, stuck to the underside of the fascia, is also acceptable, provided that its adhesive film is flexible and permanent.

Spacer

Most – but not all – inductive touch constructions use a spacer layer to provide the separation between the target and the coils. Constructions which use an injection molded fascia do not typically require a spacer layer since the separation distance can be molded as an integral feature of the plastic. A spacer layer can also be built into the PCB through the use of an additional PCB layer, provided that the area immediately above the sensor is open and free of obstructions that would limit the deformation of the fascia and target, as illustrated in Figure 2.

The thickness of the spacer should be approximately 1%-3% of the diameter of the coil. The spacer layer can be made from a wide range of materials but should be a mechanically stiff and electrically insulating material such as FR4, FR2, resin bonded paper, ABS or other plastic.

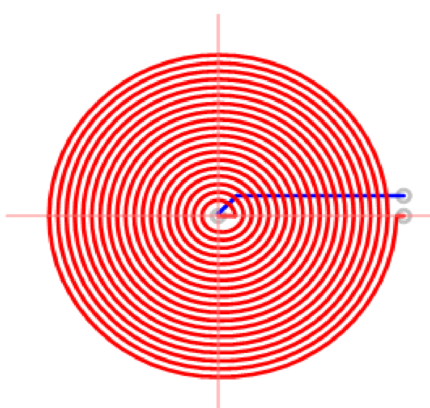
FIGURE 2: TYPICAL SANDWICH CONSTRUCTION OF THE FASCIA, TARGET, SPACER AND COIL



Sensor Coils

The sensor coils are one or more inductors, preferably implemented as flat spiral coils, etched into the copper layer of a PCB, as shown in Figure 3.

FIGURE 3: PLAN VIEW SCHEMATIC OF A SPIRAL WOUND INDUCTOR ON A 2 LAYER PCB



The inductance of the coil is determined by the number of turns and the dimensions of the pattern etched into the PCB. Equation 1 shows the relationship between physical dimensions and inductance for metric units. Equation 2 shows the same relationship for imperial units.

EQUATION 1: METRIC

$$L = \frac{r^2 N^2}{(2r + 2.8d) x 10^5}$$

where:

L = inductance in Henrys

r = outer radius of coil in meters

N = number of turns

d = depth of coil in meters (i.e., outer radius minus inner radius)

EQUATION 2: IMPERIAL

$$L = \frac{r^2 N^2}{8r + 11d}$$

where:

L = inductance in µH

r = outer radius of coil in inches

N = number of turns

d = depth of coil in inches (i.e., outer radius minus inner radius)

> **Note:** Both equations will only provide an approximate inductance because the permeability of the material chosen for the target will affect the final inductance of the coil.
>
> Additional information can be found in section **A.5 Basic Mathematical Relationships** in Appendix A.

For our discussions, it is sufficient to note that the fewer turns in the inductor design, the lower the inductance and the smaller the resulting voltage will be at the impedance converter. Therefore, using coils of less than 1-2 uH is not recommended as this places an undesirable design constraint on the impedance converter that will necessitate one of the following:

- large drive currents (> 5-10 mA)
- a higher frequency drive (> 4-8 MHz) or
- abnormally high gain in the converter's output filter

Connection of the Coils

Each of the coils is electrically insulated from the others, with only a single common connection to the reference coil (Ref coil). Figure 4 shows how the coils are configured for a multiplexer-based system. Figure 5 shows an alternative system that uses the port pins of the microcontroller (GPIO) to switch the ground side of the coils, eliminating the additional multiplexer chips. For more information concerning the two systems, please refer to *AN1237, "Inductive Touch Hardware Design"*.

> **Note:** To minimize the creation of parasitic inductance in the traces between the coils and the measuring circuitry, route both connections to the coil in parallel to each other, and with a minimal spacing. This causes the magnetic fields, generated around the two traces, to cancel out each other, significantly reducing the inductance of both traces.

FIGURE 4: MULTIPLEXED CONFIGURATION OF SENSE COILS

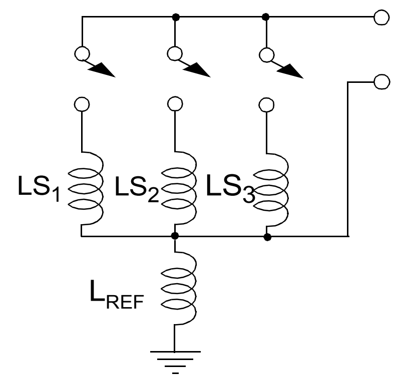


FIGURE 5: CONFIGURATION THAT USES GPIO TO MULTIPLEX THE GROUND CONNECTION TO THE SENSE COILS

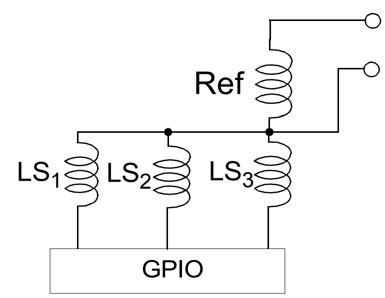


TABLE 1: ADVANTAGES AND LIMITATIONS OF GPIO VERSUS ANALOG MULTIPLEXING TOPOLOGIES

	Advantages	Limitations
GPIO	• Eliminates analog multiplexers	• Reduced gain due to offset from GPIO output resistance
Analog Multiplexer	• Eliminates the GPIO output resistance • Higher gain = more ADC counts per press • System noise is reduced	• Cost of analog multiplexers

In the recommended configuration, the Ref coil is used to act as a reference inductor, allowing a ratio-metric measurement which removes several sources of drift. However, one alternative solution is to omit the Ref coil and use a software averaging routine to compensate for drift. The main challenge with a software averaging system is determining when to average, and when not to. This can become complex and can significantly increase the burden on the microcontroller. As the only real cost to the Ref inductor is the board space to create the coil, the savings in omitting the Ref coil is minimal and therefore not recommended considering the increase in software complexity.

Ratio-metric Measurement

Several factors can cause a shift in the impedance of the sensor coil; they include variations in drive current, shifts in the resistance of the multiplexers, and temperature. These factors can even result in impedance changes that are on the same order as a shift in impedance due to a press by the user. To compensate for these changes, an averaging routine can be included in the firmware for the system, but these routines can become large and cumbersome to use.

A ratio-metric method, using an independent reference coil in series with the sensor coil, eliminates these factors automatically. Variations in temperature and drive current will affect both coils equally so, normalizing the sensor coil by dividing by the reference drops out the temperature and current dependent shifts. To be effective, the reference coil should be the same size and shape as the sensor coils, and should have a non-moving target suspended above it, at the same height as the target above the sensor coil.

Typically, the coils are formed by conductive tracks etched in to a printed circuit board. Double-sided FR4 is well suited to this application as a plated-through hole, and trace on the back of the PCB allows access to the center of the coil. Individual coils should be connected either individually to the impedance converter, in the case of a multiplexed system, or to each other through a common tie point and the impedance converter, in the case of a GPIO system.

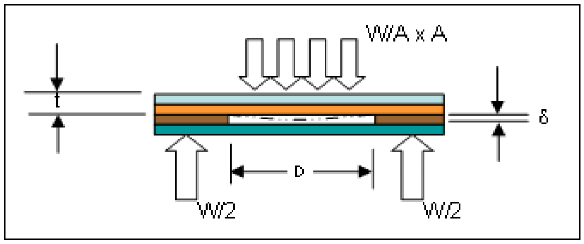
It is often beneficial to place connections between the coils and the impedance converter on the surface next to the target, when the target is a continuous conductive sheet, as this minimizes trace inductance and stray inductance effects. It is also a good idea to use wider tracks (than those of the inductor coil itself) to minimize connection resistance.

Generally, printed circuit board [PCB] constructions are well suited to inductive touch technology. Not only can the coils be formed as tracks on a PCB, but the target(s) can also be formed using a single-sided copper clad sheet.

Mechanical Construction

Most inductive touch sensors can be considered as a multi-layer sandwich construction – each layer forming a functional element, as shown in Figure 6. The fascia layer is typically acted upon by a pressure or relatively uniformly distributed load (W/A) over an area (A). The applied pressure causes the fascia and target to deform by an amount δ.

FIGURE 6: MECHANICAL CONSTRUCTION OF A SENSOR SANDWICH



δ is proportional to W, t^3, D^2 and the effective Young's modulus (E) or stiffness of the fascia and target. Consequently, large increases in δ can be achieved with only modest changes in D or t.

> **Note:** A free software sensor design tool is available from the Microchip web site. It can be used to determine the appropriate thickness of material for the fascia and target materials, based on the Young's modulus of the material, the diameter of the aperture, and the minimum deformation required.

Point loading, rather than distributed loading, tends to increase δ but this effect is negated by the reduced inductive % change effect.

The minimum displacement of the target, which will produce a measurable shift in the impedance of the sensor coil, is 10 micrometers. A displacement of 20 um is considered to be more reasonable as it generates a larger shift, which is more easily differentiated from system noise. In general, opening with larger D values (20-50 mm) will produce this displacement with less force by the user, while smaller openings (<10-15 mm) will require either materials that are more elastic or thinner.

The optimum spacing between the sensor and the target is recommended to be approximately 3-5% of the diameter of the opening in the spacer (see Figure B-2 in Appendix B). This will allow sufficient shift of the material, as well as providing a sufficient separation for a partial coupling of the shorted secondary (target) and the sensor coil.

The maximum force that will be applied by the user should also be considered. For small deflections, the material will deform elastically. However, if the material is stressed beyond this elastic region, the material will become plastic and retain a portion of the deformation resulting in a loss of sensitivity for the sensor. It is therefore recommended that careful consideration of both the minimum and maximum actuation force applied by the users should be included in the selection of an alloy for the fascia/target.

In order for the pressure to cause a deformation of the target relative to the coils, rather than displacement of the complete assembly, the coil layer should be mechanically supported, so that a supporting force is applied. The supporting force is equal and opposite to the force caused by the applied pressure.

The sandwich construction can be bonded together using a variety of mechanical means such as:

- adhesives
- screws
- heat bonding
- ultrasonic welding

A variety of adhesives can be used with the specific choice being dependent on the application's operating and environmental conditions. Toughened cyanoacrylate (such as Loctite™ 480 or 330) and 2 part epoxy (Araldite™ or equivalent) have produced good test results, provided the bonded constructions are made following the manufacturer's instructions – taking particular care to ensure compliance with surface coverage, cure time, avoidance of greasy/dirty surfaces and pressing time, in particular.

In injection molded constructions, self tapping screws can be used to hold the various laminations together and secure them to the (molded) fascia. Similarly, sacrificial posts which are deformed and flattened by application of heat and pressure during the final stages of assembly, can be molded.

CONCLUSION

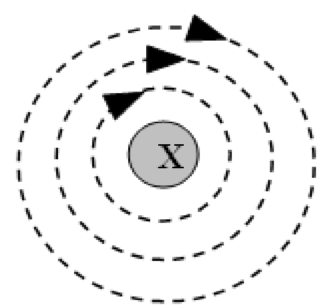
The actual construction of an inductive touch sensor system is not in itself complicated. The construction is simply an etched coil on a PCB, with a spacer, target and fascia, bonded to it. However, the choice in materials will have a significant effect on the performance of the touch sensor. If the materials are too stiff, then the sensor will require excessive force to actuate. If the materials are too soft, then the deformation will not be elastic and the deformation of the fascia and target may be permanent, preventing future actuation. As a result, designers should carefully consider both the electrical and mechanical aspects of the design.

APPENDIX A: COIL INDUCTANCE

A.1 Magnetic Field Due To an Electric Current

When a conductor carries a current, a magnetic field is produced around that conductor, as discovered by Oersted, at Copenhagen in 1820. He discovered that when a wire carrying an electric current was placed above a magnetic needle, the needle was deflected clockwise or counter-clockwise depending on the direction of the current. As a result, if we look along the conductor and the current is flowing away from us, as shown by the cross inside the conductor in Figure A-1, the magnetic field has a clockwise direction and the lines of magnetic flux can be represented by concentric circles around the wire.

FIGURE A-1: MAGNETIC FLUX DUE TO A CURRENT IN A STRAIGHT CONDUCTOR WHEN VIEWED ALONG THE CONDUCTOR



A.2 Inductance

Inductance (measured in Henrys) is an effect which results from the magnetic field that forms around the current-carrying conductor. Electrical current through the conductor creates a magnetic field, proportional to the current. A change in this current creates a change in magnetic field that, in turn, generates an electromotive force (emf) that acts to oppose the change in current. Inductance is a measure of the generated emf for a unit change in current.

For example, an inductor with an inductance of 1 Henry produces an emf of 1V when the current through the inductor changes at the rate of 1 ampere per second. The number of turns, the area of each loop/turn, and what it is wrapped around affect the inductance.

A.3 Hydraulic Model

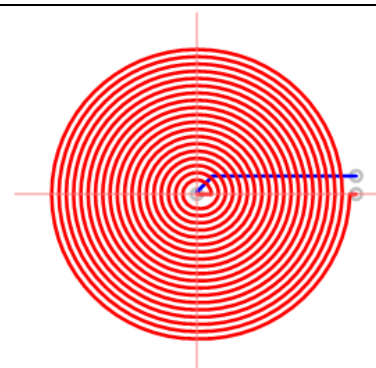
Electrical current can be modeled by the hydraulic analogy. The inductor can be modeled by the flywheel effect of a turbine, rotated by the flow. As can be intuitively and mathematically demonstrated, this mimics the behavior of an electrical inductor; voltage is proportional to the derivative of current with respect to time. Thus, a rapid change in current will cause a big voltage spike. Likewise, in cases of a sudden interruption of water flow, the turbine will generate a high pressure across the blockage.

A.4 Inductor Construction

Traditionally, an inductor is constructed as a coil of conducting material, typically copper wire, wrapped around a core, either of air or a ferromagnetic material. Inductors come in many shapes and sizes but, typically, the inductors used in inductive touch technology are small inductors and can be etched directly onto a printed circuit board by laying out the trace in a spiral pattern to form a planar or laminar inductor.

The spiral pattern is connected to the external circuit by means of a link from the inside to the outside of a spiral, as illustrated in Figure A-2.

FIGURE A-2: PLAN VIEW SCHEMATIC OF A SPIRAL WOUND INDUCTOR ON A 2 LAYER PCB



A.5 Basic Mathematical Relationships

In general, the relationship between the time-varying voltage $v(t)$ across an inductor with inductance L, and the time-varying current $i(t)$ passing through it is described by the differential Equation A-1 below:

EQUATION A-1:

$$v(t) = L\frac{di}{dt}$$

When there is a sinusoidal alternating current (AC) through an inductor, a sinusoidal voltage is induced. The amplitude of the voltage is proportional to the product of the amplitude (I_P) of the current, and the frequency (f) of the current, as shown in Equation A-2:

EQUATION A-2:

$$i(t) = I_P \sin(2\pi f t)$$

$$\frac{di(t)}{dt} = 2\pi f I_P \cos(2\pi f t)$$

$$v(t) = 2\pi f L I_P \cos(2\pi f t)$$

In this situation, the phase of the current lags that of the voltage by 90 degrees.

A.6 Inductance of a Flat Spiral Air Core Coil

Inductance of a flat spiral air core coil is given approximately as:

EQUATION A-3:

$$L = \frac{r^2 N^2}{(2r + 2.8d) \times 10^5}$$

L = inductance in Henrys

r = outer radius of coil in meters

N = number of turns

d = depth of coil in meters (i.e., outer radius minus inner radius)

Hence a spiral coil with 8 turns, with an outer radius of 12.5 mm and a depth of 10 mm would have an inductance of 5.13 μH.

The same approximate formula in imperial units is:

EQUATION A-4:

$$L = \frac{r^2 N^2}{8r + 11d}$$

where:

L = inductance in μH

r = outer radius of coil in inches

N = number of turns

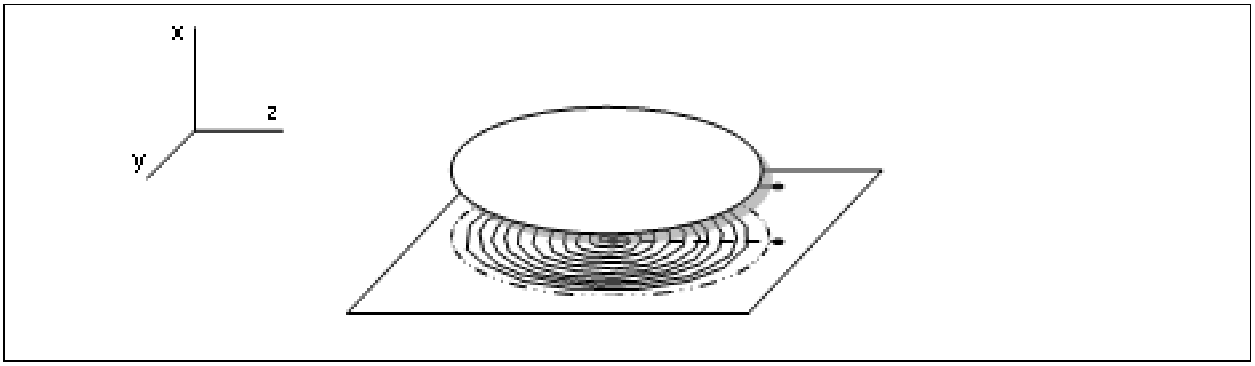
d = depth of coil in inches (i.e., outer radius minus inner radius)

APPENDIX B: INDUCTANCE VARIATION

The fundamental principle of operation of the inductive touch technology is that the inductance of an inductor varies when a nearby magnetically permeable or electrically conductive material moves relative to the inductor. This is because the magnetically permeable or electrically conductive material provides an alternative route for the magnetic flux which, in turn, varies the inductance. The closer the magnetically permeable or electrically conductive material is to the inductor, the greater the effect.

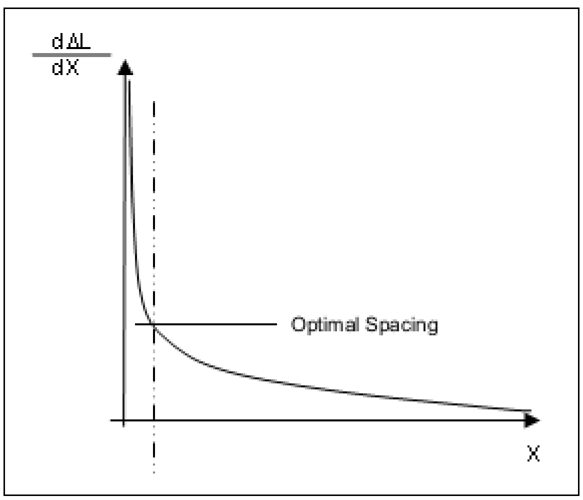
Consider a planar, spiral wound inductor (shown in Figure B-1) arranged facing, but at a relatively short distance from a conductive lamination (the 'target'). The inductance of the coil reduces as the target approaches the coil in the x-axis.

FIGURE B-1: SCHEMATIC ARRANGEMENT OF PLANAR SPIRAL COIL AND A TARGET



The coil's inductance decreases as the target approaches and, to a limit, vice versa. The rate of change of inductance with respect to axial separation increases in inverse proportion to the axial separation between target and coils, as illustrated in Figure B-2.

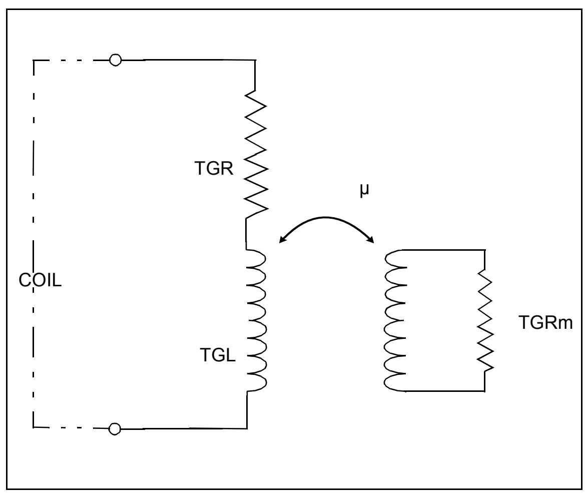
FIGURE B-2: RATE OF CHANGE OF INDUCTANCE VERSUS AXIAL SEPARATION OF TARGET AND COILS



B.1 Simulation Model

As shown in Figure B-3, the electrical circuit model for each inductor, when placed close to a conductive target, is that of an inductor coupled to a secondary coil "shorted" via a small resistance. This represents the energy lost through eddy currents flowing in the target.

FIGURE B-3: CIRCUIT MODEL



The equivalent impedance of the inductor coil, looking into its terminals, is given by Equation B-1.

EQUATION B-1:

$$X(x) := (TGL \cdot w) \cdot 1i + TGR \cdot 2.0 - \left[\frac{[(w \cdot \mu(x)) \cdot 1i]^2}{(TGL \cdot w) \cdot 1i + TGRm}\right]$$

Where:

x = separation distance

w = 2 * π * frequency

μ(x) = mutual inductance as a function of ‘x’

TGL = coil inductance without target present

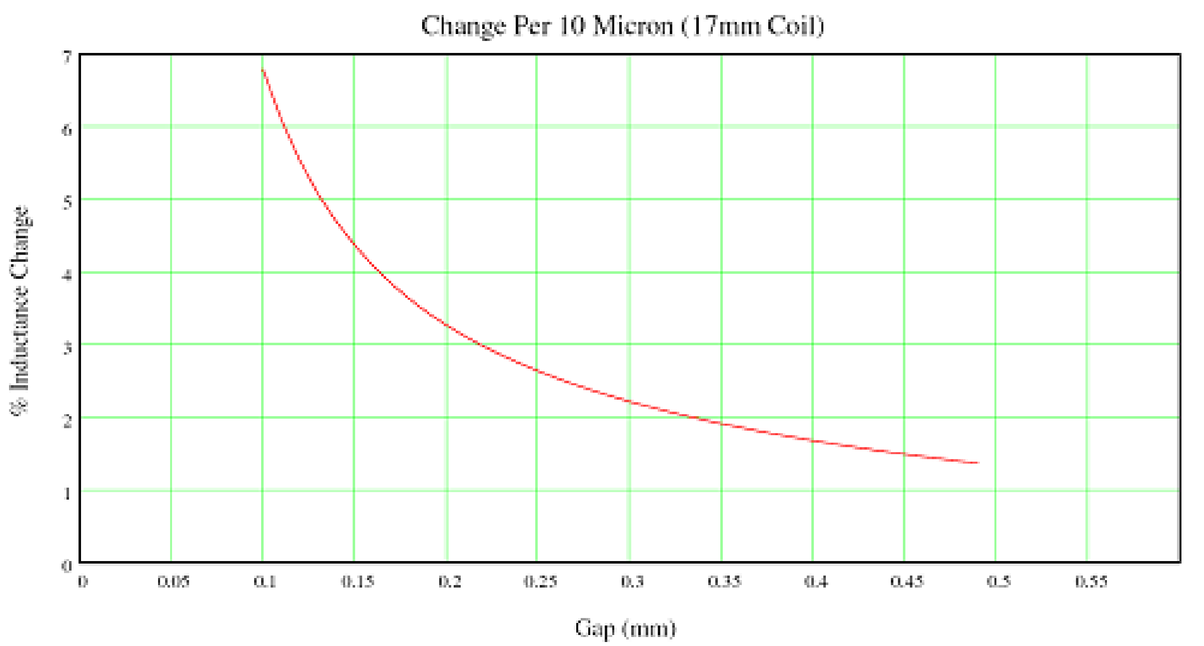
TGR = coil resistance without target present

(x nominal factor of 2 to allow for increased AC resistance)

TGRm = equivalent resistance of the target metal

If we study the equation we can see that the effect of placing the target close to the inductor is to reduce its equivalent series inductance and to increase its series resistance. The best sensitivity will then be achieved if the coil impedance is much larger than the equivalent resistance of the target metal. The following graphs show typical results from a flat spiral coil mutual inductance calculation and assuming a target equivalent resistance of 1 Ohm.

FIGURE B-4: EXAMPLE SENSITIVITY CURVE FOR A 17 MM DIAMETER COIL



The graph in Figure B-4 shows that, if the target is spaced by a very small distance away from the coils, it only needs to move very slightly to produce a large variation in the coil’s inductance. Such small movements might be, for example, caused when a finger presses against a fascia panel. A greater percentage change can be achieved in the diaphragm case by using a coil which is smaller than the diaphragm in diameter, and placed at its center. This greater sensitivity is achieved at the expense of a smaller initial inductance value.

APPENDIX C: TARGET MATERIALS

As the above model shows, the lower the target resistance, the better. In practice, what is important is only that the target equivalent resistance is small, compared to the coil impedance. The target equivalent resistance depends on a number of factors but most importantly, on its sheet resistivity and also on its thickness. In the latter case, the target material thickness only needs to be greater than a few multiples of skin depth. The skin depth is a measure of the zone within which current flow is confined at the surface of a conductor. The skin depth decreases with the increasing frequency and with the increasing conductivity. The skin depth also decreases with the increasing permeability. In cases where the skin depth is very small, a poor surface finish may also increase the equivalent resistance.

Table C-1 shows resistivity, permeability and skin depth information for typical target metals.

In practice, for a typical coil operating at 1-2 MHz, the same sensitivity is produced when using 100 um thickness copper (3 oz. foil) as for 35 um thickness (1 oz. foil). In the latter case, the thickness is less than a skin depth. However, the equivalent resistance is still much lower than the coil impedance. In the same way it is found that a stainless steel target, with its much higher resistivity, can still achieve around 80% or more of the sensitivity of a copper target. Aluminium targets will normally produce almost the same effect as copper.

Mild steel has lower sheet resistivity than stainless steel. Still, it has a magnetic effect which opposes the eddy current losses and so the sensitivity (inductance change versus target displacement) is lower. The relative permeability of mild steel does reduce with frequency, from a value of >200 at a few hundred Hz.

Note: The percentage change in inductance for a planar target wholly displaced by a distance d relative to a coil (of roughly the same area) is typically about 3 times greater than a target diaphragm, which is deformed up to a maximum distance d by a point load at its centre. This is because the effect is proportional to the integral of displacement distance x area.

TABLE C-1: RESISTIVITY AND PERMEABILITY OF EXAMPLE TARGET MATERIALS

Material	Resistivity (Ohm m)	Relative Permeability
Copper	1.70E-08	1
	Frequency (MHz)	Skin Depth (microns)
	1	66
	2	46
	3	38
	4	33
Aluminium	2.70E-08	1
	Frequency (MHz)	Skin Depth (microns)
	1	83
	2	58
	3	48
	4	41
ST. Steel	7.20E-07	1
	Frequency (MHz)	Skin Depth (microns)
	1	427
	2	302
	3	247
	4	214
Mild Steel	1.80E-07	80
	Frequency (MHz)	Skin Depth (microns)
	1	24
	2	17
	3	14
	4	12

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