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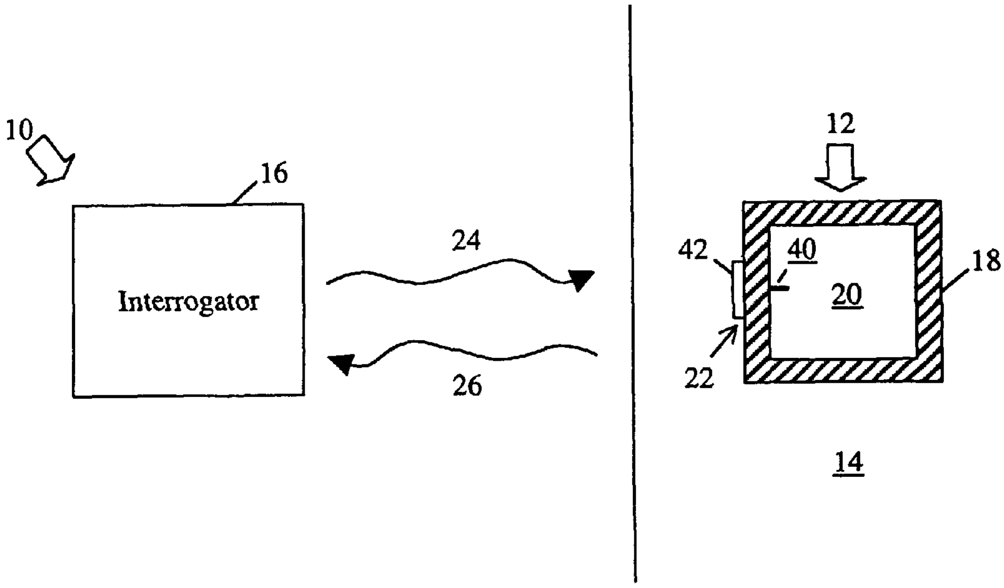
(54) Title: MEASURING STRAIN IN A STRUCTURE (BRIDGE) WITH A (TEMPERATURE COMPENSATED) ELECTROMAGNETIC RESONATOR (MICROWAVE CAVITY)



(57) **Abstract:** The system (10) comprises a sensor (18) 90x90x90x30 mm as an electromagnetic microwave cavity (20) with a coupler (22) with a wire (40) and an antenna (42). Cavity (20) produces a response signal (26) in response to an interrogation signal (24) from interrogator (16). Sensor (18) is coupled to a structure (14) to allow a strain to alter the resonance properties. 3.6 GHz is used with a detection of a 2.5 kHz change. If not temperature via strain is detected a mechanical amplifier is used with cavity (20) for temperature compensation. Continuous or intermittent narrowband signals are used as interrogation signals (24). Used with bridges for structural health monitoring. Also for aircrafts, dams, buildings, vehicles.

Title: A Sensor System And Method For Measuring Strain in Structure

FIELD OF THE INVENTION

[0001] The present invention is related to a system and method for measuring strain that is experienced by structures. More particularly, the present invention is directed towards a wireless sensor system and method for measuring strain in structures based on electromagnetic resonance.

BACKGROUND OF THE INVENTION

[0002] In the 1930's the U.S. and Canadian governments began public work programs to develop a transportation infrastructure comprising roadways and bridges. The increased weight and numbers of today's trucks compared with design loads that were used for the roads and bridges at the time of construction, combined with aging, environmental conditions and the use of corrosive salts has resulted in deterioration and increasing structural deficiencies. Currently, the U.S. has 542,000 bridges that consume billions of dollars each year in construction, rehabilitation and maintenance. In Canada, there are an estimated 10,000 railroad bridges and 30,000 automobile bridges with 40% of these bridges requiring repair or replacement. A similar situation is said to exist in Europe and Asia. It can be appreciated that other structures, such as, for example, but not limited to, aircrafts, dams and buildings can also suffer from similar structural degradation.

[0003] In light of these problems, significant research has been directed over the last few years towards the field of structural health monitoring in order to mitigate potential hazards to the general public. The research has been directed towards improved methodologies in detecting and monitoring structural degradation with an eye towards improving service life and minimizing down time for maintenance. Ongoing monitoring may be used on these structures to control and predict maintenance and replacement costs and also to increase the lifetime and reliability of these structures. For example, structural information gathered on bridges is important in determining whether or not load ratings should be changed, to catch faults early enough so that repairs may be done, or to find structural problems that require the bridge to be replaced.

[0004] The current movement towards structural monitoring involves a detection suite of distributed smart sensors which can detect potential construction flaws or structural fatigue to expose a potential hazard to the public. Structures having these sensors are referred to as smart structures. Embedded smart structure technology (actuators and sensors) offers the unique ability to assess structures on demand to determine the current condition of the structure. These sensors may also be designed to monitor specific conditions. For example, these devices can provide event-based information such as the condition of structural integrity after a sudden impact from an earthquake, or continuous measurement of data for a range of strain and damage conditions.

[0005] Two main groups of prior art sensors have been developed for use in smart structures. The first group of prior art sensors comprise sensors that require hardwiring and include traditional strain gauges and fiber-optic strain gauges. The traditional strain gauges are made of metal foil and are bonded to the structure. The strain is determined by measuring the resistance of the metal foil or by determining the mechanical resonant frequency of the metal foil. The foil gauges require a physical connection to transmit the information regarding the structural strain as well as a DC signal for providing power for the strain gauge. Fiber-optic strain gauges were developed to address some of the problems associated with traditional strain gauges. Fiber optic strain gauges are embedded into the structure but require a fiber-optic connection to make a measurement. One technique for measuring structural strain uses the center reflectivity wavelength of the optical fiber Bragg gratings. Systems based on both traditional strain gauges and fiber-optic strain gauges result in a series of connected sensors throughout the structure.

[0006] Both traditional strain gauges and fiber-optic strain gauges require a link to the outside world. Accordingly, when these sensors are installed in a structure, provisions for this link, such as wires, must be provided. Over time these wires can corrode and compromise the integrity of the monitoring system. In addition, fiber-optic units can be difficult to install and can be subject to temperature drift. Furthermore, when the connections linking these sensor systems break then the monitoring system will not function.

[0007] The second group of prior art sensors comprise passive sensors that do not require a physical connection. Passive sensors include acoustic sensors and sensors that employ passive circuits for detecting strain.

SUMMARY OF THE INVENTION

[0008] The present invention is directed towards a sensor system and method for measuring strain experienced by a structure. The sensors of the sensor system would be installed into a structure such as a bridge, building or the like, to detect the strain experienced by the structure. Several sensors can be strategically placed at various locations of the structure that are susceptible to forces. The sensors do not require a source of power and could be activated on demand by a remote interrogator which could be brought within relative proximity to each sensor to activate and record measurements from each sensor individually.

[0009] Each sensor has an electromagnetic resonator such as, for example, an electromagnetic cavity having a resonant frequency that is related to the dimensions of the cavity. The dimensions of the cavity are dependant upon the strain experienced by the structure. Accordingly, strainexperienced by the structure would be represented by changes in the resonant frequency of the sensor. The interrogator utilizes an interrogation signal having a frequency content that matches the resonant frequency of the electromagnetic cavity. Upon excitation by the interrogation signal, the electromagnetic cavity would produce a response signal that is related to the resonant frequency of the cavity. The interrogator would process the response signal to determine the strain that is experienced by the structure.

[0010] Accordingly, in a first aspect, the invention is directed towards a system for measuring strain experienced by a structure. The system comprises a sensor with a body having an electromagnetic resonator. The electromagnetic resonator produces a response signal in response to an interrogation signal. The body is coupled to the structure to allow the strain to alter the resonance properties of the electromagnetic resonator thereby altering the response signal. The sensor further includes a coupler that is coupled to the body. The coupler transfers the interrogation signal into the electromagnetic resonator and transfers the response signal out of the electromagnetic resonator. The system further includes an interrogator that generates and transmits the interrogation signal to the sensor. The interrogator also receives the response signal.

[0011] In another aspect, the present invention provides a sensor for measuring strain experienced by a structure. The sensor comprises a body having an electromagnetic resonator. The electromagnetic resonator produces a response signal in response to an interrogation signal. The body is coupled to the structure to allow the strain to alter the resonance properties of the electromagnetic resonator thereby altering the response signal. The sensor also includes a coupler that is coupled to the body. The coupler transfers the interrogation signal into the electromagnetic resonator and transfers the response signal out of the electromagnetic resonator.

[0012] In a further aspect, the present invention provides a method for measuring strain experienced by a structure. The method comprises:

a) coupling a sensor having an electromagnetic resonator to the structure;

b) providing an interrogation signal to the electromagnetic resonator to evoke a response signal; and,

c) receiving the response signal.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] For a better understanding of the present invention and to show more clearly how it may be carried into effect, reference will now be made, by way of example only, to the accompanying drawings which show a preferred embodiment of the present invention and in which:

[0014] Figure 1 is a partial, cross-sectional front view of a sensor system comprising an interrogator and a sensor having an electromagnetic cavity for measuring the strain that is experienced by a structure in accordance with the present invention;

[0015] Figure 2a is a front view of the sensor with a plate removed;

[0016] Figure 2b is a rear view of the plate of the sensor;

[0017] Figure 2c is a front view of the plate secured to the sensor;

[0018] Figures 3a, 3b and 3c are front views of various embodiments of the electromagnetic cavity;

[0019] Figure 4a is a block diagram of an electromagnetic cavity before being affected by a strain;

[0020] Figure 4b is a block diagram of an electromagnetic cavity while being affected by a strain;

[0021] Figure 5a is a front view of an alternative embodiment of the sensor having a mechanical amplifier;

[0022] Figure 5b is a magnified view of the mechanical amplifier;

[0023] Figure 5c is a block diagram illustrating how the amplifier acts like a lever;

[0024] Figure 6a is a plot of response signal amplitude versus frequency illustrating a first method of determining the resonant frequency of the electromagnetic cavity;

[0025] Figure 6b is a plot of response signal amplitude versus frequency illustrating the interference that is present when the first method of determining the resonant frequency of the electromagnetic cavity is used;

[0026] Figure 7a is a plot of interrogation signal amplitude versus time illustrating the interrogation signal that is used for a second method of determining the resonant frequency of the electromagnetic cavity;

[0027] Figure 7b is a plot of response signal amplitude versus time when the second method of determining the resonant frequency of the electromagnetic cavity is used;

[0028] Figure 7c is a plot of response signal amplitude versus time when gating is used to eliminate unwanted reflections;

[0029] Figure 7d is a plot of response signal amplitude versus frequency when the second method of determining the resonant frequency of the electromagnetic cavity is used;

[0030] Figure 8a is a block diagram of an embodiment of the interrogator;

[0031] Figure 8b is a block diagram of an alternate embodiment of the interrogator; and,

[0032] Figure 9 is a flowchart of a method for sensing the force in a structure.

DETAILED DESCRIPTION OF THE INVENTION

[0033] Referring now to Figure 1, shown therein is a partial cross-sectional front view of a sensor system **10** for determining strain **12** experienced by a structure **14**. The sensor system **10** comprises an interrogator **16** and a plurality of sensors **18**. The structure **14** could be for example, but not limited to, a bridge, a road, an overpass, a building, an aircraft or the like and the strain **12** may result from for example, but not limited to, force, temperature, or the like. The integrity of the structure **14** could be monitored at any given time to indicate when repair or replacement is necessary for the structure **14**. To achieve this, several sensors **18** would be strategically placed at various locations of the structure **14** that are susceptible to strain (these locations are known to those skilled in the art). For simplicity of illustration and explanation only one sensor **18** and only a partial view of the structure **14** is shown in Figure 1. The sensors **18** do not require a source of power and could be activated on demand by a remote interrogator **16** as described further below. The interrogator **16** would be brought within relative proximity of each sensor **18** to activate and record measurements from each sensor **18** individually.

[0034] The sensor **18** has a body that defines an electromagnetic resonator. For the embodiment illustrated in Figure 1, the sensor **18** has a body comprising side walls that, define an electromagnetic cavity **20** therein. The sensor **18** also includes a coupler **22**. The interrogator **16** provides an interrogation signal **24** that is coupled to the electromagnetic cavity **20** via the coupler **22**. In response, the electromagnetic cavity **20** produces a response signal **26** that is radiated via the coupler **22**. The interrogation signal **24** may be at least partially absorbed by the electromagnetic cavity **20** if the interrogation signal **24** has a frequency content that matches the resonant frequency of the electromagnetic cavity **20**. In this case, there will not be much energy at the resonant frequency of the electromagnetic cavity **20** that is reflected by the electromagnetic cavity **20** while the interrogation signal **24** is being transmitted. Accordingly, the response signal **26** will have a small signal component at the resonant frequency of the electromagnetic cavity **20**. Alternatively, the interrogation signal **24** may not have a frequency content that matches the resonant frequency of the electromagnetic cavity **20**. In this case, most of the interrogation signal **24** will be reflected by the electromagnetic cavity **20** and the response signal **26** will comprise most of the interrogation signal **24**. In this fashion, it is possible to determine the resonant frequency of the electromagnetic cavity **20**. This is important since the resonant frequency of the electromagnetic cavity **20** will vary depending on the dimensions of the electromagnetic cavity **20** which in turn depends on the strain **12** experienced by the structure **14**. Hence, the change in the resonant frequency of the electromagnetic cavity **20** provides an indication of the strain **12** experienced by the structure **14**.

[0035] Referring now to Figure 2a, shown therein is a front view of an embodiment of the sensor **18** with the electromagnetic cavity **20**. The sensor **18** has side walls **30** that encircle the electromagnetic cavity **20**, and a plurality of apertures **32** situated on the side walls **30**. The electromagnetic cavity **20** may also contain a suitable dielectric if so desired.

[0036] The sensor **18** may preferably be made of a non-corrosive metal so that the sensor **18** remains functional for the lifetime of the structure **14**. For example, the sensor **18** may be made from steel. The sensor **18** is a relatively small object so that it does not compromise the structural integrity of the structure **14** when the sensor **18** is coupled with the structure **14**. For example, the sensor **18** may be a rectangular, hollow metal block having dimensions of 90 mm x 90 mm x 30 mm.

[0037] Referring now to Figure 2b, shown therein is a rear view of a plate **34** which forms one of the side walls of the electromagnetic cavity **20**. The plate **34** has a plurality of apertures **36** which are aligned with the apertures **32** so that the plate **34** may be secured to the side walls **30** via suitable fasteners such as for example, but not limited to, pins, screws, nuts and bolts. Alternatively, pressure fitted fins could be placed on the plate **34** and the side walls **30** so that the plate **34** can be secured to the side walls **30** by compression fitting. The plate **34** also has an aperture **38** to allow a conductive wire **40** to protrude within the electromagnetic cavity **20** when the plate **34** is fastened to the ridge **30**. The wire **40** forms part of the coupler **22** which will be discussed further below.

[0038] Referring now to Figure 2c, shown therein is a front view of the sensor **18** as it would be appear in use with the plate **34** attached to the side walls **30**. There is an antenna **42** on the front of the plate **34** which forms part of the coupler **22**. The sensor **18** is constructed to have a tight seal to prevent any debris from entering the electromagnetic cavity **20** which may compromise the resonance properties of the electromagnetic cavity **20** or damage the wire **40**.

[0039] The side walls **30**, plate **34** and the bottom wall (not shown) of the sensor **18** define the boundaries of the electromagnetic cavity **20**. The side walls **30**, plate **34** and bottom of the sensor **18** are preferably rigid to maintain the structural integrity of the sensor **18**, but at the same time these surfaces are also reasonably flexible to allow the volume of the electromagnetic cavity **20** to change in response to the strain **12** experienced in the structure **14**.

[0040] The electromagnetic cavity **20** is enclosed by conducting walls that are capable of containing oscillating electromagnetic fields that produce standing waves. Accordingly, when electromagnetic energy is transferred to the electromagnetic cavity **20**, the electromagnetic energy will oscillate between the conductive walls transforming between an electric field and a magnetic field and become more intensified in a resonating fashion depending on the frequency of the transferred electromagnetic energy. Accordingly, the electromagnetic cavity **20** possesses resonant properties within narrow frequency bands centered about discrete frequencies called resonances or resonant frequencies. Resonance will occur when the frequency of the transferred electromagnetic energy has a frequency content that matches the resonant frequency of the electromagnetic cavity **20**.

[0041] Any completely enclosed conductive surface, regardless of its shape, can act as an electromagnetic cavity resonator. This allows a cavity resonator to be built for different applications and have a resonant frequency in different frequency ranges. Accordingly, the electromagnetic cavity **20** may also have a variety of shapes such as cubic (Figure 3a), rectangular (Figure 3b) and cylindrical (Figure 3c). Other shapes may also be useful. The choice of a particular shape for the electromagnetic cavity **20** may depend on the direction upon which the strain **12** is to be measured as well as the frequency range of operation.

[0042] Referring now to Figure 3a, an example of an electromagnetic cavity **20** for use with the sensor **18** is illustrated. For the illustrated embodiment, the electromagnetic cavity **20** resembles a section of a square waveguide that is closed at both ends by conducting plates. The frequency at which resonance occurs, for a particular mode, is the frequency of the electromagnetic field at which nulls occur at the walls of the electromagnetic cavity **20**. Therefore, the physical size of the electromagnetic cavity **20** affects the resonant frequency. In general, the smaller the electromagnetic cavity, the higher the resonant frequency. However, another controlling factor of the resonant frequency is the shape of the electromagnetic cavity **20** and the mode of the electromagnetic fields that exist within the electromagnetic cavity **20**.

[0043] The resonant frequency of the electromagnetic cavity **20** may be changed by changing the dimensions of the electromagnetic cavity **20** which is known as shape tuning. For instance, varying the distance L will result in a new resonant frequency because the inductance and the capacitance of the electromagnetic cavity **20** are changed by differing amounts. If the dimensions of the electromagnetic cavity **20** are decreased, the resonant frequency will increase. This will occur when there is a change in the strain **12** within the structure **14**. This is shown in Figures 4a and 4b, where an increase in the strain **12** (Figure 4a) on a portion of the body of the sensor **18** surrounding the electromagnetic cavity **20** results in a decrease in the dimensions of the electromagnetic cavity **20'** (Figure 4b). Alternatively, the resonant frequency will decrease if the dimensions of the electromagnetic cavity **20** increases. This will occur when there is a strain that is pulling on the body of the sensor **18** surrounding the electromagnetic cavity **20**.

[0044] For a rectangular electromagnetic cavity, such as the one shown in Figure 3b having dimensions in the x, y and z direction represented by the parameters a, b and d, the electromagnetic cavity **20** can support TE_{mnp} and TM_{mnp} modes, where TE stands for transverse electric wave, TM stands for transverse magnetic wave and m, n, and p are integers indicating the mode of the enclosed fields. Both the TE_{mnp} and TM_{mnp} modes resonate at the frequency f_{mnp} given by:

$$f_{mnp} = \frac{c}{2}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{d}\right)^2} \quad (1)$$

where c is the speed of light (3 x 10^8 m/sec).

[0045] Assuming that no TE or TM modes are excited in the z direction (i.e. p = 0) and only the first mode is excited in the x and y directions (i.e. m = n = 1) then the resonant frequency (f_r) is given by equation 2.

$$f_r = \frac{c}{2}\sqrt{\left(\frac{1}{a}\right)^2 + \left(\frac{1}{b}\right)^2} \quad (2)$$

Now letting a = b = h and assuming a change in the y direction of Δh, the resonant frequency is given by equation 3.

$$f_r = \frac{c}{2}\sqrt{\left(\frac{1}{h}\right)^2 + \left(\frac{1}{\Delta h + h}\right)^2} \quad (3)$$

Furthermore, if Δh << h, the resonant frequency is closely approximated by equation 4.

$$f_r = \frac{c}{\sqrt{2}h}\sqrt{1 - \frac{\Delta h}{2h}} \quad (4)$$

The resonant frequency (f_u) with no strain is:

$$f_u = \frac{c}{\sqrt{2}h} \quad (5)$$

The resonant frequency (f_s) that occurs due to strain is:

$$f_s = f_u\left(1 - \frac{1}{\sqrt{2}}\mathrm{E}\right) \quad (6)$$

where E = Δh/h is defined as strain. Accordingly, the strain E, can be calculated from the resonant frequencies f_u and f_s according to:

$$\mathrm{E} = \frac{\sqrt{2}(f_u - f_s)}{f_u} \quad (7)$$

The strained resonant frequency f_s can be larger or smaller than the unstrained resonant frequency f_u. This depends if the strain **12** is positive or negative.

[0046] By selecting a high frequency range for the interrogation signal, the sensor system **10** is able to make precise measurements of small amounts of strain. For instance, given values of f_u = 3.6 GHz and f_s = 3.599995 GHz, i.e., a change in resonant frequency of 2.5 KHz, the strain would be:

$$E = \frac{\sqrt{2}(3.6 - 3.5999975)}{3.6} \approx 1\ \mathit{microstrain} \qquad (8)$$

Therefore, operating at 3.6 GHz, results in a shift in resonance of 2.5 KHz for every change in strain of 1 microstrain. Accordingly, the sensor system **10** will be able to make precise measurements of small amounts of strain, even in parts per million.

[0047] A strain of 0.1%, for example, would result in a frequency change of 2.5 MHz. Accordingly, to measure such a strain, the sensor system **10** would need a bandwidth of at least 2.5 MHz. Since the regulatory commissions would dictate the frequency that could be used for the sensor system **10**, some possible frequency ranges that may be used would be centered at 900 MHz, 2.5 GHz and 5.8 GHz. The frequency range at 2.5 GHz may be used since it would have a bandwidth from 2.4 to 2.6 GHz (200 MHz) which is more than adequate for sensing the 0.1% strain mentioned above.

[0048] As mentioned previously, the coupler **22** transfers or injects the interrogation signal **24** into the electromagnetic cavity **20** and the coupler **22** also transfers or radiates the response signal **26** to the interrogator **16**. Energy can be inserted or removed from an electromagnetic cavity **20** by the same methods that are used to couple energy into and out of waveguides. The operating principles of probes (electric coupling), loops (magnetic coupling), and slots are the same whether used in an electromagnetic cavity or a waveguide as is commonly known in the art. Therefore, any one of these three methods may be used to transfer energy into or out of the electromagnetic cavity **20**. If a slot were used for the coupler **22**, the degree of coupling would be determined by the size, shape and position of the slot.

[0049] The coupler **22** preferably comprises the antenna **42** coupled to the wire **40**. The antenna **42** allows the coupler **22** to receive the interrogation signal **24** and transmit the response signal **26** while the wire **40** injects the interrogation signal **24** into the electromagnetic cavity **20** and transmits the response signal **26** to the antenna **42** for transmission. The antenna **42** should be preferably matched to the unstrained resonant frequency of the electromagnetic cavity **20** so that there is efficient coupling for the frequency components of the interrogation signal **24** that match the resonant frequency of the electromagnetic cavity **20**. A variety of types of antennas may be used for the antenna **42** such as a patch antenna or a loop antenna.

[0050] The wire **40** acts as a probe and the interrogation signal **24** generates a current flow in the probe to set up an electric field within the electromagnetic cavity **20**. For efficient coupling, the wire **40** should be placed at the location of maximum electric field intensity within the electromagnetic cavity **20** which depends on the mode of the electromagnetic field contained in the electromagnetic cavity **20**. The amount of energy that is coupled to the electromagnetic cavity **20** may be reduced by decreasing the length of the wire **40**, by moving the wire **40** away from the location of the maximum electric field intensity, or by shielding the wire **40**. Furthermore, the size and shape of the wire **40** determines the frequency, bandwidth and power-handling capability of the wire **40**. For instance as the diameter of the wire **40** increases, the bandwidth and power-handling capability of the wire **40** both increase. The greater power-handling capability is directly related to the increased surface area of the wire **40**. Removal of energy from the electromagnetic cavity **20** is a reversal of the injection process using the same type of wire **40**.

[0051] In an alternative embodiment, there may be two couplers connected with the sensor **18**. The first coupler may be used to inject electromagnetic energy into the electromagnetic cavity **20** and the second coupler may be used to transmit electromagnetic energy from the electromagnetic cavity **20**.

[0052] An alternative method of transferring or injecting energy into the electromagnetic cavity **20** is by setting up a magnetic field in the electromagnetic cavity **20**. This can be accomplished by incorporating a small loop at the end of the wire **40** which carries current into the electromagnetic cavity **20**. A magnetic field builds up around the loop and expands to fill the electromagnetic cavity **20**. If the frequency of the current in the loop is within the resonant bandwidth of the electromagnetic cavity **20** then energy will be transferred to the electromagnetic cavity **20**. For efficient coupling to the electromagnetic cavity **20**, the loop should be placed at a location of maximum magnetic field intensity which depends on the mode of the electromagnetic field contained in the electromagnetic cavity **20**. When less efficient coupling is desired, the loop may be moved or rotated so that the loop encircles a smaller number of magnetic field lines within the electromagnetic cavity **20**. Furthermore, when the diameter of the loop is increased, the bandwidth and power-handling capabilities of the loop also increase. Removal of energy from the electromagnetic cavity **20** is a reversal of the injection process using the same loop and wire **40**.

[0053] The electromagnetic cavity **20** has advantageous properties when it is designed to have a resonant frequency in the RF range. With a resonant frequency in the RF range it should be possible to measure strains on the order of 1 μE. Furthermore, a resonant frequency in the RF range allows for a more compact design of the electromagnetic cavity **20**. In addition, with an electromagnetic cavity **20**, different resonant frequencies result in the excitation of different modes of the electromagnetic field within the electromagnetic cavity **20** which can make the sensor **18** sensitive to strains in different directions.

[0054] Another advantageous property of an electromagnetic cavity is a high Q factor. The Q factor is a measure of the resonant frequency relative to the resonance bandwidth:

$$Q = \frac{f_o}{\Delta f} \tag{9}$$

where f_o is the resonant frequency and Δf is the resonance bandwidth. The Q factor of an electromagnetic cavity also represents the amount of stored energy compared with the energy lost due to the imperfectly conducting walls, the imperfect dielectric within the electromagnetic cavity (if present) and the coupling to the outside world, as represented by equations 10 and 11.

$$Q = \frac{2\pi f_o \cdot (\text{energy stored})}{\text{average power loss}} \tag{10}$$

$$Q = \frac{\pi \cdot (\text{energy stored})}{\text{energy loss per half cycle}} \tag{11}$$

[0055] In general, electromagnetic cavities may be designed to have a Q factor in excess of 1,000. A high Q factor allows for an accurate determination of the resonant frequency of the electromagnetic cavity **20**. In addition, larger values for the Q factor are associated with higher-quality resonances and smaller losses.

[0056] The Q factor of the electromagnetic cavity **20** also determines the rate at which the response signal **26** decays when the interrogation signal **24** is removed or turned off. The intensity of the electric field will decay when excitation is removed from the electromagnetic cavity **20** as given in equation 12:

$$E(t) = E_o \cdot e^{-(\Pi f_o/Q)t} \tag{12}$$

where E_o is the initial value of the electric field intensity when the excitation (i.e. the interrogation signal **24**) is removed and E(t) is the time dependent value of the electric field intensity.

[0057] Referring now to Figure 5a, shown therein is an alternative embodiment of the sensor **18'** having an electromagnetic cavity **20"** which is coupled to a mechanical amplifier **44** which is shown in more detail in Figure 5b (please note that Figures 5a and 5b are not drawn to scale). The mechanical amplifier **44** amplifies the effect of the strain **12** on the electromagnetic cavity **20"**. The mechanical amplifier **44** also allows the electromagnetic cavity **20"** to be temperature insensitive. The embodiment of the mechanical amplifier **44** shown in Figure 5a is but one type of mechanical amplifier. Other types of mechanical amplifiers comprising various arrangements of flexures could also be used.

[0058] The mechanical amplifier **44** comprises a first member **48** and a second member **49** coupled to the first member **48**. The first member **48** has a first region **50** with a first length L_1. The second member **49** has a second region **51** with a second length L_2 which is larger than the first length L_1. The first region **50** is coupled to the second region **51** by a fulcrum region **52**. If a strain **53,** having a magnitude E_1, is acting to the right of the sensor **18** in the left direction, the first region **50** is exposed to the strain **53** and transfers the strain **53** to the second region **51** which experiences a strain **54** having a magnitude E_2. The second region **51** forms a portion of the body surrounding the electromagnetic cavity **20"** and accordingly transfers the strain **54** thereto. However, due to the different lengths of the first and second regions **50** and **51**, the magnitude of the strain **53** is amplified by an amplification factor A according to equation 13.

$$A = \frac{L_2}{L_1} \tag{13}$$

Accordingly, the regions **50, 51** and **52** act like a lever as shown in Figure 5c. The effect of any changes in the magnitude of the strain **53** on the sensor **18'** will be magnified which will produce a larger change in the dimensions of the electromagnetic cavity **20"**. This in turn will produce a larger change in the resonant frequency of the electromagnetic cavity **20"**.

[0059] The sensor **18'** further comprises slots **56** and **58** to provide an electrical short circuit for the electromagnetic cavity **20"** to make it appear as if the electromagnetic cavity **20"** is totally enclosed. This is not the case since the sensor **18'** has the mechanical amplifier **44** which will move due to the strain **53**. To further implement the electrical short circuit, the side walls **30'**

are slightly lower in height than side walls **30** to provide a small air gap underneath the plate **34** so that electromagnetic energy flows from the electromagnetic cavity **20"** into the slot **56**, travels over the first member **48**, enters the slot **58** and returns to the electromagnetic cavity **20"**. The electrical length of the path just described is preferably half the wavelength of the resonant frequency of the electromagnetic cavity **20"**.

[0060] Thermal drift can be a problem with prior art sensors because the accuracy of the prior art sensors vary since measurements change with temperature fluctuations. This makes it difficult to compare measurements taken during the winter and summer months which in turn makes it difficult to know if the strain in a structure has changed during the winter months or if the variations in measurements are due to temperature. The mechanical amplifier **44** shown in Figures 5a and 5b will not amplify thermal drift because temperature variations will affect the length of the first and second members **48** and **49** by the same factor which cancels out in equation 13.

[0061] The resonant frequency of the electromagnetic cavities **20**, **20'** and **20"**, and hence changes in the strain **12** within the structure **14**, can be determined in one of two ways. The first method of determining the resonant frequency involves the continuous presentation of the interrogation signal **24** during the determination of the resonant frequency. Referring to Figure 6a, when the interrogation signal **24** has a frequency content that matches the resonant frequency of the electromagnetic cavity **20**, during excitation by the interrogation signal **24**, the electromagnetic cavity **20** absorbs this frequency content which will be absent in the response signal **26**. Thus, while the interrogation signal **24** is exciting the electromagnetic cavity **20**, all frequencies in the interrogation signal **24**, other than those that match the resonant frequency of the electromagnetic cavity **20** will be reflected which is represented by a minimum at the frequency f_u in Figure 6a. When the sensor **18** experiences a change in the strain **12**, the resonant frequency changes which is represented by the minimum at the frequency f_s in Figure 6a. Accordingly, the interrogator **16** may be built to detect a minimum in the response signal **26** which represents the resonant frequency of the electromagnetic cavity **20**.

[0062] However, while the interrogation signal **24** is being transmitted to the sensor **18**, there are a lot of objects within the structure **14**, such as steel reinforcements, which may reflect and/or absorb the transmitted energy. The result is the introduction of many valleys and peaks at different frequencies within the response signal **26** as shown in Figure 6b. This makes it difficult to determine the resonant frequency of the electromagnetic cavity **20**. In this case, some pre-processing of the response signal **26** may be necessary such as bandpass filtering to remove noise. Furthermore, a thresholding scheme could be used to detect the notch which corresponds to the resonant frequency.

[0063] The second method of determining the resonant frequency of the electromagnetic cavity **20** circumvents the problem due to interference from other objects in the structure **14** that was just discussed. After the interrogation signal **24** is turned off, the electromagnetic cavity **20** will continue to produce the response signal **26** for a period of time according to equation 12. However, now the response signal **26** contains energy at the resonant frequency of the electromagnetic cavity **20**. The other objects in the structure **14** will also continue to reflect energy after the interrogation signal **24** has been turned off. However, because the electromagnetic cavity **20** has such a high Q factor, the reflections from the objects within the structure **14** will stop before the electromagnetic cavity **20** stops producing the response signal **26**. For instance, given a Q factor of 1000, the response signal **26** may be radiated by the electromagnetic cavity **20** for 1000 cycles while the interfering reflections from the other objects in the structure **14** will be radiated for far fewer cycles. (1 cycle is the period related to the resonant frequency, i.e. 1 cycle = $1/f_r$).

[0064] Referring now to Figure 7a, the interrogation signal **24** may be modulated or pulsed so that it is on for a period of time and then turned off. The interrogation signal **24** is shown here as pulses **60** to show the occasions when the interrogation signal **24** is on. In practice, the interrogation signal **24** may actually be a sinusoid or a broadband signal as discussed below. Referring now to Figure 7b, an example of the response signal **26** is shown. The jagged portion **62** of the response signal **26** represents the portion of the response signal **26** that is reflected as well as the interference from the other objects in the structure **14** while the interrogation signal **24** is being transmitted. The exponentially decaying portion **64** of the response signal **26** predominantly represents the exponentially decaying energy that is produced by the electromagnetic cavity **20** when the interrogation signal **24** is turned off and the electromagnetic cavity **20** has been excited to resonate. Accordingly, after waiting for a brief period of time for the reflected interfering energy to subside, the interrogator **16** can sense the response signal **26** to detect a peak in the reflected energy which represents the resonant frequency of the electromagnetic cavity **20**. This is represented in Figure 7c which shows the employment of gating to remove the interfering reflections from the response signal **26**. The detected resonant frequency would appear as shown in Figure 7d with the unstrained resonant frequency represented by f_u and the strained resonant frequency represented by f_s.

[0065] Referring now to Figure 8a, shown therein is an embodiment of the interrogator **16**. The interrogator **16** comprises a signal generator **70** for generating the interrogation signal **24** and an antenna **72** for transmitting the interrogation signal **24** to the sensor **18** and for receiving the response signal **26** from the sensor **18**. The signal generator **70** is coupled to the antenna **72** via a directional coupler **74**. The interrogator **16** further comprises a detection module **76** that is coupled to the directional coupler **74**. The detection module **76** analyzes the response signal **26** to detect the resonant frequency of the electromagnetic cavity **20**. The interrogator **16** further comprises an output module **78** that is coupled to the detection module **76**. The output module **78** provides an indication of any changes in the strain **12** that acts on the sensor **18**.

[0066] The interrogator **16** also comprises a memory module **80** for storing previous values of the resonant frequency of each sensor **18** in the sensor system **10** and a control module **82** for controlling the operation of the interrogator **16**. The memory module **80** is coupled to the signal generator **70**, the detection module **76** and the control module **82**. The control module **82** is connected to each module of the interrogator **16** and the signal generator **16**. The control module **82** co-ordinates the operation and timing of each of the components of the interrogator **16**. The control module **82** may be a microprocessor or a DSP. The interrogator **16** further comprises an input module **84** that is connected to the control module **82**. The input module **84** is used to activate the interrogator **16** to interrogate one of the sensors **18**. The input module **84** may also be used to alter the operational parameters of the interrogator **16** such as selecting which method is used to determine the resonant frequency of the sensor **18**. The input module **84** may be a keypad or another suitable input device.

[0067] The signal generator **70** generates the interrogation signal **24** according to one of the two methods for determining the resonant frequency of the electromagnetic cavity that were discussed above. In either case, the signal generator **70** generates the interrogation signal **24** with the underlying purpose of exciting the electromagnetic cavity **20**. Unfortunately, the resonant frequency of the electromagnetic cavity **20** is not known *a priori* since the strain **12** experienced by the sensor **18** is not known *a priori*. However, after taking a baseline measurement, perhaps upon first coupling the sensor **18** with the structure **14**, an approximate value of the resonant frequency of the electromagnetic cavity **20** can be determined for a subsequent measurement. The baseline measurement may first comprise taking a series of measurements of the sensor **18** before coupling the sensor **18** with the structure **14** to get an average value for the unstrained resonant frequency. After the sensor **18** has been coupled with the structure **14**, a series of measurements may then be taken to produce an average measurement of the strained resonant frequency. Averaging is used to prevent taking spurious readings. The value of the baseline resonant frequency can be stored in the memory module **82** for later retrieval. Accordingly, during the next measurement, the frequency content of the interrogation signal **24** may be varied about the baseline resonant frequency to determine the current resonant frequency. Once the current resonant frequency is determined, this value may also be stored in the memory module **82**. In this fashion, during the measurement of a subsequent resonant frequency, the last measured resonant frequency can be retrieved from the memory module **82** and the interrogation signal **24** varied about this frequency. Accordingly, the memory module **82** records information related to past strains such as the magnitude of each strain and the associated resonant frequency of the electromagnetic cavity **20**.

[0068] If the interrogation signal **24** is a narrowband signal, such as a sinusoidal signal, the signal generator **70** may sweep the center frequency of the interrogation signal **24** within a certain sweep range of the previously measured resonant frequency to determine the current resonant frequency of the electromagnetic cavity **20**. To generate a sinusoidal interrogation signal, a variable frequency oscillation circuit such as a voltage controlled oscillator may be used for the signal generator **70**. Alternatively, a crystal controlled oscillator that provides adequate frequency stability may also be used. For each frequency used to generate the sinusoidal signal, the magnitude of the response signal may be recorded by the detection module **76** to generate a plot such as that shown in Figure 6a. The detection module **76** may then analyze this recorded data to determine the resonant frequency.

[0069] Alternatively, a broadband signal, such as a chirp signal, may be used for the interrogation signal **24**. Such an interrogation signal **24** may be advantageous since the interrogation signal **24** would not have to be swept through the sweep range just mentioned. In this case, the interrogation signal **24** may have a center frequency that is equivalent to a previously measured resonant frequency. Furthermore, the interrogation signal **24** would have a bandwidth that is sufficient to detect the change in the resonant frequency of the electromagnetic cavity **20** under expected changes in the strain **12**

experienced within the structure **14**. In this case, the response signal **26** can be measured by the detection module **76** which may then perform frequency analysis on the response signal **26** to detect the resonant frequency as discussed further below.

[0070] As previously discussed, due to interference from reflections and absorption by other objects in the structure **14**, a plot of the magnitude of the response signal **26** versus frequency will be contaminated by unwanted reflections as shown in Figure 6b. Accordingly, it will be difficult to detect the resonant frequency of the electromagnetic cavity **20** in the presence of the interference. In this case, the signal generator **70** may be implemented to facilitate the second method of determining the resonant frequency of the electromagnetic cavity **20**. The signal generator **70** could generate an interrogation signal **24** such as the narrowband or broadband signals that were previously described (if a narrowband signal is used for the interrogation signal **24** then frequency sweeping is required). The signal generator **70** would also have a modulator to modulate the interrogation signal **24** with a modulation signal to turn the interrogation signal **24** on and off as shown in Figure 7a. The modulation signal may be a pulse train having an appropriate period and duty cycle such that the response signal **26** from the electromagnetic cavity **20** decays to a small level prior to the application of the next portion of the interrogation signal **24** (i.e. the next portion **60**). Alternatively, a switch may be used to couple the signal generator **70** to the directional coupler **74**. The switch could be open and closed, under the control of the control module **82**, to produce an on/off interrogation signal **24** as shown in Figure 7a.

[0071] The antenna **72** may be any antenna suitable for generating and receiving RF signals. For instance the antenna **72** may be a dipole antenna or a patch antenna. There may also be another embodiment of the interrogator **16** in which there are two antennas wherein the first antenna is used for transmitting the interrogation signal **24** and the second antenna is used to receive the response signal **26**. In this case there would be no need for the directional coupler **74**. The first antenna would be coupled to the signal generator **70** via some signal conditioning circuitry such as an amplifier and the second antenna would be coupled to the detection module **76** also via some signal conditioning circuitry to reduce the noise and interference in the response signal **26**.

[0072] The directional coupler **74** is a commonly used passive component in RF devices which is used to transmit a signal in either the forward or backward direction. A bi-directional coupler transmits signals in both directions so that a signal may be transmitted while another signal is being received. The directional coupler **74** is preferably a bi-directional, four port coupler with the ports connected to the signal generator **70**, the antenna **72** and the detection module **76**. The remaining port would be left floating. When the interrogation signal **24** is sent to the antenna **72**, half of the energy is sent to the antenna **72** and the other half of the energy is sent to the floating port. When the response signal **26** is received by the antenna **72**, half of the energy is sent to the detection module **76** and the other half of the energy is sent to the signal generator **70**.

[0073] The detection module **76** analyzes the response signal **26** to detect the resonant frequency of the electromagnetic cavity **20**. The detection module **76** may be implemented in a number of ways depending on which method is used for the determination of the resonant frequency of the electromagnetic cavity **20**. In all cases, the detection module **76** would pre-process the response signal **26** to reduce the amount of noise in the response signal **26** and to translate the frequency content of the response signal **26** to another frequency band for more efficient signal processing as is commonly known to those skilled in signal processing. For instance, the detection module **76** may include a bandpass filter for removing noise from the response signal **26** as well as a mixer to demodulate the response signal to an intermediate frequency or to the baseband for analysis. If the interrogator **16** is implemented using a digital signal processor or another embedded processor then downsampling may also be performed to reduce the amount of data that is recorded.

[0074] When the first method of determining the resonant frequency is used by the interrogator **16**, and a narrowband signal is used for the interrogation signal, the detection module **76** may be an envelope detector that is used to detect the magnitude of the response signal **26**. The envelope detector may be a diode detector or a peak detector as is commonly known to those skilled in the art. The magnitude of the response signal **26** is measured and indexed by the center frequency of the narrow band signal that was transmitted during the measurement of the response signal **26**. The detection module **76** then determines which measurement is smaller than its neighboring measurements (i.e. to locate the minimum).

[0075] Alternatively, if a broadband signal is used for the interrogation signal **24**, the detection module **76** may incorporate frequency analysis to analyze the measured response signal **26** across frequency to determine the resonant frequency. In this case, the detection module **76** may include a bank of correlators or a filterbank, which are each associated with a frequency, and locate which correlator or filter has the smallest output to determine the minimum. Alternatively, the detection module **76** may incorporate an FFT module (which may be implemented in hardware or software if a microprocessor or DSP is used to implement the interrogator **16**) to perform a frequency analysis of the measured response signal **26**. A thresholding algorithm may be used on the FFT of the measured response signal **26** to detect the minimum. Furthermore, the use of a broadband signal allows the same interrogation signal **24** to be repeatedly transmitted so that time averaging may be done on the resultant response signals **26**. Time averaging would reduce the magnitude of the noise in the response signal **26** provided that the time lag for each response signal **26** is similar.

[0076] When the second method of determining the resonant frequency is used by the interrogator **16**, and either a narrowband or a broadband signal is used for the interrogation signal **24**, the detection module **76** incorporates a timer, or a gating device to delay the measurement of the response signal **26** until the interference from the other objects in the structure **14** has diminished (i.e. to measure the portion **64** of the response signal **26** as shown in Figure 7c). If a narrowband signal is used for the interrogation signal **24**, the detection module **76** may incorporate an envelope detector to detect when the response signal **26** is a maximum. There will only be significant response energy during the portion **64** of the response signal **26** when the frequency of the narrowband signal includes the resonant frequency of the electromagnetic cavity **20**. Since this event would be detected before changing the center frequency of the narrowband signal to the next frequency in the sweep range, the resonant frequency would be the frequency that was last selected for the interrogation signal **24**.

[0077] Alternatively, if a broadband signal is used for the interrogation signal **24**, the detection module **76** may perform frequency analysis on the response signal **26** to determine the resonant frequency using any of the frequency analysis techniques previously discussed. However, in this case, a peak in the amplitude of the response signal versus frequency denotes the resonant frequency (i.e. see Figure 7d). A thresholding method may be used to determine the peak in the FFT data. Furthermore, the use of a broadband signal allows the same interrogation signal **24** to be transmitted so that time averaging may be used on the response signal **26**. Time averaging will reduce the magnitude of the noise in the response signal **26** provided that the time lag for the portion **64** of the response signals **26** are similar.

[0078] The output module **78** provides an indication of any changes in the strain **12** that acts on the sensor **18**. The output module **78** receives the detected resonant frequency from the detection module **76** and calculates the change in force according to equation 7 above. Accordingly, the output module **78** is further coupled to the memory module **80** to obtain a previous resonant frequency value which may be the baseline resonant frequency value to determine an absolute change in structural strain. Alternatively, the output module **78** may obtain the latest resonant frequency that was measured to monitor the ongoing change in structural strain across time. The output module **78** may further comprise an output device such as an LCD screen to show the calculated change in structural strain or to show the detected resonant frequency. Alternatively, the output device may also comprise a speaker with associated circuitry that generates an audible tone that is related to the degree of change in structural strain. In this fashion, an alarm may be sounded when the change in structural strain exceeds a certain criteria and structural failure is imminent. Alternatively, the output device may comprise a paper printout device that provides a hardcopy of the calculated information.

[0079] Alternatively, referring to Figure 8b, another embodiment of the interrogator **16'** comprises a modulator **86** that is in communication with the signal generator **70** and the control module **82**. When the second method of determining the resonant frequency of the electromagnetic cavity **20** is used by the interrogator **16'**, the modulator **86** generates a modulating signal, which may be a pulse train as discussed above, that is then multiplexed with the signal that is generated by the signal generator **70** which may be a narrowband or broadband signal as discussed above. The remainder of the interrogator **16'** operates in the same fashion as the interrogator **16** and will not be discussed.

[0080] Referring now to Figure 9, shown therein is a method **90** for measuring the change in the strain **12** in the structure **14**. The method **90** starts at step **92** where the sensor **18** that houses the electromagnetic cavity **20** is coupled to the structure **14**. Coupling may involve embedding the sensor **18** within the structure **14** or attaching the sensor **18** to the outside of the structure **14**. The next step **94** is to provide the interrogation signal **24** to the sensor **18** to excite the electromagnetic cavity **20** and evoke the response signal **26**. The response signal **26** is in turn related to the strain **12** experienced by the structure **14**. The method **90** then moves to step **96** where the response signal **26** is processed to determine the resonant frequency of the electromagnetic cavity **20** and hence the strain **12** experienced by the structure **14**.

[0081] The method **90** may further comprise the step of amplifying the strain **12** experienced by the structure **14** in a mechanical fashion to amplify the magnitude of the strain **12** on the electromagnetic cavity **20**. This will allow the sensor **18** to sense smaller changes in strain **12**.

[0082] Step **94** of the method **90** may involve providing the interrogation signal **24** as a narrowband signal and sweeping the center frequency of the narrowband signal in a sweep range while measuring the response signal **26**. Processing the response signal **26** in step **96** would then comprise performing frequency analysis or a form of envelope detection (as described above) to determine a minimum in the response signal **26** at a frequency within the sweep range.

[0083] Alternatively, the method may comprise providing the interrogation signal **24** as a broadband signal with a center frequency equal to a previously measured resonant frequency while measuring the response signal **26**. Processing the response signal **26** in step **96** would then comprise performing frequency analysis on the response signal **26** to detect a minimum that is related to the resonant frequency of the electromagnetic cavity **20**.

[0084] Alternatively, step **92** of the method **90** may involve modulating the interrogation signal **24** to provide an intermittent interrogation signal **24**. The response signal **26** would then be measured shortly after the interrogation signal **24** is off to allow for the interference from other objects contained in the structure **14** to decrease in amplitude. Processing the response signal **26** in step **96** would then comprise performing frequency analysis or a form of envelope detection (as described above) on the response signal **26** to detect a peak that is related to the resonant frequency of the electromagnetic cavity **20**.

[0085] In use, a structural inspector may carry the interrogator **16** to various locations in or on the structure **14** where the sensors **18** are located.

The structural inspector would then point the interrogator **16** towards the sensor **18** and push a button to generate and transmit the interrogation signal **24** to the sensor **18**. The interrogator **16** would then detect the resonant frequency of the sensor **18** and calculate the strain at that portion of the structure **14**. The interrogator **16** could be any distance away from the sensor **18** as long as the interrogation signal **24** is strong enough to excite the electromagnetic cavity **20** and the response signal **26** is strong enough so that the interrogator **16** may determine the resonant frequency.

[0086] The electromagnetic cavity **20** of the sensor **18** can be built to handle relatively large amounts of power. Furthermore, the sensor **18** has a simple and rugged construction and is a passive embedded sensor which can be wirelessly interrogated thereby eliminating the need for a power source and any permanent electrical or optical connections that are subject to breaking, becoming dislodged or damaged by vandals. In addition, the sensors **18** work independently of one another due to the lack of electrical or optical hardwiring. Accordingly, if for some reason one of the sensors is not functioning properly it will not have any effect on the operability of any of the other sensors.

[0087] The sensor system **10** is also very portable and easy to install. Anyone on the job site may install the sensors **18** during the time of construction of the structure **14**. The sensors **18** would be placed at structural locations where maximum strains are experienced. The sensors **18** may be embedded in a concrete structure **14** while the concrete is still wet. For instance, the sensor **18** may be covered by approximately 10 cm of concrete. Alternatively, the sensors **18** may be attached to the reinforcing bars of the structure **14**. The embedded sensors **18** also do not jeopardize the soundness of the structure **14**.

[0088] The sensors **18** may also be attached to steel and wooden structures after the structures have been completed. In this case, the right type of adhesive is needed so that the strain experienced by the structure **14** is coupled/transferred to the sensor **18**. For example, the sensor **18** may be attached to a steel structure by drilling a hole in the structure and bolting the sensor **18** to the structure.

[0089] There are a variety of uses for the sensor system **10** of the present invention. For instance, the sensor system **10** could be used for dynamic testing of the structure **14** in response to a test strain. This would allow standardized testing of structural health in response to known strains, and would also be useful in the design phase of such structures.

[0090] Alternatively, the sensor system **10** could be used to assess damage in civil structures. For instance, after the occurrence of a natural disaster such as an earthquake, the sensor system **10** may be used to determine the change in strain experienced by the structure to determine whether it is safe for emergency personnel to enter the structure. The changes in strain may be measured over time to determine whether the structure will fail and how long it would take for this failure to occur.

[0091] This invention may also be used to evaluate the performance and health of civil structures. For example, as a bridge is constructed several of the metal boxes would be embedded at strategic sites. When construction of the bridge was complete each of these sensors would be interrogated to determine if the bridge meets its specifications and to establish a baseline reading. After this baseline was established the embedded sensors would be periodically interrogated to determine the health or level of deterioration of the structure.

[0092] Although the examples and embodiments described above illustrate that the body of the sensor **18** has an electromagnetic cavity **20**, it should be understood by those skilled in the art that the sensor **18** has a body that is capable of supporting resonant electromagnetic modes. Furthermore, the electromagnetic cavity **20** may be considered, in general, to be an electromagnetic resonator that resonates at a frequency related to the dimensions of the electromagnetic resonator. For instance, the electromagnetic resonator may also be a dielectric body within an insulating material to form a dielectric resonator. In this case the coupler **20** would not require the wire **40**.

[0093] Furthermore, it should be understood that various modifications can be made to the preferred embodiments described and illustrated herein, without departing from the present invention, the scope of which is defined in the appended claims. For instance, a similar sensor system may be developed to monitor the structural integrity of vehicles. In this case, the frequency range would likely need to be increased to produce smaller sensors.

Claims:

1. A system for measuring strain experienced by a structure, said system comprising:

    a) a sensor including:

        i) a body having an electromagnetic resonator, said electromagnetic resonator adapted to produce a response signal in response to an interrogation signal, said body being coupled to said structure to allow said strain to alter the resonance properties of said electromagnetic resonator thereby altering said response signal; and,

        ii) a coupler coupled to said body, said coupler adapted to transfer said interrogation signal into said electromagnetic resonator and transfer said response signal out of said electromagnetic resonator; and,

an interrogator being adapted to generate and transmit said interrogation signal to said sensor, said interrogator being further adapted to receive said response signal.

2. The system of claim 1, wherein said electromagnetic resonator is a dielectric resonator.

3. The system of claim 1, wherein said electromagnetic resonator is an electromagnetic cavity.

4. The system of claim 3, wherein said electromagnetic cavity is rectangular.

5. The system of claim 3, wherein said electromagnetic cavity is cubic.

6. The system of claim 3, wherein said electromagnetic cavity is cylindrical.

7. The system of claim 3, wherein said sensor further comprises a mechanical amplifier coupled to said electromagnetic cavity, said mechanical amplifier being adapted to amplify the magnitude of said strain on said electromagnetic cavity.

8. The system of claim 7, wherein said mechanical amplifier comprises a first member having a first region with a first length and a second member having a second region with a second length, said second region being coupled to said first region, wherein said first region is exposed to said strain and said second region is coupled to said electromagnetic cavity, wherein the magnitude of said strain experienced by said electromagnetic cavity is amplified by a factor equal to the ratio of said second length to said first length.

9. The system of claim 1, wherein said interrogator comprises:

a) an antenna for transmitting said interrogation signal and receiving said response signal; and,

b) a signal generator coupled to said antenna, said signal generator being adapted to generate said interrogation signal.

10. The system of claim 9, wherein said interrogator further comprises a detection module coupled to said antenna, said detection module being adapted to process said response signal to determine a value indicative of said strain.

11. The system of claim 10, wherein said interrogator further comprises:

a) an output module coupled to said control module, said output module being adapted to provide an output indicative of said strain; and,

b) a control module coupled to said signal generator, said detection module and said output module for controlling the operation thereof.

12. The system of claim 11, wherein said interrogator further comprises:

a) a memory module in communication with said signal generator, said detection module and said control module, said memory module being adapted to store information related to previously determined strains; and,

b) an input module in communication with said control module, said input module being adapted to allow a user to operate said interrogator.

13. The system of claim 10, wherein said interrogation signal is a continuous narrowband signal having a center frequency that is varied in a sweep range that includes a resonant frequency of said electromagnetic resonator and said detection module is adapted to detect a minimum in said response signal at a frequency within said sweep range, wherein said minimum occurs at said resonant frequency.

14. The system of claim 10, wherein said interrogation signal is a broadband signal having a frequency content that includes a resonant frequency of said electromagnetic resonator, and said detection module is adapted to detect a minimum in said response signal wherein said minimum occurs at said resonant frequency.

15. The system of claim 10, wherein said interrogation signal is a modulated narrowband signal having a center frequency that is varied in a sweep range that includes a resonant frequency of said electromagnetic resonator and said detection module is adapted to detect a peak in said response signal at a frequency within said sweep range, wherein said peak occurs at said resonant frequency.

16. The system of claim 10, wherein said interrogation signal is a modulated broadband signal having a frequency content that includes a resonant frequency of said electromagnetic resonator, and said detection module is adapted to detect a peak in said response signal wherein said peak occurs at said resonant frequency.

17. A sensor for measuring strain experienced by a structure, said sensor comprising:

a) a body having an electromagnetic resonator for producing a response signal in response to an interrogation signal, said body being coupled to said structure to allow said strain to alter the resonance properties of said electromagnetic resonator thereby altering said response signal; and,

b) a coupler coupled to said sensor, said coupler adapted to transfer said interrogation signal into said electromagnetic resonator and transfer said response signal out of said electromagnetic cavity.

18. The sensor of claim 17, wherein said electromagnetic resonator is a dielectric resonator.

19. The sensor of claim 17, wherein said electromagnetic resonator is an electromagnetic cavity.

20. The sensor of claim 19, wherein said electromagnetic cavity is rectangular.

21. The sensor of claim 19, wherein said electromagnetic cavity is cubic.

22. The sensor of claim 19, wherein said electromagnetic cavity is a cylindrical cavity.

23. The sensor of claim 19, wherein said sensor further comprises a mechanical amplifier coupled to said electromagnetic cavity, said mechanical amplifier being adapted to amplify the magnitude of said strain on said electromagnetic cavity.

24. The sensor of claim 23, wherein said mechanical amplifier comprises a first member having a first region with a first length and a second member having a second region with a second length, said second region being coupled to said first region, wherein said first region is exposed to said strain and said second region is coupled to said electromagnetic cavity,

wherein the magnitude of said strain experienced by said electromagnetic cavity is amplified by a factor equal to the ratio of said second length to said first length.

25. A method for measuring strain experienced by a structure, said method comprising:

a) coupling a sensor having an electromagnetic resonator to said structure;

b) providing an interrogation signal to said electromagnetic resonator to evoke a response signal; and,

c) receiving said response signal.

26. The method of claim 25, wherein said method further comprises processing said response signal to determine said strain.

27. The method of claim 25, wherein said electromagnetic resonator is an electromagnetic cavity and said method further comprises:

d) amplifying said strain in a mechanical fashion to amplify the magnitude of said strain experienced by said electromagnetic cavity.

28. The method of claim 25, wherein step b) comprises:

e) providing said interrogation signal as a continuous narrowband signal; and,

f) sweeping the center frequency of said narrowband signal in a sweep range that includes a resonant frequency of said electromagnetic resonator.

29. The method of claim 28, wherein step c) comprises processing said response signal to detect a minimum at a frequency within said sweep range indicative of the resonant frequency of said electromagnetic resonator.

30. The method of claim 25, wherein step b) comprises:

a) providing said response signal as a continuous broadband signal having a frequency content that includes a resonant frequency of said electromagnetic resonator.

31. The method of claim 30, wherein step c) comprises processing said response signal to detect a notch at a frequency indicative of the resonant frequency of said electromagnetic resonator.

32. The method of claim 25, wherein step b) comprises:

e) modulating said interrogation signal to provide an intermittent narrowband signal; and,

f) sweeping the frequency of said intermittent narrowband signal in a sweep range that includes a resonant frequency of said electromagnetic resonator.

33. The method of claim 32, wherein step c) comprises processing said response signal to detect a peak at a frequency within said sweep range indicative of the resonant frequency of said electromagnetic resonator.

34. The method of claim 25, wherein step b) comprises:

a) modulating said interrogation signal to provide an intermittent broadband signal having a frequency content that includes a resonant frequency of said electromagnetic resonator.

35. The method of claim 34, wherein step c) comprises processing said response signal to detect a peak at a frequency indicative of the resonant frequency of said electromagnetic resonator.

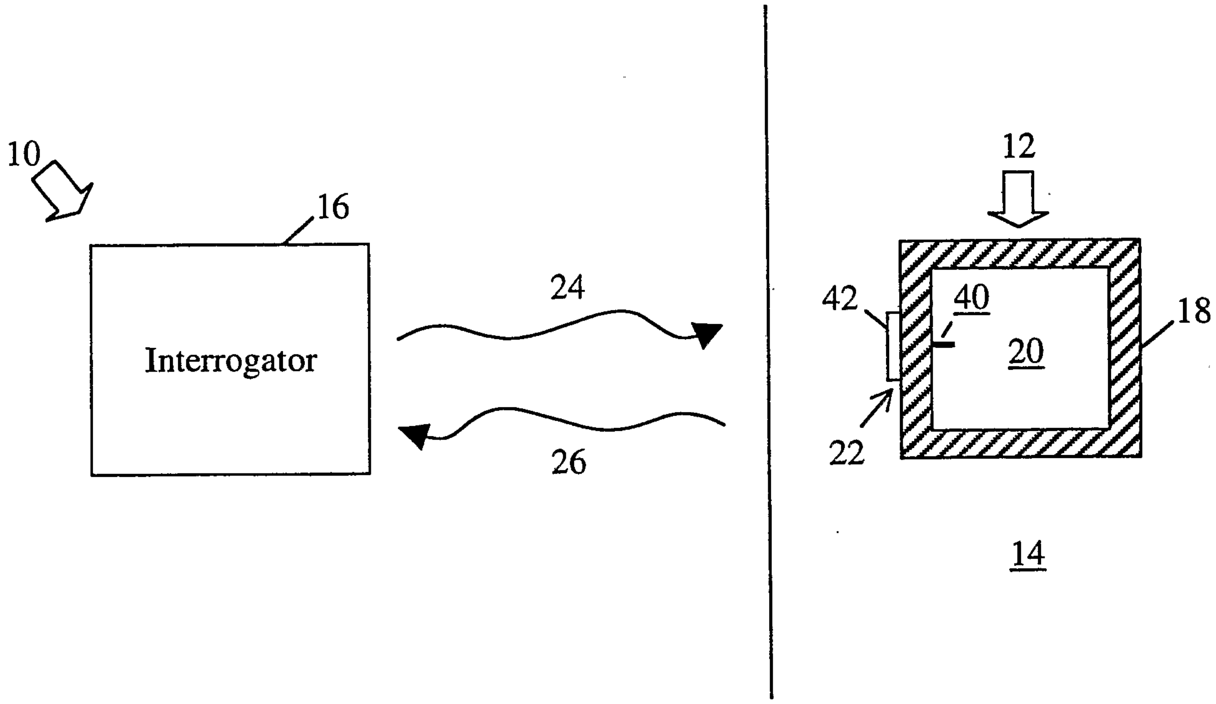


Figure 1

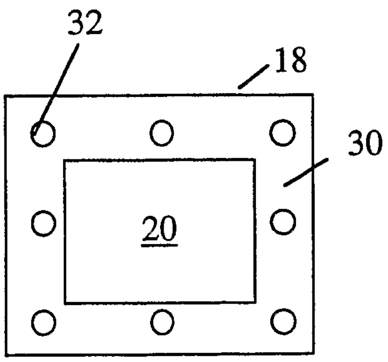


Figure 2a

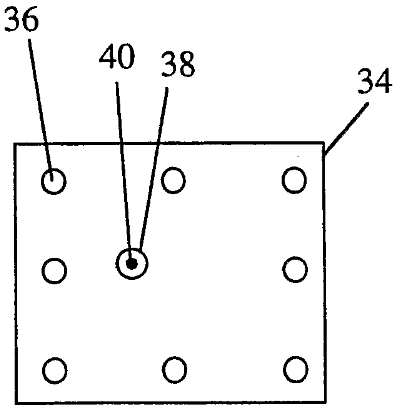


Figure 2b

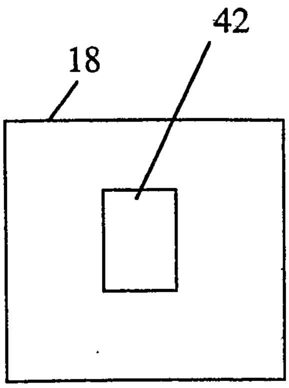


Figure 2c

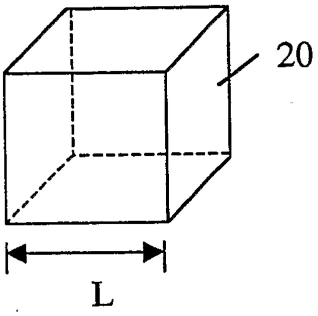


Figure 3a

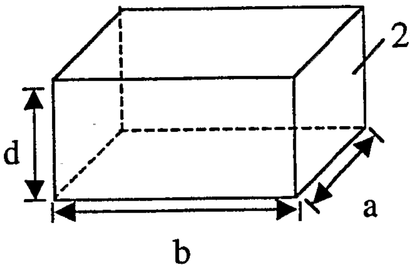


Figure 3b

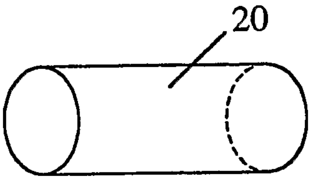


Figure 3c

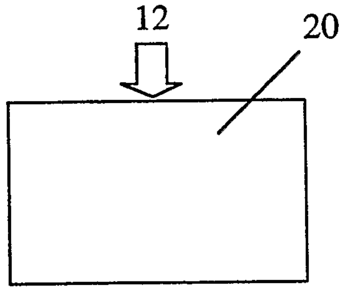


Figure 4a

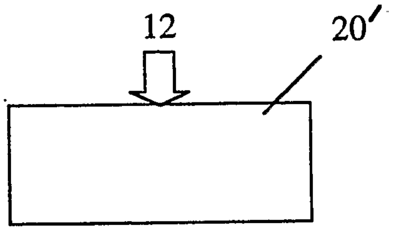


Figure 4b

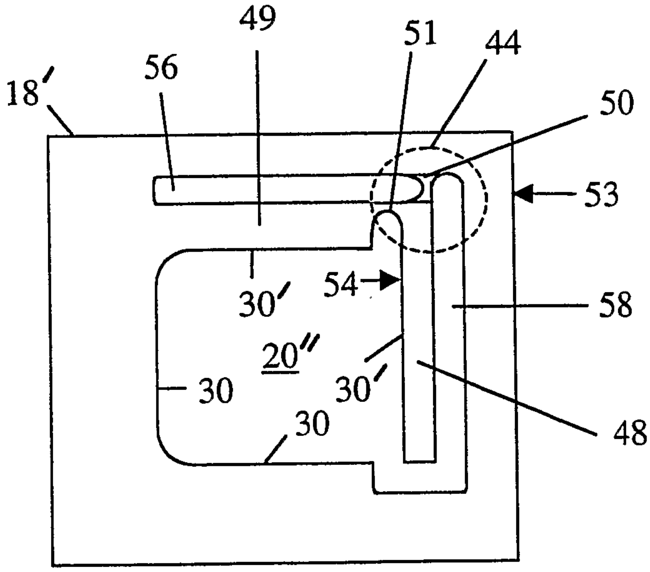


Figure 5a

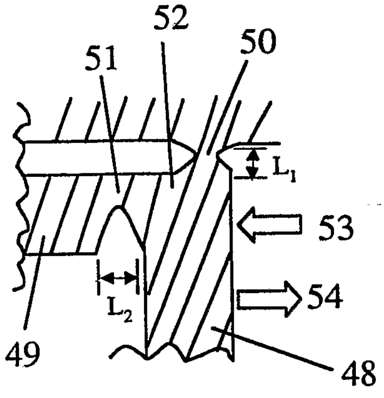


Figure 5b

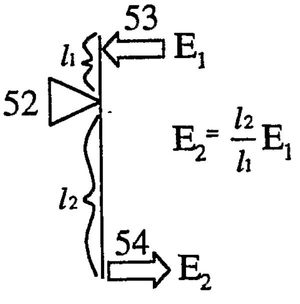


Figure 5c

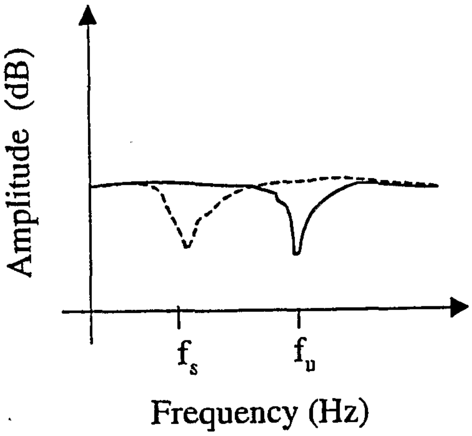


Figure 6a

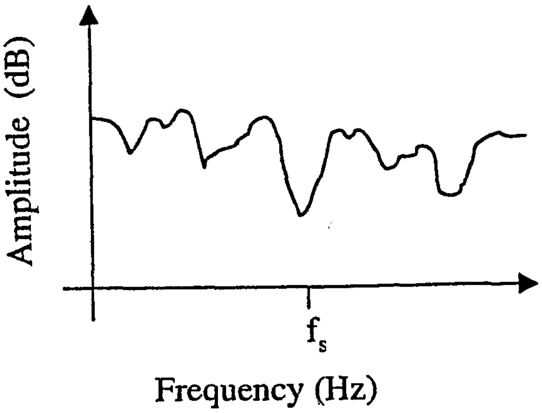


Figure 6b

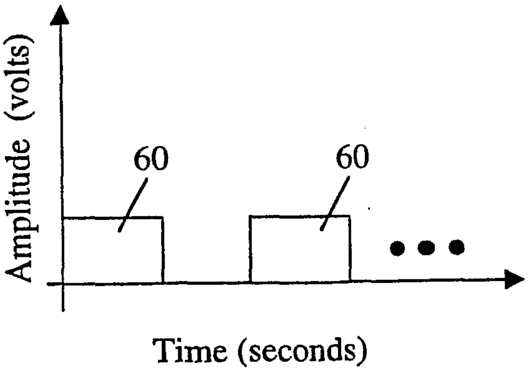


Figure 7a

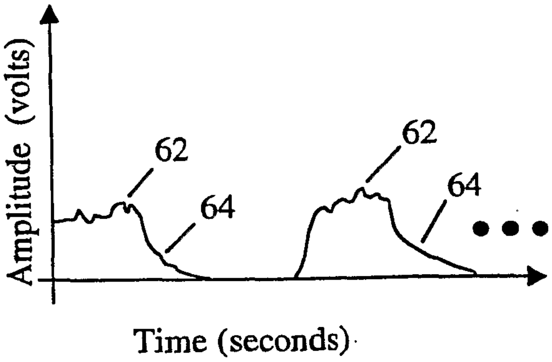


Figure 7b

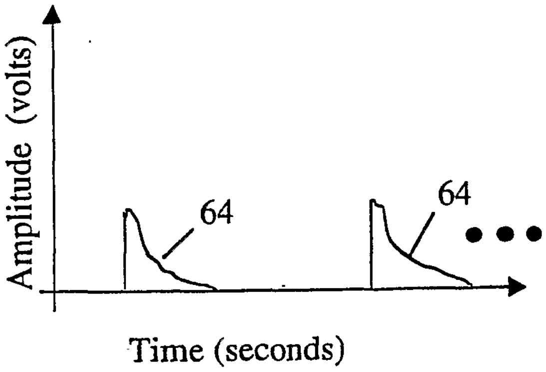


Figure 7c

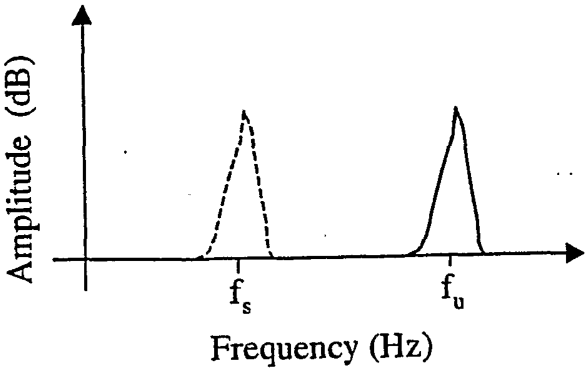


Figure 7d

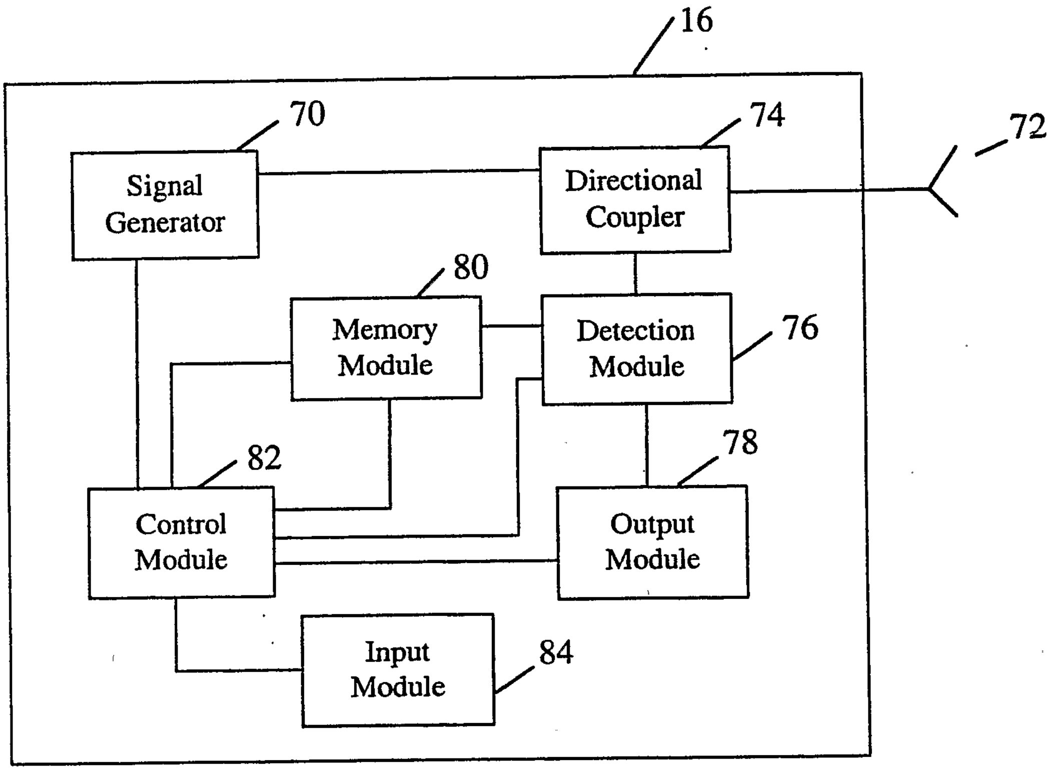


Figure 8a

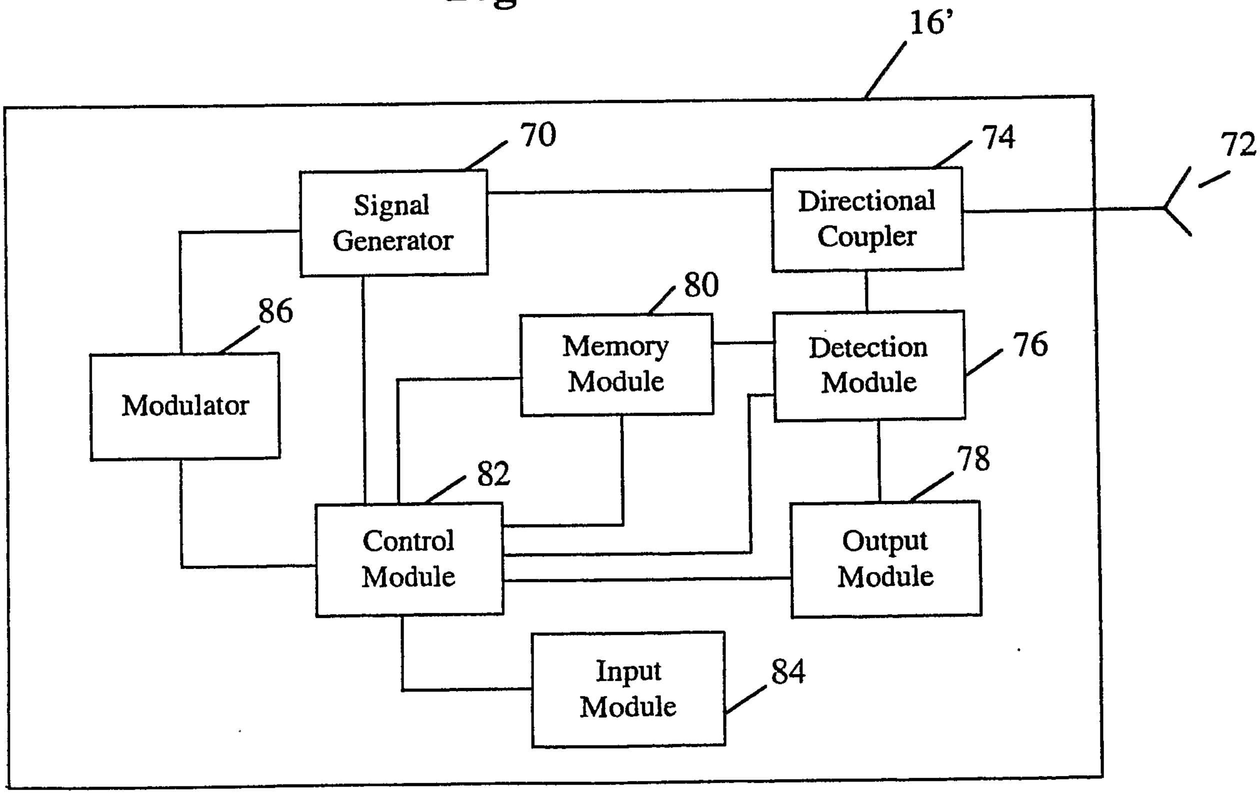


Figure 8b

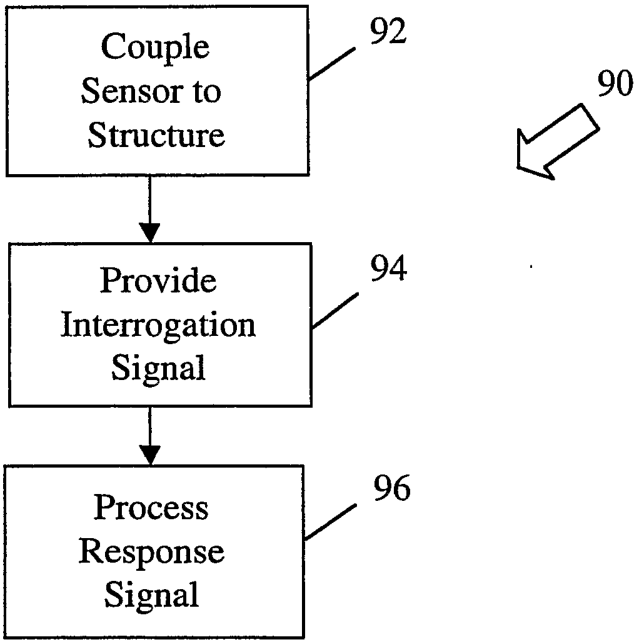

Couple Sensor to Structure
92
90
Provide Interrogation Signal
94
Process Response Signal
96

Figure 9

INTERNATIONAL SEARCH REPORT

International Application No
PCT/CA 03/00952

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01L1/25 G01B15/06 G01M19/00 G01D5/48 E01D19/00

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 7 G01L G01B G01M G01D E01D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	GB 2 212 273 A (MR. FARLEY) 19 July 1989 (1989-07-19) claim 1; figure 1 ---	1,17
X	FR 2 700 846 A (MR. BRUGIDOU) 29 July 1994 (1994-07-29) page 1, line 6 - line 15 page 3, line 9 - line 19; claim 1; figure 1 ---	25
A	JP 60 203828 A (TOSHIBA) 15 October 1985 (1985-10-15) figures 1-4 ---	
A	JP 05 264474 A (DAIPOOLE) 12 October 1993 (1993-10-12) figures 1-4 --- -/--	

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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"&" document member of the same patent family

Date of the actual completion of the international search 17 September 2003	Date of mailing of the international search report 01/10/2003
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Authorized officer Mielke, W

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/CA 03/00952

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	DE 20 07 447 A (DECCA) 17 September 1970 (1970-09-17) page 6, line 17 - line 30; figure 1 ---	
A	US 3 909 713 A (USERDA) 30 September 1975 (1975-09-30) column 3, line 19 - line 23; figure 1 ---	
A	US 5 181 423 A (HBM) 26 January 1993 (1993-01-26) column 4, line 24 - line 33; figure 1 -----	

INTERNATIONAL SEARCH REPORT

Infor[illegible]on patent family members

International [illegible]ication No
PCT/CA 03/00952

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