(54) Title: SELF-TUNING DRIVE SOURCE EMPLOYING INPUT IMPEDANCE PHASE DETECTION
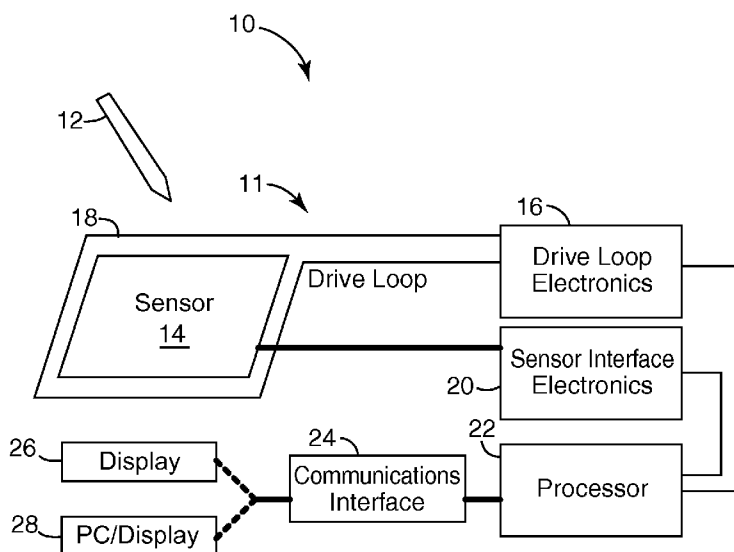
(57) Abstract: An untethered device is configured to inductively couple to a source device. The source device includes a driver circuit configured to generate a varying magnetic field and comprising a drive coil circuit. A phase detector is coupled to the driver circuit and configured to detect a phase of an input impedance of the driver circuit in response to the source device inductively coupling with the resonant circuit of the untethered device. A controller is coupled to the phase detector and the driver circuit, and is configured to adjust a frequency of a source voltage applied to the driver circuit in response to an output signal of the phase detector. The controller adjusts the source voltage frequency so that the phase of the input impedance as indicated by the output signal of the phase detector is substantially zero.

SELF-TUNING DRIVE SOURCE EMPLOYING
INPUT IMPEDANCE PHASE DETECTION

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The present invention relates generally to communication between an untethered device and a sensing system and, more particularly, to sensing systems and methods that employ an untethered stylus as a user input implement.

10   **BACKGROUND**

Personal computing systems of varying type and configuration typically provide one or more user interface devices to facilitate user interaction with such computing systems. Well known user interface devices include a keyboard, mouse, trackball, joystick, and the like. Various types of personal computing devices, such as tablet PCs,

15   provide a pen apparatus that can be manipulated by the user, much in the same way as a pencil or ink pen.

Conventional computing devices that provide for user input via a pen or other pointer implement typically employ an electromagnetic inductive system. The electromagnetic inductive system usually comprises an electromagnetic pen or pointer

20   apparatus and a digitizer in the form of a tablet. Changes in pen location relative to the digitizer's sensing surface are detected and location computations are made to determine the coordinates of the pen.

SUMMARY OF THE INVENTION

25   The present invention is directed to systems and methods for enhancing communication between an untethered device and a sensing system. According to embodiments of the present invention, an untethered device is configured to inductively couple to a source device. The source device includes a driver circuit configured to generate a varying magnetic field and comprising a drive coil circuit. A phase detector is

30   coupled to the driver circuit and configured to detect a phase of an input impedance of the driver circuit in response to the source device inductively coupling with the resonant circuit of the untethered device. A controller is coupled to the phase detector and the

driver circuit. The controller is configured to adjust a frequency of a source voltage applied to the driver circuit in response to an output signal of the phase detector. The controller adjusts the source voltage frequency so that the phase of the input impedance as indicated by the output signal of the phase detector is substantially zero.

5   The controller may be configured to adjust the source voltage frequency to compensate for a change in a resonance frequency of the resonant circuit of the untethered device. The controller may be configured to adjust the source voltage frequency to compensate for a change in a parameter of the resonant circuit of the untethered device.

In some embodiments, the source device includes a digitizer and the untethered
10   device is configured as a stylus. In other embodiments, the source device includes an RFID reader and the untethered device is configured as an RFID tag. The controller may include a voltage controlled oscillator.

In accordance with other embodiment, a system of the present invention may include an untethered device comprising a resonant circuit and a source device configured
15   to inductively couple to the untethered device. The source device may include a driver circuit configured to generate a varying magnetic field and comprising a drive coil circuit. The source device may further include a phase detector coupled to the driver circuit and configured to detect a phase of an input impedance of the driver circuit in response to inductively coupling the source device and the untethered device. A controller of the
20   source device is coupled to the phase detector and the driver circuit, and may be configured to adjust a frequency of a source voltage applied to the driver circuit in response to an output signal of the phase detector. The controller adjusts the source voltage frequency so that the phase of the input impedance as indicated by the output signal of the phase detector is substantially zero.

25   The controller may be configured to adjust the source voltage frequency to compensate for a change in a resonance frequency of the resonant circuit of the untethered device. The controller may be configured to adjust the source voltage frequency to compensate for a change in a parameter of the resonant circuit of the untethered device, such as a change in one or more of a resistive element, inductive element, and a capacitive
30   element of the resonant circuit. Controller adjustment of the source voltage frequency preferably maximizes a voltage developed over a capacitive element of the resonant circuit of the untethered device.

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In accordance with other embodiments, methods of the present invention may be implemented involving an untethered device configured to inductively couple to a source device. Methods of the present invention may involve driving a drive coil circuit of the source device with a source voltage having an adjustable frequency, the drive coil circuit
5   generating a varying magnetic field. Methods may further involve detecting a phase of an input impedance of the drive coil circuit in response to inductively coupling the source device and the untethered device, and adjusting the source voltage frequency so that the phase of the input impedance of the drive coil circuit is substantially zero.

Adjusting of the source voltage frequency preferably compensates for a change in
10   a resonance frequency of the resonant circuit of the untethered device or a change in a parameter of the resonant circuit of the untethered device, such as a parameter of one or more of a resistive element, inductive element, and a capacitive element of the resonant circuit. Adjusting of the source voltage frequency preferably maximizes a voltage developed over a capacitive element of the resonant circuit of the untethered device.

15   In various embodiments, the source device may include an RFID reader and the untethered device may include an RFID tag. In other embodiments, the source device includes a digitizer and the untethered device is configured as a stylus.

The above summary of the present invention is not intended to describe each embodiment or every implementation of the present invention. Advantages and
20   attainments, together with a more complete understanding of the invention, will become apparent and appreciated by referring to the following detailed description and claims taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

25   Figure 1 is a diagram of a location sensing system that includes an untethered stylus and a location sensing device in accordance with embodiments of the present invention;

Figure 2 is a diagram of various components of a location sensing device that cooperates with a stylus in accordance with embodiments of the present invention;

30   Figure 3 is a diagram of an apparatus for generating an excitation magnetic field which is received by a stylus in accordance with embodiments of the present invention;

Figure 4 is an illustration of various components of a stylus implemented in accordance with embodiments of the present invention;

Figure 5 shows a schematic model of a parallel coil-capacitor circuit that may be incorporated in a stylus or other device, such as an RFID tag, in accordance with embodiments of the present invention;

Figure 6 is a block diagram of one illustrative implementation that provides for continuous tuning of resonant circuitry of an untethered device, such as a stylus or RFID tag, in accordance with embodiments of the present invention;

Figure 7 is a schematic of circuitry of a source device and an untethered device in accordance with embodiments of the present invention;

Figure 8 is a block diagram of a frequency control circuit in accordance with embodiments of the present invention;

Figure 9 is a plot of $\cos\varphi$ versus normalized resonance frequency f_{res}/f_s for different $R_1 C$ time constants in connection with the circuitry shown in Figure 7, the plot of Figure 9 showing a desired zero value at the imposed source frequency f_s in accordance with embodiments of the present invention;

Figure 10 is a schematic of circuitry for controlling the resonance frequency of inductive-capacitive (LC) circuitry of an untethered device in accordance with embodiments of the present invention;

Figures 11 and 12 show the results of changing a control voltage, V_c, on the resonance frequency of LC circuitry shown in Figure 10;

Figure 13 is a block diagram of components that provide for self-tuning of the frequency of a drive source that inductively couples to an LC circuit of an untethered device, such as a stylus or RFID tag, in accordance with embodiments of the present invention;

Figure 14 is a schematic of circuitry that may be incorporated in the source device and untethered device shown in Figure 13;

Figure 15 is a plot of capacitor voltage and input impedance phase as a function of frequency in connection with the circuitry depicted in Figures 13 and 14; and

Figure 16 is a plot of the phase of source device input impedance, Z_{in}, for different values of k in connection with the circuitry depicted in Figures 13 and 14.

While the invention is amenable to various modifications and alternative forms, specifics thereof have been shown by way of example in the drawings and will be described in detail. It is to be understood, however, that the intention is not to limit the invention to the particular embodiments described. On the contrary, the intention is to

5   cover all modifications, equivalents, and alternatives falling within the scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION OF EMBODIMENTS

In the following description of the illustrated embodiments, reference is made to

10   the accompanying drawings which form a part hereof, and in which is shown by way of illustration, various embodiments in which the invention may be practiced. It is to be understood that the embodiments may be utilized and structural changes may be made without departing from the scope of the present invention.

The present invention is directed to methods and systems for effecting

15   communication between an untethered device and a sensing system. Embodiments of the present invention provide for enhanced communication of information, such as analog and/or digital information, between the untethered device and the sensing system. Exemplary embodiments of the untethered device include a stylus or RFID tag. Exemplary embodiments of the sensing system include a device locating sensor or touch

20   location sensor, such as a digitizer, or a RFID reader. Other examples of untethered devices include game pieces that interacts with a game board or other structure that incorporates a sensing system. It is understood that methods and systems in accordance with the present invention may be implemented in a wide range devices and systems other than those particularly described herein.

25   Embodiments of the present invention are directed to tuning of resonant circuitry provided at an untethered device, such as a stylus or RFID tag. Implementations of such embodiments provide for optimal continuous tuning of resonant circuitry in an untethered device, such as by extracting an error control signal that can be used in a feedback mechanism to self-tune the resonance frequency of inductive-capacitive circuits. In this

30   manner, the need for time consuming hand tuning of individual circuits at the manufacturing level is eliminated, and optimal performance under varying external conditions, such as temperature, is achieved.

Other embodiments of the present invention are directed to controlling the resonance frequency of LC circuits in an untethered device using a control voltage to change the capacitance, *C,* of this LC circuit. An automatic mechanism using feedback according to such embodiments provides for precise and continuous tuning of the

5   capacitor value, *C,* in order to ensure optimal circuit performance. Such a mechanism obviates time consuming and expensive manual tuning of component values and subsequent detuning because of slowly changing conditions.

According to further embodiments of the present invention, methodologies provide for self-tuning the frequency of a source device, so as to optimize an induced voltage over

10   a capacitor in an LC circuit of an untethered device. Such embodiments provide methodologies for self-tuning the frequency of a driver that inductively couples to the LC circuit of an untethered device so that a maximum voltage is developed over the capacitor *C* in the LC circuit.

Embodiments of an untethered stylus of the present invention may be implemented

15   in the context of a location sensing system, embodiments of which are illustrated in Figures 1-3. According to the embodiments shown in Figures 1-3, a location sensing system 10 includes a stylus 12 that interacts with a sensing device 11. The sensing device 11 includes a location sensor 14, such as a digitizer. The stylus 12 is preferably configured as a tetherless or cordless implement that does not have a battery. Rather, the

20   stylus 12 derives power from a magnetic field generated by the sensing device 11. Although preferred embodiments of an untethered stylus do not include a battery, some embodiments may employ a battery, such as a rechargeable battery that is recharged from energy derived from the magnetic field of the drive signal. A battery may be used to provide power to various circuits of the stylus, such as a modulator or pressure sensor

25   (e.g., tip or eraser pressure sensor).

The sensing device 11 is shown to include a drive loop or coil 18 coupled to drive loop electronics 16 that cooperate to generate a magnetic field, which may be a continuously varying magnetic field. Drive coil 18 may comprise one or more coils or loops. The stylus 12, having derived power from the magnetic field emanating from the

30   drive coil 18, broadcasts a signal from which stylus location and status may be determined by the sensing device 11.

The stylus 12 is preferably configured to include one or more user-actuatable buttons or switches, such as those commonly employed to implement various mouse functions (e.g., right and left mouse buttons). The tip of the stylus 12 may incorporate a pressure sensor from which applied pressure can be resolved and transmitted to the sensing device 11. Eraser functionality may also be incorporated in the form of a switch or pressure sensor at the stylus end opposite the tip.

Sensor interface electronics 20 is coupled to the sensor 14 and facilitates measurement of signals developed at the sensor 14 in response to signals broadcast by the stylus 12. According to one configuration, the sensor 14 includes a digitizer that incorporates a detection grid and electronics as is known in the art. For example, such a detection grid may include pairs of position resolving conductors each of which forms one or more differential coil elements in the sensor 14, with each conductor pair receiving a magnetic signal transmitted by the stylus 14. An illustrative example of a digitizer having such a detection grid configuration, elements of which may be employed in a location sensor system of the present invention, is disclosed in U.S. Patent Nos. 4,786,765; 5,218,174; 5,633,471; 5,793,360; 6,667,740; and 7,019,672; which are hereby incorporated herein by reference.

According to another configuration, the sensing device 11 may incorporate a sensor 14 that effectively incorporates a digitizer and a touch-sensitive sensor. The digitizer, according to this configuration, allows the location and status of the stylus 12 to be determined. The touch-sensitive sensor allows the location of a finger touch to be determined. This configuration allows a user to use either the stylus 12 or a finger to indicate a desired location on a computer display, as well as determine the location and status of the stylus 12.

The touch-sensitive sensor 14 typically includes a matrix that capacitively couples to the stylus 12 and/or a finger. In this configuration, the sensor 14 of the sensing device 11 is preferably made up of a series of transparent conductors placed upon a glass or plastic cover that can be placed in front of an LCD display. One side of the glass or plastic sheet has conductors in the X direction, and the opposite side has conductors in the Y direction. Examples of suitable touch sensitive sensors 14 are disclosed in commonly owned U.S. Patent Nos. 6,133,906 and 6,970,160, in commonly owned U.S. Published Application No. 2005/0083307, in U.S. Patent Nos. 6,762,752 and 6,690,156, and in U.S.

Published Application No. 2004/0095333, each of which is hereby incorporated herein by reference.

An embodiment that incorporates a digitizer and touch-sensitive sensor advantageously allows a user to point a stylus at a computer display and have the location
5   and status of the pointing device determined and, when a finger is used to point at the display device, allows for the determination of the location of a finger touch at the display device. The dual use aspects of this embodiment of a sensing device 11 make it particularly useful in tablet PC applications.

For example, a digitizer arrangement allows a user to use a stylus to input
10   information, indicate operations the user wants to take, and write or draw on the display. The touch-sensitive sensor allows the user to "type" information onto a virtual keyboard on the display screen, for example. This would allow the vendor of the computing system, in which a dual touch location sensor system of the present invention is implemented, to eliminate the keyboard and the associated bulk it requires. It is understood that a digitizer
15   and a touch-sensitive sensor need not be implemented together in all configurations, but inclusion of both sensing devices provides for enhanced user interaction with a computing system that incorporates a sensing system 10 of the present invention.

According to one embodiment, the drive coil 18 may be constructed of wire, such as 36 gauge wire, looped several times (e.g., 4 times) around the periphery of the frame of
20   sensing device 11. In one implementation, the drive coil 18 may have an inductance of about 21 μH and an impedance of about 14 Ohms at 100 kHz. The drive coil 18 is connected to a signal generator of the drive loop electronics 16. The signal generator may be configured to produce 200 periods of a 100 kHz sine wave signal gated at 250 Hz. The signal generator may, for example, produce an output signal of 0.4 V_{pp}, resulting in
25   approximately 28mA of current that flows in the drive coil 18.

Figure 3 is a simplified illustration of drive coil 18 and a signal generator 17 that cooperate to generate a magnetic excitation field. In this illustrative example, one or more coils are preferably arranged in the plane of the location sensor. A sinusoidal current is produced by the signal generator 17 with peak magnitude A_I at radian frequency ω_1 and is
30   applied to the rectangular coil 18.

The stylus 12 is configured to collect energy from the magnetic field generated by drive coil 18/drive loop electronics 16 using a tank circuit. The tank circuit is preferably

tuned to resonate at the frequency that the drive coil 18 is driven. In this illustrative example, the frequency is set at 100 kHz. The tank circuit of the stylus 12 builds amplitude during the burst produced by the drive coil 18 and then gradually loses signal amplitude after the drive coil 18 is turned off. The time associated with the exponential

5   charging and discharging of the resonant tank circuit of the stylus 12 is determined by the capacitive and inductive elements in the tank circuit. Matching of the tank circuit's resonance frequency and the drive signal frequency is preferably accomplished using one or more of the techniques described hereinbelow.

        Referring again to Figure 1, the sensor interface electronics 20 is preferably

10   connected to the sensor 14 via a shielded connector. The sensor interface electronics 20 includes circuitry for measuring the signal levels present on the individual traces of the sensor 14, and is typically configured to reject as much noise as possible.

        As is shown in Figure 2, an envelope detector circuit 30 of the sensor interface electronics 20 is configured to detect signals developed on individual traces of the sensor

15   14. The signals output by the envelope detector circuit 30 are digitized by use of analog-to-digital (A/D) converters 32. Each trace of the sensor 14 may have a dedicated A/D converter 32. Alternatively, two or more traces may share a common A/D converter 32 via a switch having a sufficient switching frequency. The envelope detector circuit 30 is configured to provide sufficient gain to make the resultant signal match the requirements

20   of A/D converters 32. The envelope detector circuit 30 may be configured to generate a signal having the same shape as an imaginary line describing the upper bound of the sensor signal. In such a configuration, the envelope detector circuit 30 effectively transforms the 100 kHz signal into a DC or low frequency signal that is more readily digitized. The envelope detector circuit 30 preferably incorporates one or more

25   synchronous demodulators.

        A processor 22 is coupled to the drive loop electronics 16, sensor interface electronics 20, and a communications interface 24, as is shown in Figure 1. The processor 22 coordinates the operations of drive loop electronics 16 and sensor interface electronics 20, and is configured to determine stylus/finger location and stylus status. Stylus/finger

30   location and stylus status determinations may be made by the processor 22 using known approaches, such as those discussed in the patent references incorporated herein by reference. In one embodiment, processor 22 determines stylus/finger location and stylus

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status in accordance with the methodologies disclosed in commonly owned U.S. Patent Application No. 11/557,829, entitled "Touch Location Sensing System and Method Employing Sensor Data Fitting to a Predefined Curve," filed on November 8, 2006, which is hereby incorporated herein by reference.

5   The location and status information computed by the processor 22 is communicated to a computer and/or display 26 via a communications interface 24. The communications interface 24 may be configured as an RS-232 or USB interface, for example. The processor 22 may be configured to drive a display 26 directly. Alternatively, a computer 28 may be coupled to the communications interface 24 and

10   receive the location and status information from the processor 22, and drive its display. The processor 22 or computer 28 may be configured to control cursor velocity, momentum and other factors to enhance the user experience with the sensing system 11.

       Referring now to Figure 4, there is shown an embodiment of an untethered stylus 12 of the present invention that may be implemented in the context of a location sensing

15   system as described above or other sensing system known in the art. In accordance with the embodiment shown in Figure 4, a stylus 12 houses electronics 52, which includes frequency sensitive LC circuitry, and a coil 54 wrapped around a ferrite cylinder 53. The ferrite cylinder 53 serves to increase signal amplitude. An applied harmonic magnetic field produced at the surface of the location sensor (e.g., digitizer) or a display, for

20   example, couples flux through the ferrite cylinder 53 and thus to the coil 54 when the stylus 12 is placed in the applied field.

       The ferrite coil arrangement 56 resonates with a separate parallel-connected capacitor of the electronics 52 and is tuned to the excitation field frequency. In various embodiments, circuitry 55 is provided in the untethered stylus 12 to provide for self-

25   tuning of the resonance frequency of the frequency sensitive LC circuitry in accordance with one or more techniques described herein. In other embodiments, the frequency of a source voltage produced by the source device that generates the excitation field is adjusted so that the phase of an input impedance of the source device is substantially zero, thereby maximizing a voltage across the capacitor of the frequency sensitive LC circuitry of the

30   untethered stylus 12.

       The parallel coil-capacitor combination is connected between the stylus tip 57 and the stylus shield 59. The shield 59 may form part of, or otherwise be connected to, the

stylus housing so that it can be touched, and therefore grounded, by a user's hand when held. The shield 59 may be situated to extend over the circuitry region of the stylus 12, and preferably has a discontinuous shape, such as a "C" shape, so as to avoid eddy currents that could otherwise arise in a closed loop shield arrangement.

5   The stylus tip 57 couples capacitively to the location sensor from which location information is derived. To provide stylus status information, the ferrite coil arrangement 56 powers the electronics 52 which amplitude modulates the stylus tip voltage at the reference frequency or frequencies. The frequency of the oscillations is changed to reflect the stylus status, such as switch closures or tip pressure changes.

10   Alternatively, the invention may be implemented with magnetic-sensing digitizer systems as are known in the art. An untethered magnetic stylus is similar to the capacitive stylus shown in Figure 4, except the resonant circuit comprising ferrite coil arrangement 56 and separate parallel-connected capacitor of the electronics 52 need not be connected to tip 57 nor to a shield 59. Untethered magnetic styluses are well known in the art, and are

15   described in previously incorporated U.S. Patent Nos. 4,786,765; 5633471; 5793360; 6,667,740, and 7,019,672. Embodiments of the present invention that are implemented using an untethered magnetic stylus may employ a location sensor that includes multiple drive loops as disclosed in the referenced patents. In such embodiments, a separate sensing grid and separate drive loops need not used. Rather, each of the drive loop coils is

20   alternately coupled to transmitting circuitry and then to receiving circuitry to alternately transmit and receive from one of multiple drive loop coils that are placed in the active area, typically under the display.

           Figure 5 shows a schematic model of a parallel coil-capacitor circuit that facilitates an enhanced understanding of the present invention. The parallel coil-capacitor circuit

25   shown in Figure 5 (i.e., tank circuit) may be incorporated in a stylus as part of, or coupled to, resonance frequency tuning circuitry in accordance with embodiments of the present invention. Figure 5 shows a capacitor $C1$ connected in parallel with a coil 54 to resonate at the excitation frequency or the transmitted frequency. The voltage developed across the coil 54, which is shown modeled as voltage generator 61, is coupled to the stylus tip 57

30   and then capacitively coupled to the location sensor, such as sensor 14 shown in Figure 1. The voltage developed across the resonating coil 54 is preferably modulated with one or a combination of known techniques. An added ferrite cylinder 53 about which coil 54 is

preferably wrapped, as shown in Figure 5, has the effect of increasing the magnetic flux B and signal coupled by the drive coil of the location sensor to the receiving coil 54 of the stylus 12.

The capacitance value of capacitor $C1$ shown in Figure 5 is selected such that the capacitance, C, of capacitor $C1$ resonates with the coil inductance, L, at the excitation angular frequency ω so that there is no voltage drop across the LC combination. Two different voltages in this circuit can be considered. The first voltage of consideration is the voltage V (shown in terms of voltage source 61) that develops across the coil 54 through magnetic induction. It is well understood that this voltage 61 is basically equal to the number of stylus coil turns N times the coil cross section A times the rate of change of the magnetic flux density passing through the ferrite cylinder, which is given by $V=N*A*dB/dt$.

The second voltage of consideration is the voltage that develops across the capacitor $C1$. This voltage V_C is also the stylus tip voltage. From basic circuit analysis at resonance, it follows that: $V_C = V/(\omega RC) = V(\omega L/R)$ with the quantity $1/(\omega RC) = (L\omega)/R$ defined as the resonant circuit quality factor Q, where ω is expressed in terms of radians per second. This second voltage may be modulated for purposes of communicating stylus status data to a location sensor.

With continued reference to Figure 5, one approach to transmitting stylus status information in addition to stylus position information is through addition of a second capacitor $C2$ connected to the first capacitor $C1$ through a switch 16. Opening and closing the switch 16 causes the resonance frequency of the coil-capacitor combination 54/$C1$ to change. This change may be detected by observing a change in phase of the stylus transmitted frequency or though a transient frequency change caused when the drive coil current is turned off.

This method of data transmission, however, is not suitable for a stylus powered by a constantly varying magnetic field and capacitively coupled to the digitizer. Constant excitation does not allow a transient measurement of the stylus resonance, and phase modulation is difficult to detect as the phase of the digitizer received signal varies dramatically as the stylus is moved across the location sensor (e.g., digitizer). Frequency modulation of an amplitude-modulated signal using multiple reference frequencies generated at the stylus, for example, removes these difficulties. The location sensor may

be configured to demodulate the amplitude modulation and detect the reference frequencies of the modulation.

Figure 6 is a block diagram of one illustrative implementation that provides for continuous tuning of resonant circuitry of an untethered device 12, such as a stylus or

5   RFID tag. According to this illustrative embodiment, the untethered device 12 implements a method of extracting an error control signal that can be used in a feedback mechanism to self-tune the resonance frequency of LC circuitry of the untethered device 12.

According to the implementation shown in Figure 6, an untethered device 12

10   includes a tunable resonant circuit 62, which includes inductive and capacitive circuit components. The tunable resonant circuit 62 has a resonance frequency that can be continuously adjusted to match the frequency of the source device 60. The source device 60 typically generates a varying magnetic field having a fixed frequency.

The untethered device 12 is further shown to include a frequency control circuit

15   64, which is coupled to the tunable resonant circuit 62 via a control line 66. The frequency control circuit 64 is configured to produce a control signal, S_c, using signals developed within the tunable resonant circuit 62. In this illustrative example, voltage signals V_1 and V_2, developed within the tunable resonant circuit 62, are extracted for use in tuning the tunable resonant circuit 62. The control signal, S_C, generated by the frequency

20   control circuit 64, is useable to adjust the resonance frequency of the tunable resonant circuit 62 to match the fixed frequency of the source device 60.

Turning now to Figure 7, there is shown a schematic of circuitry of a source device 60 and an untethered device 12 in accordance with embodiments of the present invention. In configurations in which the untethered device 12 is implemented as an RFID tag, the

25   L_1-C circuit 72, 74 is referred to as the "tag," while the L_0 inductance component 71 is part of a "reader," with fixed frequency f_s. It is understood that the circuitry shown in Figure 7 and in other Figures may be employed in systems and devices other than those that employ untethered styli and RFID tags.

In conventional implementations, the components L_1 72 and C 74 are fixed, such

30   that the resonance frequency, f_{res}, of the L_1-C combination 72, 74 is defined as:

$$f_{res} = \frac{1}{2\pi\sqrt{L_1 C}}$$

The resonance frequency, f_{res}, of the L_1-C combination 72, 74 is not exactly equal to the source frequency, f_s. As a result, the voltage V_2 that develops across the capacitor C 74 is lower than desired. Because this voltage, V_2, is often used to power additional circuitry or communication electronics, a reduced voltage across the capacitor C 74 results in suboptimal performance. A tunable resonant circuit with frequency control in accordance with the present invention provides an improvement in performance, in that L_1 72, C 74 or both may be automatically and continuously tuned so that the resonance frequency, f_{res}, of the L_1-C combination 72, 74 becomes exactly equal to the frequency, f_s, of the source device 60.

Defining the angular resonance frequency $\omega_{res} = 2\pi f_{res}$ and applying Kirchoff's laws to the circuit in Figure 7 leads to the following:

$$\frac{V_2}{V_1} = \frac{\left(\omega^2 - \omega_{res}^2\right)}{\omega_{res}^2}\frac{R_2}{R_1} - j\omega R_2 C$$

so that the phase angle, φ between V_1 and V_2 is given by:

$$\varphi = \arctan\frac{\omega_{res}^2}{\omega_{res}^2 - \omega^2}\omega R_1 C = \arctan\frac{2\pi f R_1 C}{\left(1-\left(f/f_{res}\right)^2\right)}$$

Voltage signals V_1 and V_2 developed as shown in Figure 7 are preferably fed to a frequency control circuit, a general embodiment of which is shown in Figure 6. Using the voltage signals V_1 and V_2 as inputs, the frequency control circuit produces a control signal that is fed back to the resonant circuitry which, in response, results in adjustment of the resonance frequency of the untethered device 12 to match the frequency of the source voltage produced by the source device 60.

In general, the control signal generated by the frequency control circuit is preferably a signal that is proportional to the voltage signals V_1 and V_2. The control signal may also be a signal that is proportional to the voltage signal V_2. According to one

approach, the control signal is preferably produced by a multiplication of the voltage signals V_1 and V_2. If V_1 and V_2 are harmonic and have the same frequency but a phase shift of φ, as defined above, the multiplication results in the following:

$$
\begin{aligned}
V_{out} &= V_1 \cos\omega t * V_2 \cos(\omega t - \varphi) \\
&= \frac{V_1 V_2}{2} \{\cos\varphi + \cos(2\omega t - \varphi)\}
\end{aligned}
$$

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The first term in the brackets of the resultant equation, $\cos\varphi$, is the desired control signal component. The second term, $\cos(2\omega t - \varphi)$, is a double frequency signal component that is undesirable. This second term is preferably filtered out of the control signal, which, after filtering, can be represented as $V_c \cos\varphi$. Those skilled in the art will appreciate that

10   various known techniques used in a variety of mixing and superheterodyning applications may be employed to extract a control signal usable to adjust the resonance frequency of the tunable resonant circuit of the untethered device 12 to match the fixed frequency of the source device 60 in accordance with the present invention.

15   Figure 8 is a diagram of one implementation of a frequency control circuit in accordance with embodiments of the present invention. The frequency control circuit shown in Figure 8 includes a multiplier 93 coupled to a low pass filter 95. The voltage signals V_1 and V_2, such as those shown in Figures 6 and 7, are fed into the multiplier 93. The output of the multiplier 93, V_{out}, is a voltage signal produced by a direct

20   multiplication of V_1 and V_2, such that $V_{out} = V_1 * V_2$.

As discussed above, if V_1 and V_2 are harmonic and have the same frequency but a phase shift of φ, then V_{out} is calculated according to the equation above. This signal, V_{out}, is then fed to the low pass filter 95, which may be configured to filter out the double frequency signal component discussed above or to simply pass only a DC signal. The

25   output of low pass filter 95 is the control signal $V_c \cos\varphi$. It is noted that both V_1 and V_2 will not vanish near the resonance frequency, f_{res}, of the untethered device's tunable resonant circuit, so that V_c will always have an acceptable amplitude.

In low frequency applications (e.g., < 1 MHz), the multiplier 93 may include an analog multiplier chip, such as a four-quadrant analog multiplier model AD633 available

from Analog Devices, Inc. For high frequency applications (i.e., > 1 MHz), any suitable mixer may be used.

Figure 9 is a plot of $\cos\varphi$ versus normalized resonance frequency f_{res}/f_s for different R_1C time constants in connection with the frequency control circuit shown in Figure 8. The plot of Figure 9 clearly shows a desired zero value at the imposed source frequency f_s. Thus, the signal $V_c\cos\varphi$ can be used as a control signal to force the L_1-C circuit shown in Figure 7 to adjust f_{res} to become equal to f_s through a feedback mechanism. Figure 9 shows that the dynamic range of $\cos\varphi$ is greater for smaller values of R_1 and C. A small value of R_1 is consistent with the requirement that the resonance circuit has a high Q value.

Figure 10 is a schematic of circuitry for controlling the resonance frequency of LC circuitry of an untethered device in accordance with other embodiments of the present invention. Control circuitry implemented in accordance with embodiments encompassed by Figure 10 provides for controlling the resonance frequency of LC circuitry of an untethered device using a control voltage that changes the capacitance, C, of the LC circuitry.

It is understood by those skilled in the art that inductances (L) and capacitances (C), as well as other factors, influence the resonance frequency of a circuit made up of these components. For high quality circuits, for example, resonance frequency variation can be very sensitive for even slightly different component values. To avoid time consuming and thus expensive manual tuning of component values, and to avoid subsequent detuning because of slowly changing conditions, an automatic mechanism using feedback in accordance with embodiments of the present invention provides for precise continuous tuning of the capacitor value, C, to ensure optimal circuit performance.

Figure 10 shows one configuration of a voltage controlled resonance frequency LC circuit in accordance with embodiments of the present invention. In the implementation shown in Figure 10, a coil 79 represents an inductance L of the circuit, and C_1 81 and C_2 82 are varactor diodes that are always driven in reverse so that they behave as capacitances. An output of an OPAMP 80 is shown coupled to the center tap of the coil 79. In this arrangement, the OPAMP output voltage as the center tap voltage for coil 79 placed both varactor diodes 81, 82 in reverse bias with the same voltage, so that both V_b and V_c can control the resonance frequency of the L, C_1, C_2 combination.

The bias voltage, V_b, is essentially DC and the control voltage, V_c is at most slowly varying compared to the resonance frequency of the LC circuit. The OPAMP output voltage, V_o, is given by:

$$V_o = -\frac{R_3}{R_1}V_c - \frac{R_3}{R_2}V_b$$

Demanding that varactor diodes C_1 81 and C_2 82 are always driven in reverse or that the OPAMP output voltage, V_o, is always negative, as given below:

$$-V_s < V_o < 0$$

results in the following allowed operating range for the control voltage, V_c :

$$-\frac{R_1}{R_2}V_b < V_c < \frac{R_1}{R_3}V_s - \frac{R_1}{R_2}V_b$$

When R_1 70 = R_2 77 = R_3 78, and with $V_b = 0.5V_s$, the control voltage, V_c, has the following desirable range:

$$-\frac{V_s}{2} < V_c < \frac{V_s}{2}$$

Because of the anti-series arrangement of the varactor diodes C_1 81 and C_2 82, an external alternating flux that is coupled by coil 79 will induce a voltage over coil 79 that will cause varactor diode C_1 81 to be driven less in reverse and varactor diode C_2 82 more in reverse. Assuming a linear varactor capacitance-voltage dependence $\Delta C = k\Delta V$, this means that varactor diode C_1 81 undergoes a capacitance change $+\Delta C$ whereas varactor diode C_2 82 undergoes a $-\Delta C$ change. With $C_1 = C_2 = C$, the total capacitance, C_t, formed by C_1 81 and C_2 82 is then given by:

$$\frac{1}{C_t} = \frac{1}{C + \Delta C} + \frac{1}{C - \Delta C}$$

so that:

$$C_t = \frac{C}{2} - \frac{(k\Delta V)^2}{2C}$$

meaning that the total capacitance, C_t, is virtually AC voltage amplitude independent, except for a second order effect.

In one implementation, a total of 8 varactor diodes as 2 groups of 4 parallel diodes may be used to form C_1 81 and C_2 82. A ferrite containing self-inductance (L) coil 79 of 22 mH may be used so that the total capacitance, $C_t = C_1C_2/(C_1+C_2)$, at $V_b = 7.5$ V and V_c = 0 V is estimated to be about 115 pF. Therefore, C_1 81 and C_2 82 each have a capacitance of approximately 230 pF. The sensitivity for such an implementation is around 1 kHz/V.

The circuit in Figure 10 may be implemented using silicon varactor diodes, such as MVAM115 silicon varactor diodes available from Advanced Semiconductor, Inc. OPAMP 80 is preferably a low noise OPAMP, such as OP27 Low Noise, Precision Operational Amplifier available from Analog Devices, Inc.

Figures 11 and 12 show the results of changing control voltage, V_c, on the resonance frequency. Figure 11 shows a resonance peak for $V_c = 0$ volt, at a resonance frequency ≈ 100 kHz. Figure 12 shows a resonance peak for $V_c = 5$ volt, at a resonance frequency ≈ 95 kHz. The frequency spectra in Figures 11 and 12 were obtained by inductively inducing a white spectrum into coil 79 and measuring the LC circuit response after changing V_c.

Further embodiments of the present invention are directed to self-tuning the frequency of a drive source that inductively couples to an LC circuit of an untethered device, such as a stylus or RFID tag, so that a maximum voltage develops over the capacitor, C, in the LC circuit. Figure 13 illustrates an implementation of one such embodiment, in which a source device 60 inductively couples to an LC circuit in an untethered device 12. The source device 60 is shown to include a driver circuit 92 coupled to drive coil 18, which may include one or more coils. The driver circuit 92 may be implemented as part of the drive loop electronics 16 shown in Figure 1.

Also shown in Figure 13 is a phase detector 96 coupled to the driver circuit 92, the driver circuit 92 further including a drive coil circuit. A controller 94 is coupled to the phase detector 96 and the driver circuit 92. The controller 94 may be part of, or coupled to, the processor 22 shown in Figures 1 and 2.

In operation, the driver circuit 92 and drive coil 18 cooperate to generate a varying magnetic field. The phase detector 96 detects a phase of an input impedance of the driver circuit 92 in response to the source device 60 inductively coupling with the LC circuit of the untethered device 12. The controller 94 adjusts a frequency of a source voltage

5   applied to the driver circuit 92 in response to an output signal of the phase detector 96. The controller 94, which may be implemented using a voltage controlled oscillator, adjusts the source voltage frequency so that the phase of the input impedance as indicated by the output signal of the phase detector 96 is substantially zero. In this manner, controller adjustment of the source voltage frequency compensates for a change in the

10   resonance frequency, or a parameter of the resonance frequency, of the resonant LC circuit of the untethered device 12.

Figure 14 is a schematic of circuitry that may be incorporated in the source device 60 and untethered device 12 shown in Figure 13. Figure 14 shows the source device 60 inductively coupled to an LC resonance circuit of the untethered device 12. The

15   frequency matching methodology according to this embodiment involves detecting the phase of the source device's input impedance, Z_{in} (looking into the drive coil 84 (L_1)), such as by use of a phase detector, and adjusting the frequency of the source voltage V 65 until that phase is zero. The output of the phase detector can then be used in a feedback circuit to drive a voltage controlled oscillator (VCO), for example, with V as an output

20   signal.

A variety of available phase detectors may be used to perform phase detection and comparison. In low frequency applications (i.e. < 1 MHz), for example, an analog multiplier, such as the aforementioned AD633, may be used. In higher frequency applications (i.e., > 1 MHz), a passive component, such as a PDP-201 Phase Detector

25   available from Synergy Microwave Corporation, may be used for phase detection. Other commercial components and implementation may be used that provide similar functionality and performance.

The following analysis is provided with reference to Figure 14. With sufficient coupling k, the phase of Z_{in} is zero at the frequency that corresponds with the maximum

30   voltage V_c. Applying Kirchoff's laws to the circuit in Figure 14 leads to:

$$\frac{V_c}{V} = \frac{1}{C} \cdot \frac{k\sqrt{L_1 L_2}}{\left(R_1 + j\omega L_1\right)\left(R_2 + j\omega L_2 - \frac{j}{\omega C}\right) + \omega^2 k^2 L_1 L_2}$$ [1]

with ω angular frequency, whereas Z_{in} is given by:

$$Z_{in} = R_1 + j\omega L_1 + \frac{k^2 \omega^2 L_1 L_2}{R_2 + j\omega L_2 - \frac{j}{\omega C}}$$ [2]

5

Figure 15 is a plot of capacitor voltage and input impedance phase as a function of frequency. More particularly, Figure 15 is a plot of the voltage ratio V_c/V of equation [1] and phase, Z_{in}, of equation [2] for the following values of the components shown in Figure

10   14: $L_1 = 45$ μH, $L_2 = 22$ mH, $R_1 = 9\Omega$, $R_2 = 40\Omega$, $C\ 87 = 153.5$ pF, and $k = 0.5$. As is clear in Figure 15, the capacitor voltage, V_c, is maximum near the higher frequency point where the phase of the input impedance, Z_{in}, is zero.

The source frequency self-tuning methodology described above works well for strong coupling or high values of k, where k takes on values between 0 and 1 (i.e., $0 < k <$

15   1). Figure 16 gives an indication of the phase of Z_{in} for different values of k. It can be seen from Figure 16 that the detection mechanism breaks down when k gets too small because the phase of Z_{in} no longer goes through zero. The fact that the phase of Z_{in} for $k = 0.1$ fails to go through zero in Figure 16 may not be entirely obvious, but this fact can easily be confirmed by reproducing the graph depicted in Figure 16 using Equation [2]

20   above.

The foregoing description of the various embodiments of the invention has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. It is intended that the scope of the

25   invention be limited not by this detailed description, but rather by the claims appended hereto.

CLAIMS

What is claimed is:

1.   A source device configured to cooperate with an untethered device comprising a
resonant circuit, the source device comprising:

a driver circuit configured to generate a varying magnetic field and comprising a
drive coil circuit;

a phase detector coupled to the driver circuit and configured to detect a phase of an
input impedance of the driver circuit in response to the source device inductively coupling
with the resonant circuit of the untethered device; and

a controller coupled to the phase detector and the driver circuit, the controller
configured to adjust a frequency of a source voltage applied to the driver circuit in
response to an output signal of the phase detector, the controller adjusting the source
voltage frequency so that the phase of the input impedance as indicated by the output
signal of the phase detector is substantially zero.

2.   The device of claim 1, wherein controller adjustment of the source voltage
frequency compensates for a change in a resonance frequency of the resonant circuit of the
untethered device.

3.   The device of claim 1, wherein controller adjustment of the source voltage
frequency compensates for a change in a parameter of the resonant circuit of the
untethered device.

4.   The device of claim 1, wherein the controller comprises a voltage controlled
oscillator.

5.   The device of claim 1, wherein the source device comprises a digitizer and the
untethered device comprises a stylus.

6.   The device of claim 1, wherein the source device comprises an RFID reader and
the untethered device comprises an RFID tag.

7.   A system, comprising:

an untethered device comprising a resonant circuit; and

a source device configured to inductively couple to the untethered device, the

5   source device comprising:

a driver circuit configured to generate a varying magnetic field and

comprising a drive coil circuit;

a phase detector coupled to the driver circuit and configured to detect a

phase of an input impedance of the driver circuit in response to inductively coupling the

10   source device and the untethered device; and

a controller coupled to the phase detector and the driver circuit, the

controller configured to adjust a frequency of a source voltage applied to the driver circuit

in response to an output signal of the phase detector, the controller adjusting the source

voltage frequency so that the phase of the input impedance as indicated by the output

15   signal of the phase detector is substantially zero.

8.   The system of claim 7, wherein controller adjustment of the source voltage

frequency compensates for a change in a resonance frequency of the resonant circuit of the

untethered device.

20

9.   The system of claim 7, wherein controller adjustment of the source voltage

frequency compensates for a change in a parameter of the resonant circuit of the

untethered device.

25   10.   The system of claim 9, wherein the parameter of the resonant circuit subject to

change comprises a parameter of one or more of a resistive element, inductive element,
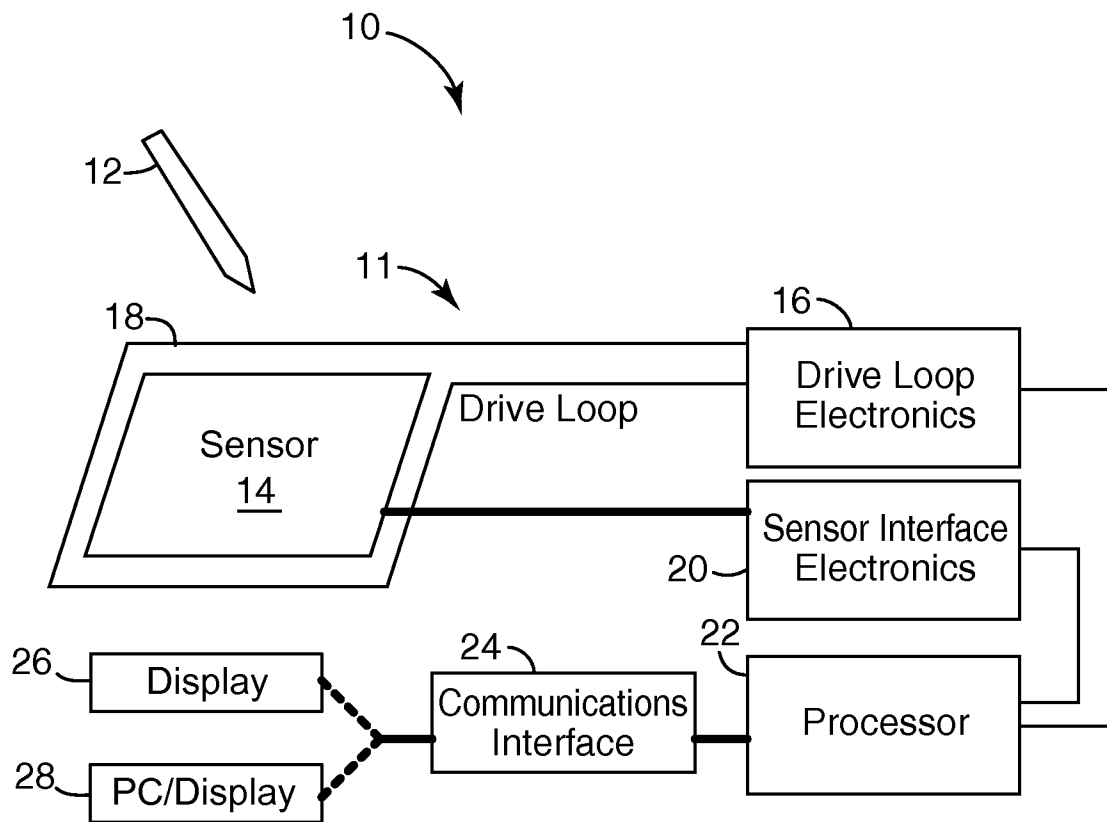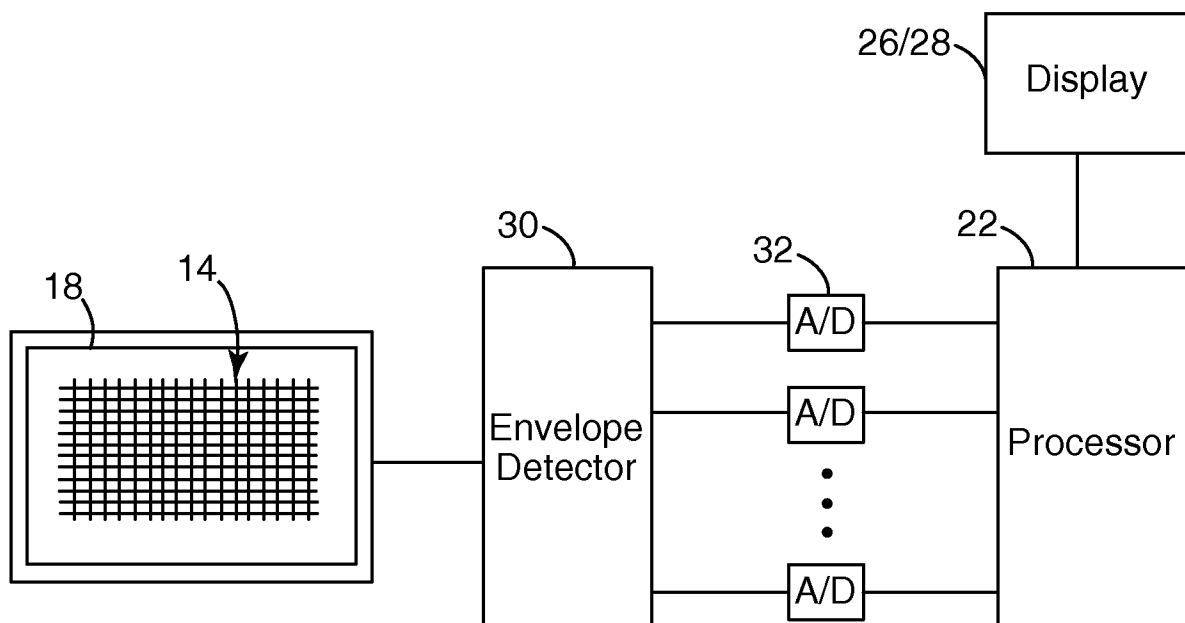
and a capacitive element of the resonant circuit.

11.   The system of claim 7, wherein controller adjustment of the source voltage

30   frequency maximizes a voltage developed over a capacitive element of the resonant circuit

of the untethered device.

12.   The system of claim 7, wherein the source device comprises an RFID reader and the untethered device comprises an RFID tag.

13.   The system of claim 7, wherein the source device comprises a digitizer and the untethered device comprises a stylus.

14.   A method implemented in a source device configured to inductively couple to an untethered device having a resonant circuit, the method comprising:

        driving a drive coil circuit of the source device with a source voltage having an adjustable frequency, the drive coil circuit generating a varying magnetic field;

        detecting a phase of an input impedance of the drive coil circuit in response to inductively coupling the source device and the untethered device; and

        adjusting the source voltage frequency so that the phase of the input impedance of the drive coil circuit is substantially zero.

15.   The method of claim 14, wherein adjusting of the source voltage frequency compensates for a change in a resonance frequency of the resonant circuit of the untethered device.

16.   The method of claim 14, wherein adjusting of the source voltage frequency compensates for a change in a parameter of the resonant circuit of the untethered device.

17.   The method of claim 16, wherein the parameter of the resonant circuit subject to change comprises a parameter of one or more of a resistive element, inductive element, and a capacitive element of the resonant circuit.

18.   The method of claim 14, wherein adjusting of the source voltage frequency maximizes a voltage developed over a capacitive element of the resonant circuit of the untethered device.

19.   The method of claim 14, wherein the source device comprises an RFID reader and the untethered device comprises an RFID tag.
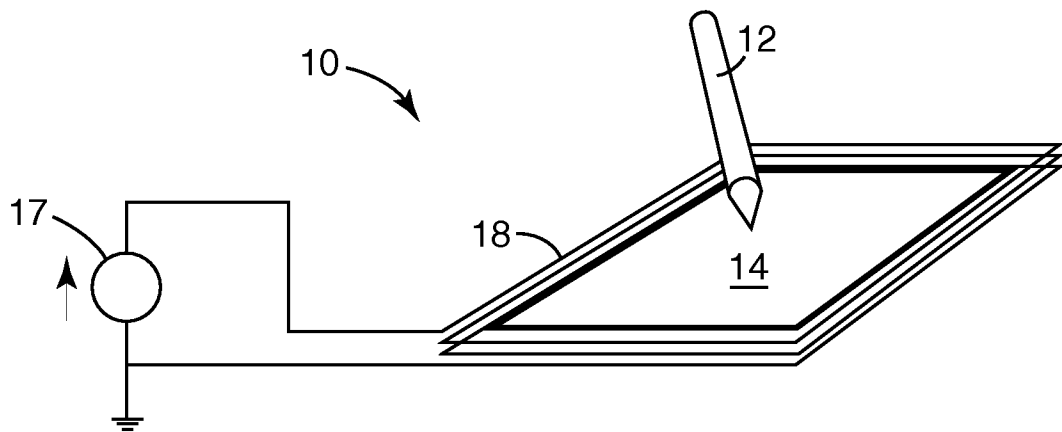
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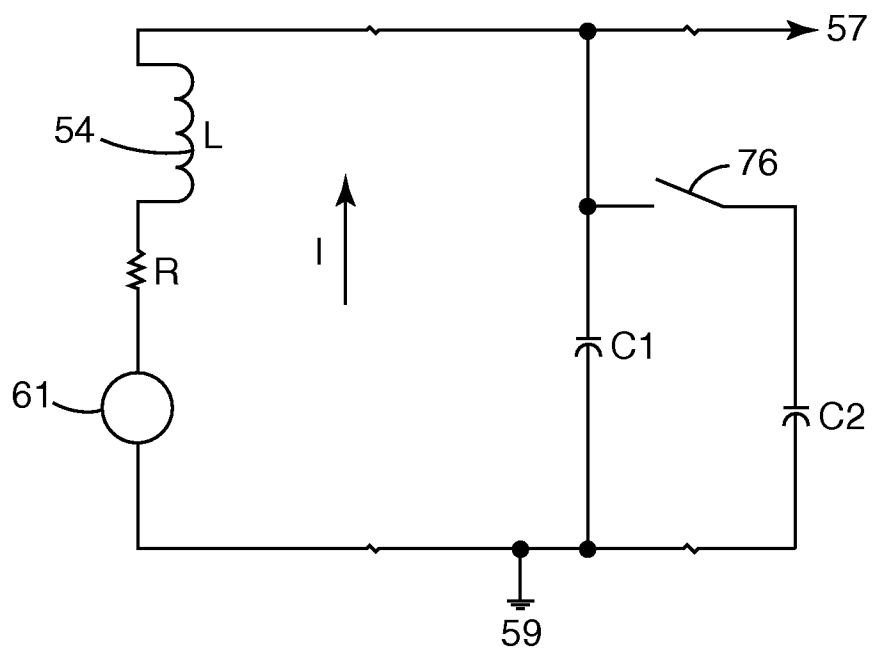20.   The method of claim 14, wherein the source device comprises a digitizer and the untethered device comprises a stylus.

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Figure 1

Figure 2

Figure 3

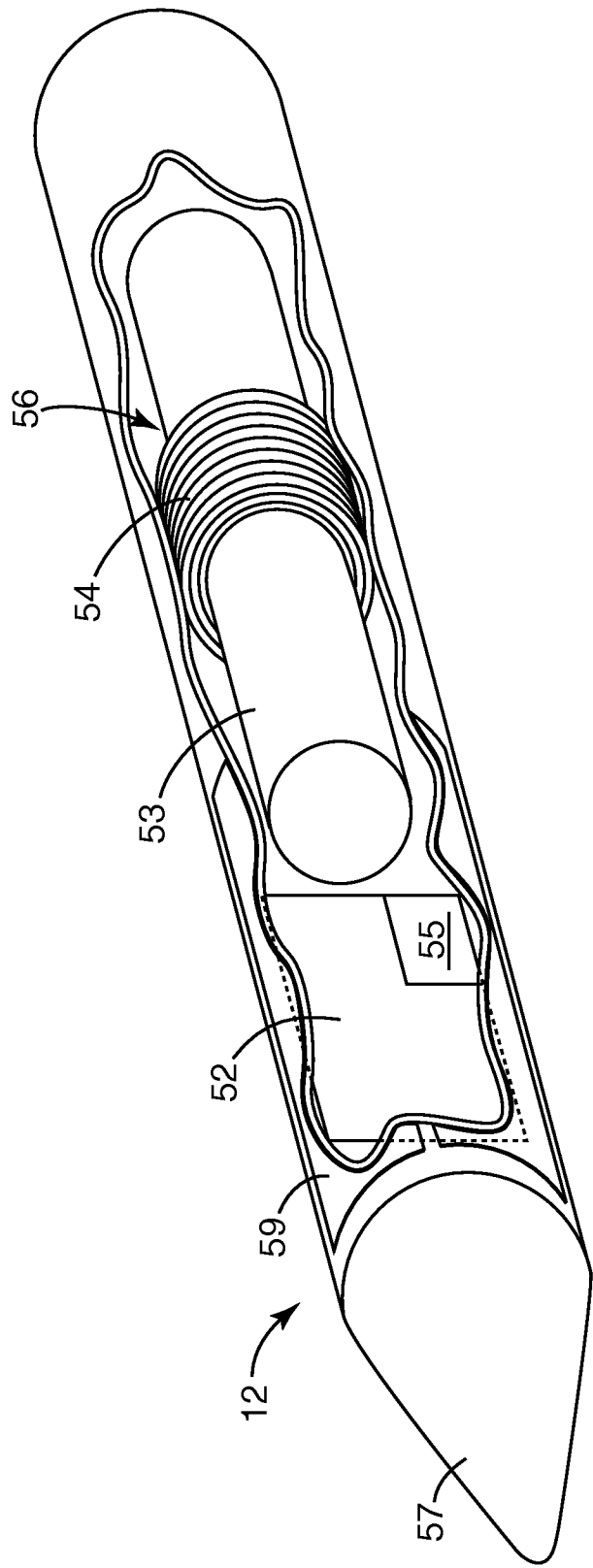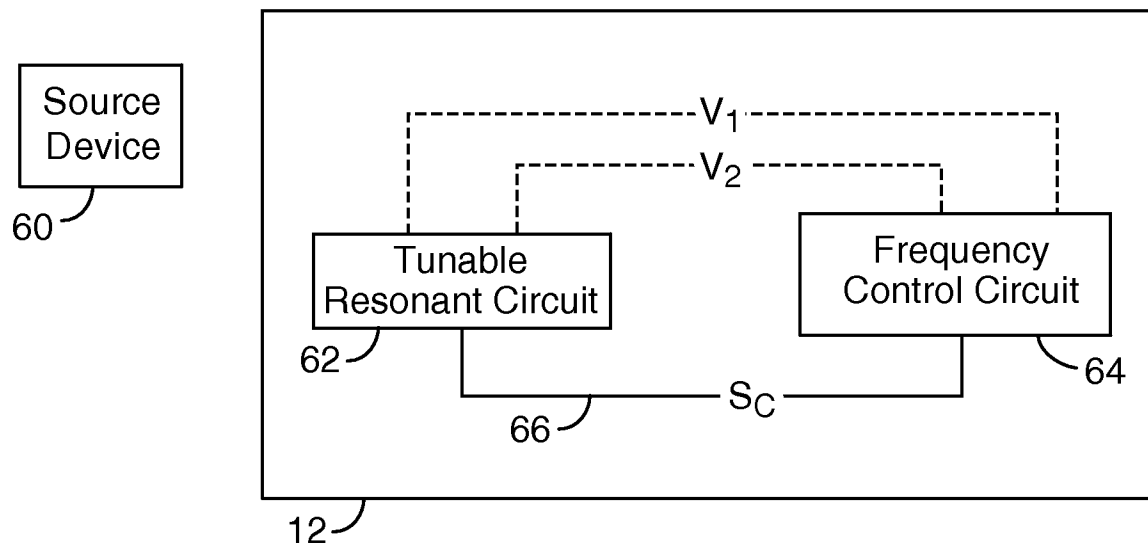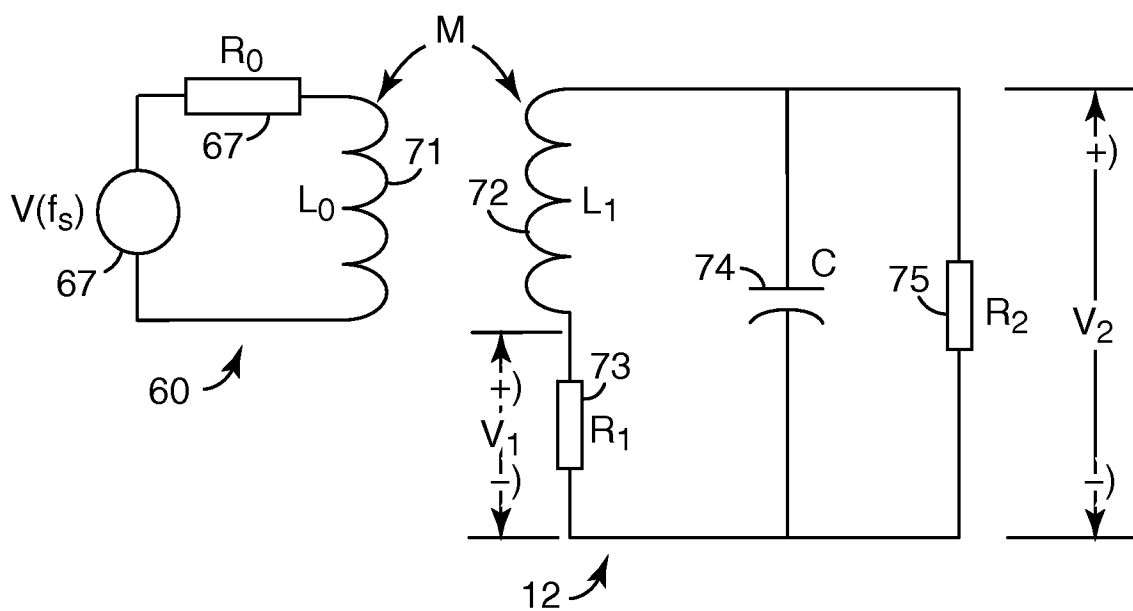*Figure 5*

Figure 4

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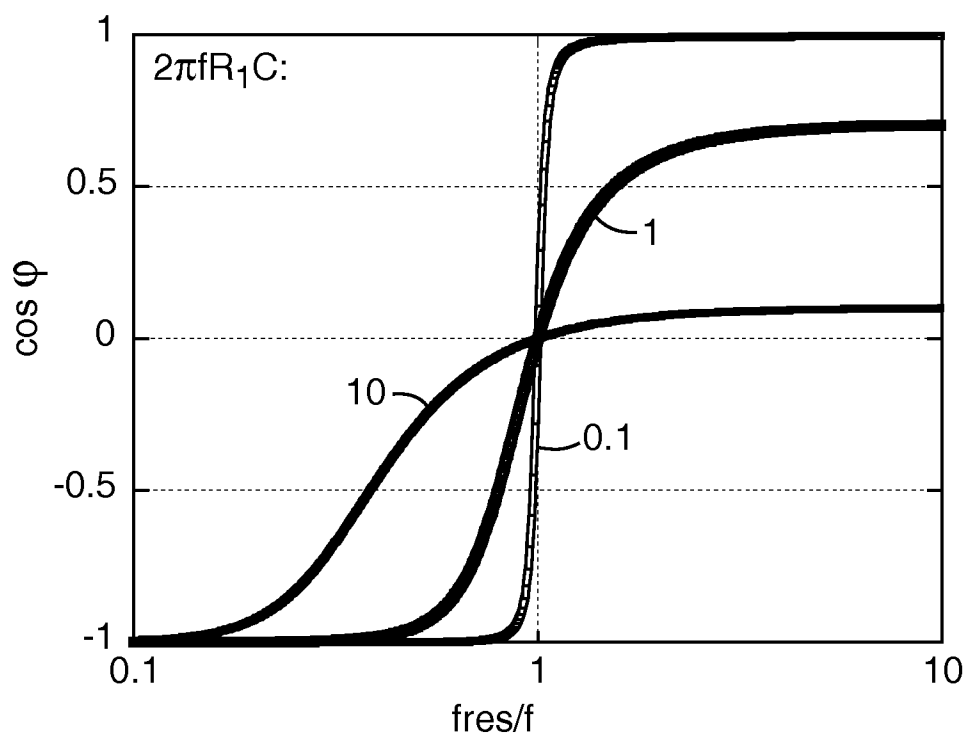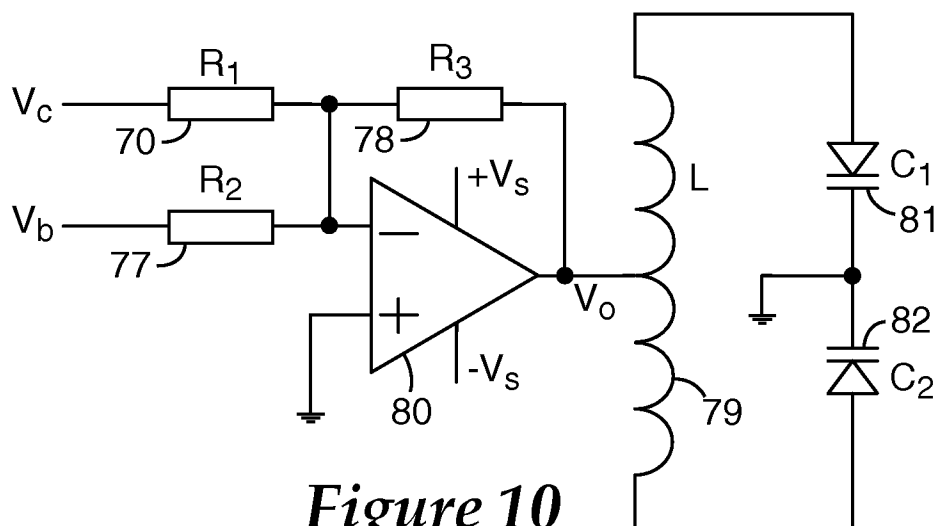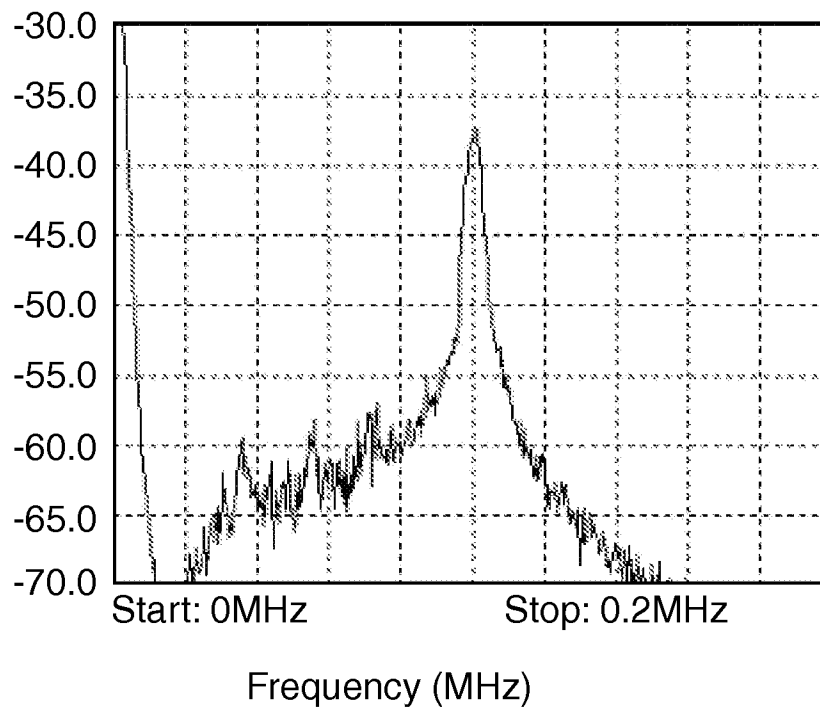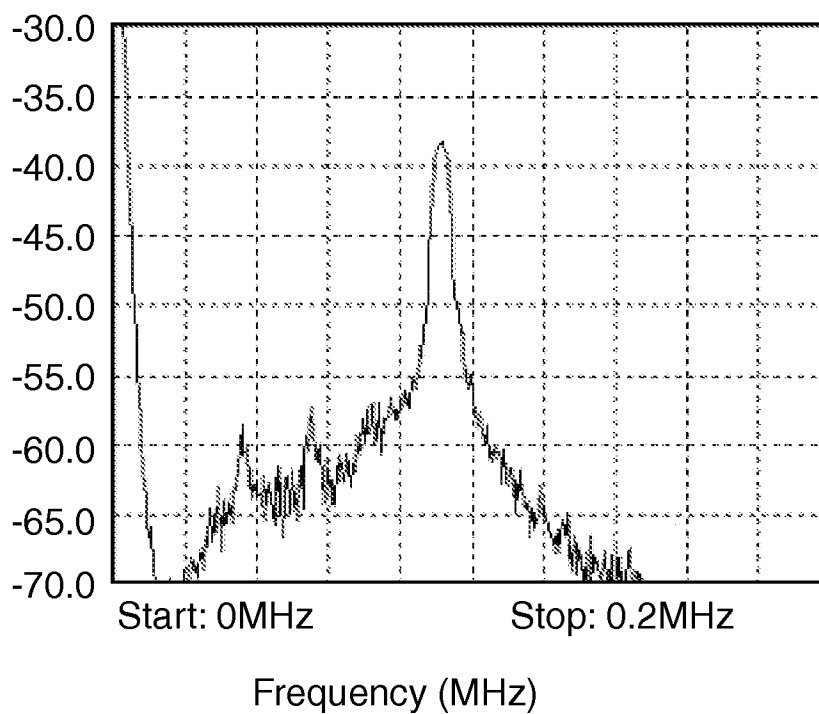*Figure 6*

Figure 7
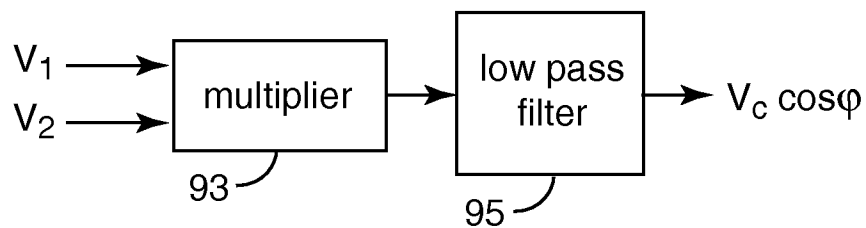
Figure 8

Figure 9

Figure 10

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Start: 0MHz   Stop: 0.2MHz

Frequency (MHz)

Figure 11

Start: 0MHz   Stop: 0.2MHz

Frequency (MHz)

Figure 12

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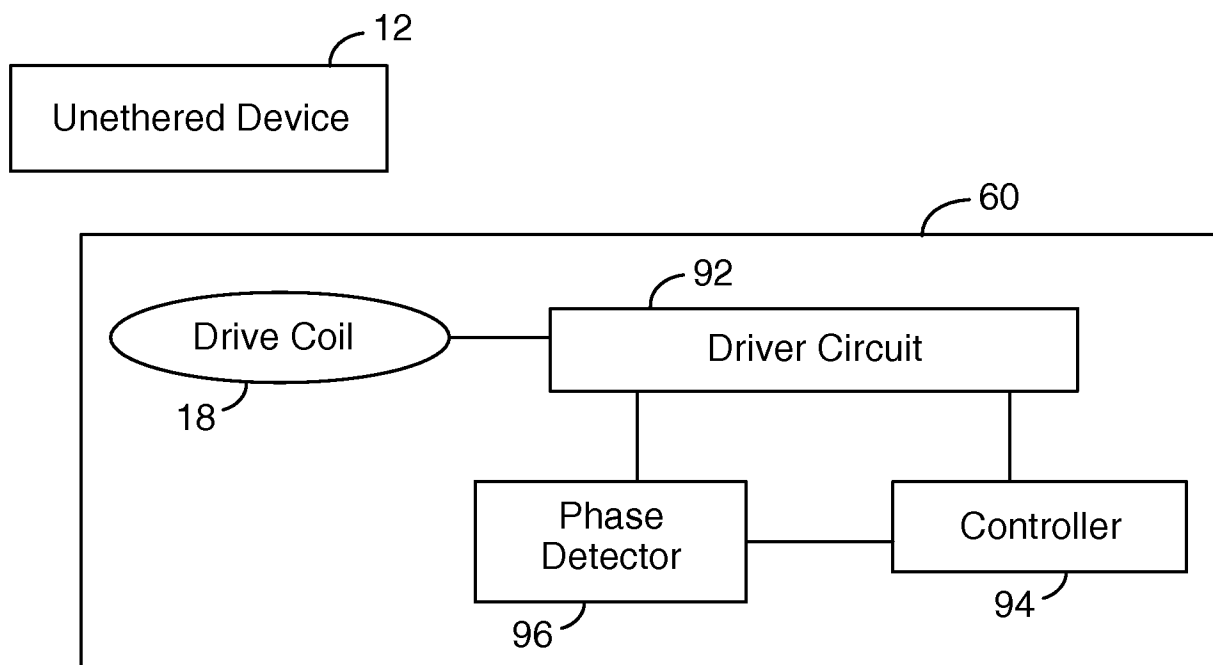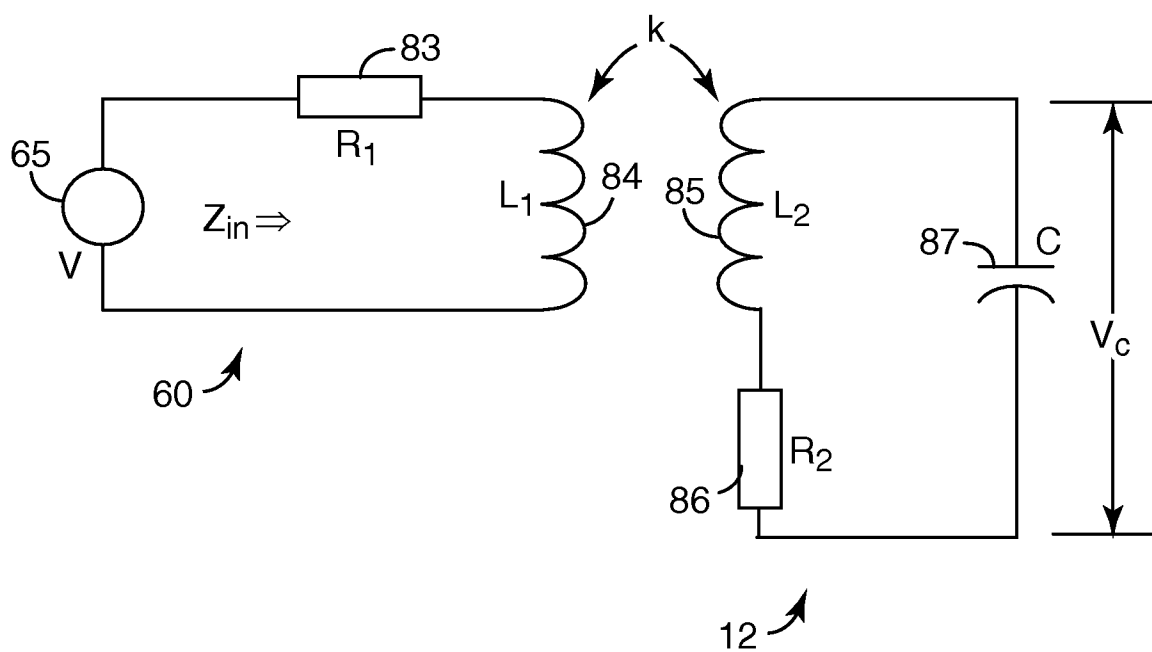
Figure 13

Figure 14

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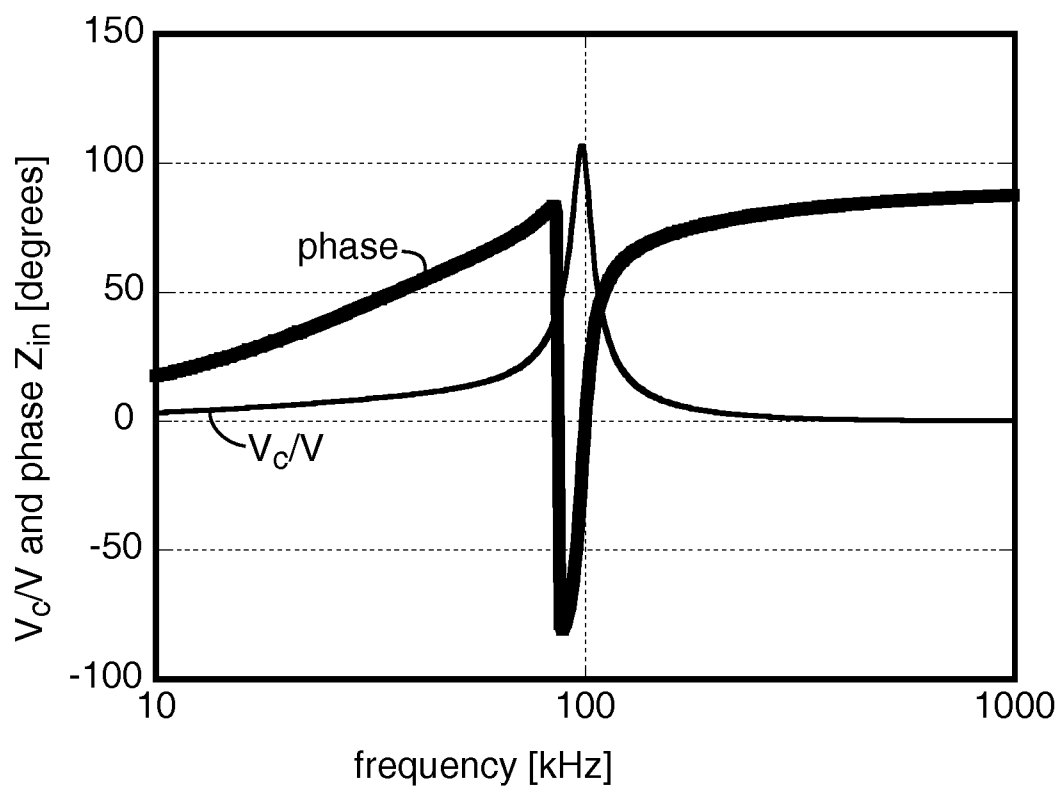
Figure 15
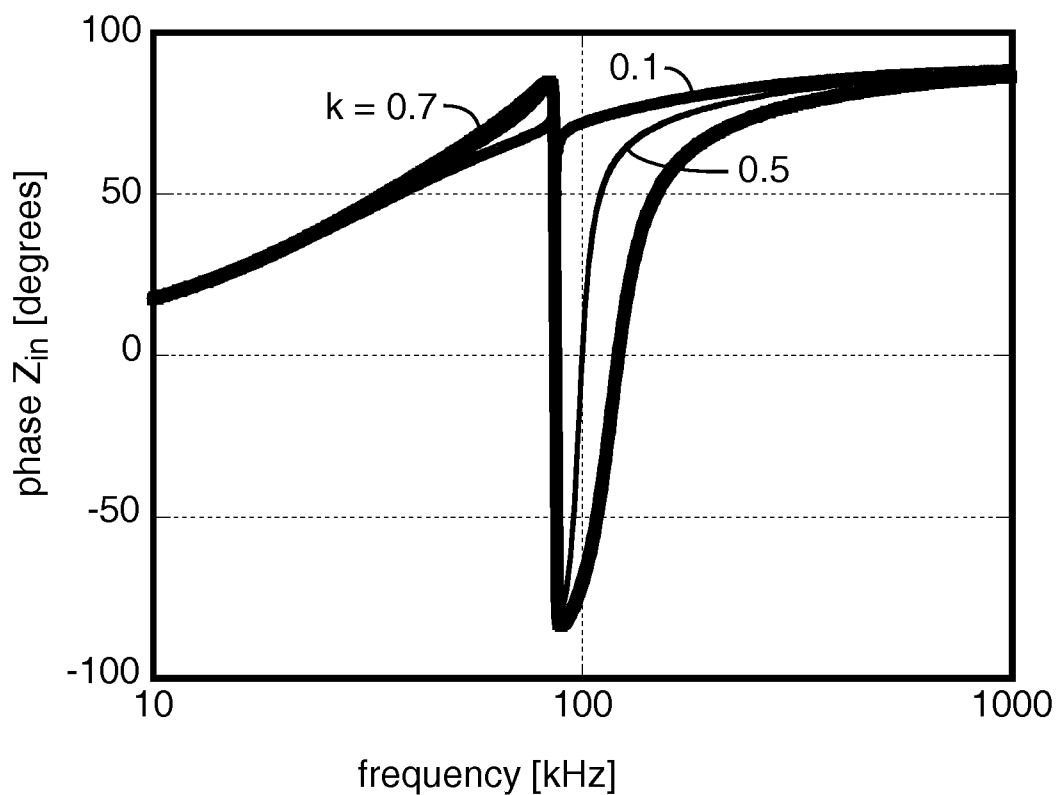
Figure 16

A.	CLASSIFICATION OF SUBJECT MATTER

G06F 3/033(2006.01)i, G06F 3/03(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B.	FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 8 G06F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean Utility Models and Applications for Utility Models since 1975
Japanese Utility Models and Applications for Utility Models since 1975

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKIPASS (KIPO internal) " Keyword : (wireless, untethered), (magnetic), (power), (resonance, resonant), (coil, inductor), (frequency), (capacitor) "

C.	DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US06667740 B2 (DAVID T. ELY, et.al.) 23 Dec. 2003 Abstract, Claims 1,6,7,17,23,37, Figs. 1,3,9, Column 1 Line 3 - Column 4 Line 3	1-20
A	US07019672 B2 (DAVID T. E. ELY) 28 Mar. 2006 Abstract, Claims 1,2,29-32,40,48, Figs. 1,3,15, Column 1 Line 9 - Column 1 Line 63	1-20
A	US06476799 B1 (JEFFREY LEE, et.al.) 05 Nov. 2002 Abstract, Claims 1,8,13, Figs. 1,3,4, Column 1 Line 7 - Column 2 Line 27	1-20
A	US04786765 A (TSUGUYA YAMANAMI, et.al.) 22 Nov. 1988 Abstract, Claims 1,7,8, Figs. 1-4, Column 1 Line 6 - Column 4 Line 3	1-20

☐ Further documents are listed in the continuation of Box C.	☒ See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	
"E" earlier application or patent but published on or after the international filing date	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of citation or other special reason (as specified)	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
20 MAY 2008 (20.05.2008)	**20 MAY 2008 (20.05.2008)**
Name and mailing address of the ISA/KR Korean Intellectual Property Office Government Complex-Daejeon, 139 Seonsa-ro, Seo-gu, Daejeon 302-701, Republic of Korea Facsimile No. 82-42-472-7140	Authorized officer CHUN, Dae Sik Telephone No. 82-42-481-5871

Form PCT/ISA/210 (second sheet) (April 2007)

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