Wireless systems for structural health monitoring

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ABSTRACT: In this work several examples of wireless monitoring systems for structural health monitoring will be presented and contrasted. A passive wireless strain sensor based on resonant radio frequency cavities has demonstrated microstrain sensitivity and 30 Hz bandwidth. Systems that are powered by inductive coupling and do not require any form of permanent power, has demonstrated chloride and corrosion sensing capability. A wide range of sensors are now available that use conventional sensors coupled to wireless systems for communication. These systems are all expected to play a role in structural health monitoring.

1. INTRODUCTION

Civil infrastructure, such as bridges and buildings, is often the most costly asset of a country. Over time structures will corrode, fatigue, weather and wear. Eventually structures decay to the point where they must be repaired or replaced. At the moment the health of these structures is determined largely through visual inspection by trained personnel. This practice is expected to decrease because of increasing pressure on infrastructure management budgets and the increasing use of structural elements which can not be evaluated by visual inspection. Structural Health Monitoring (SHM) is an emerging field that is addressing the problem through the use of innovation technology such as fiber optic sensors and the development of robust data management tools. SHM is expected to become a ubiquitous tool for the management civil infrastructure over the next decade.

One of the significant drivers of structural health monitoring is its application to the massive problem of civil infrastructure deterioration. 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.

Most existing sensing technologies for structural health monitoring have a serious deficiency in that they require some type of permanent connection to the outside world. This causes significant problems in the installation and ongoing use of these sensors. Recent cases have shown that the cost of installation and preparation of a site for monitoring equipment can easily exceed the cost of sensors and interrogation equipment. For example, the cost of installing a monitoring system in the Tsing Ma suspension bridge in Hong Kong was reported to be over $27,000 per sensor channel [1]. Therefore, a wireless technology could make the monitoring of many more sites feasible and therefore significantly increase the utility of SHM. Perhaps, even more exciting is the possibility that these sensors may be interrogated fast enough that measurements can be carried out from a vehicle moving at highway speeds and could be interrogated without the need to close down the site to traffic. In this paper the current state of wireless sensing for structural health monitoring will be sketched out and some suggestions for future research directions suggested.

2. CLASSES OF WIRELESS SENSORS

Wireless sensors replace a hard wired or fiber optic link with some form of wireless link. Although one can imagine using ultra-sonics or other types of wireless link, it is the electromagnetic wireless link that has proven most useful to date. Within electromagnetic based wireless sensors there are several different classes of sensors:

1. Passive wireless sensors: This type of sensor operates with no internal power source and relies on the power transmitted from the interrogation system in order to carry out a measurement. The broad advantage of this type of system is that the sensor itself requires no source of power and can therefore be embedded within a structure. Examples of this type are SAW [2,3] and resonant RF cavity [4] sensors.
2. Power on measurement sensors: This type of sensor uses traditional sensors such as metal foil strain gauges. Signal conditioning systems within the sensor then convert measurement into a form suitable for transmission via a radio link. The power to run the measurement electronics and the radio communication system are supplied from the interrogation system, typically through coupling coils on the sensor and the interrogator. The advantage of this type is that the sensor does not require any form of power and hence can be embedded or left in the field with no need to provide continuous power. Examples of this type are the corrosion sensor [5], chloride sensor [6,7] and mote [8].
3. Wireless communication type: This type of sensor uses traditional sensors such as metal foil strain gauges and measurement electronics, but communicates the results via a wireless link. The principle advantage of this type of system is that communications can occur over a relatively long distance. There are many systems of this type [8-14]. One major drawback of this type is that it must contains its own power source. It remains to be seen if battery or power scavenging systems can be developed that will allow these systems to be embedded in structural monitoring systems.

The optimum choice of sensor type will vary form application to application. In the next section several examples of wireless sensors will be examined and the issues for each one will be outlined.

2.1 Passive wireless sensors

One example of a passive wireless strain sensor, based on resonant RF cavities, was recently introduced by our group [4]. The sensor consists of a passive resonant cavity sensor that is embedded in the structure, and an interrogator. The interrogator emits radio waves over a wide range of frequencies into the structure. An antenna that is attached to the sensor will receive the signals and couple them into the sensor cavity which will absorb all signals except for those in a narrow frequency band, as determined by the cavity's dimensions. The remaining signals are then transmitted back to the interrogator, which uses the information received to calculate strain on the sensor. A basic diagram illustrating how this wireless strain sensor functions is shown below (Fig. 1).

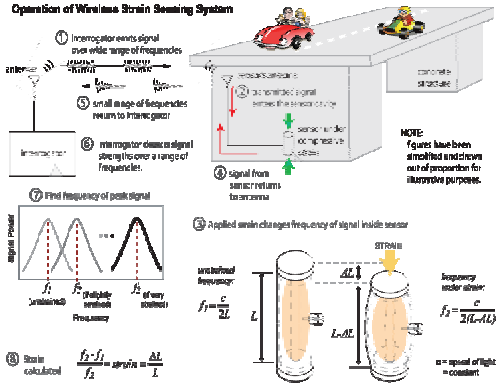

Figure 1. Illustration showing basic operating principle of a resonant cavity wireless strain sensor.

The sensor can be thought of a as a simple coaxial cavity with length l. The reason for choosing this design include a uniaxial sensitivity, and results which are simple to interpret. A small conductor extending into the cavity excites an electromagnetic field within the cavity. The resonant frequency of the cavity is a function of the cavity length as given by [15]:

$$f_{res} = \frac{c}{2l} \qquad (1)$$

where c is the speed of light in vacuum and l is the length of the cavity. When the material in which the sensor is encased is strained it will force a change in dimensions of the cavity. This change in dimension will result in a change in resonant frequency that can be used to unambiguously determine the strain in the structure. If the elastic properties of the sensor material differ from the material in which it is embedded, a gauge factor may be required. Manipulation of the equation (1) governing the

resonant frequency in the presence of a small strain of the cavity gives the approximation:

$$f_{strained} = f_{unstrained}(1-e) \quad (2)$$

Clearly as long as the unstrained resonant frequency is known then the strain can be determined with high precision and very little ambiguity. One advantage of this approach is that, unlike optical sources for fiber optic sensors, RF signals can be generated with very high accuracy and stability. RF signal generating sources can be easily frequency locked to quartz crystal oscillators which are easily obtained with error less than 1 part per million and stability within a few parts per billion [16].

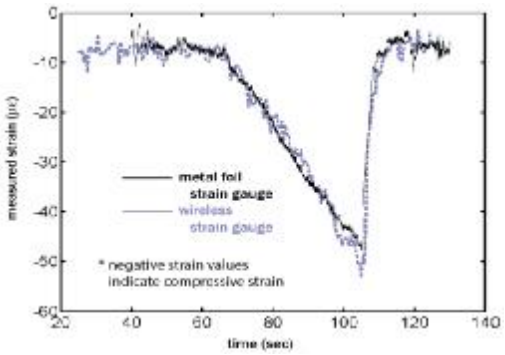

Figure 2. Comparison of wireless and metal foil strain measurement

Clearly this sensor type has the ability to measure strain with sufficient resolution for civil structural health monitoring. This type of sensor has only been demonstrated for a limited number of sensor types such as strain, temperature and PH. However, the development of these sensors is in a relatively early stage and the number of demonstrations based on this technology is expected to grow over the next few years.

2.2 Power on measurement systems

SRI in Menlo Park California has developed a wireless Chloride sensor that is intended to be embedded within bridge decks and interrogated from a moving vehicle [6,7]. The sensor consists of an electrochemical cell for chloride sensing, a signal conditioning section, a coil to pick up power from the interrogator and electronics for radio communications.

When the interrogator comes within a few meters of the sensor power is coupled to the sensor coils. The sensor then becomes active and transmits a code which identifies the sensor. The chloride sensor is then activated and a measurement of chloride concentration taken. The measurement is then transmitted back to the interrogator. This measurement can be taken in a matter of seconds. With this sensor system it is hoped that chloride measurements can be made without the need to extract concrete core samples.

Clearly there are significant advantages that can be gained from this type of sensor. There is no need for power or communications to be routed into the senor. The sensor can therefore be put into service in remote locations that would not be viable for wired or fiber optic sensors. However, the interrogator must be within a meter of the sensor in order to activate it. The architecture of this type of system is very general and it could be used with most known sensor types.

2.3 Wireless communication type sensor

There are many examples of this type of sensor system. There are several commercial versions of this type of sensor [8-14]. Most are based on widely deployed wireless communication technology. This type of system is also in its infancy and the number of sensing systems based on wireless communication available is expected to grow significantly over the next few years. However, these systems are relatively high power users and will require local power sources such as batteries or solar power. These systems will be of greatest use in applications where the distribution of power and communications is very costly. For example, this type of wireless would be a viable option on remote portions of a large bridge or a large number of small bridges in rural locations. Although the cost of the systems is expected to decrease as volumes increase the presents cost of $500 to $800 per sensor will restrict the number of applications in which wireless sensors offer an economically viable alternative to wired sensors.

These sensor systems also offer the unique ability to communicate between sensors. Although this capability is tantalizing, there has not yet been convincing demonstrations of the utility of this capability for civil structural health monitoring, Inter-sensor communication and daisy chain communication may offer a means to lower communication power requirements.

Sensor systems based on wireless communication need to have the power issue addressed. More research is needed into low power communication systems for sensing. In addition much more work is needed to demonstrate to full potential of battery powered systems. What is the expected battery life?

The table below provides a summary of the characteristics of the three types of wireless sensors.

Type	Interrogation Distance	Embeddable	Cost
Passive	~ 1m	Yes	Expected to be low
Power on measurement	~ 1m	Yes	Expected to be low
Wireless communication	Greater than 100m	Unknown	Expected to be low

Table 1: Summary of characteristics of different wireless technologies.

3. CONCLUSIONS

Wireless sensing systems offer great promise for structural health monitoring. Several systems have been demonstrated in structural health monitoring applications. Over the next few years many more wireless sensing systems will be demonstrated and many more will become commercially available.

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