Sensing of Deformations Through Grids of Antennas

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ABSTRACT

This contribution explores the possibility to monitor structural deformations by means of grids of antennas. Deformations, occurring in engineering structures due to unexpected loading conditions and to ageing, may lead to potentially dangerous events. By engineering the electromagnetic interaction among the elements of a grid of UHF Radiofrequency Identification (RFID) tags, it is possible to extract various measureable indicators useful to track the local as well the overall deformation of the body on which the antennas are attached on, and hence to monitor the "health" of sensitive structures.

INTRODUCTION

Engineering structures are designed taking into account the materials' mechanical properties and the environmental conditions that the object is going to experiment during its life span. In order to ensure the correct operation of the designed structures, it is beneficial to check the current "structural health" at regular time intervals, with the purpose to spot possible damages at an early stage, to avoid more dangerous problems.

Several methods are currently available to monitor strains in engineering structures, such as optic fibers, ultrasonic methods and so on. However, none of them is used continuously and even in real time during the structure's operation.

In the aeronautical sector, for instance, periodical inspections are carried out in order to check for possible damages and/or stresses in the structure, leading to costly airplane unavailability, often with durations of days or weeks.

While in operation, reversely, the plane is only scarsely controlled, mostly by visual inspection before each flight. This may lead to unrecorded damages, affecting the safety of passengers.

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It would then be envisaged to adopt wireless technologies also in this field: their use would help avoiding the tedious problem of cabling, which negatively impacts, both in terms of costs and dimensions, on the adoption of continuous monitoring systems.

A particularly interesting wireless technology is the Radio Frequency Identification, which is already widespread in the logistics market and is being employed more and more also for wireless sensing purposes [1].

RFID technology was born in the '60s and has its main application in the identification and tracking of objects. The RFID system (fig. 1) comprises two components: the remote transponder or tag, including an antenna and a microchip transmitter, located on the object to be identified and the local querying system or reader, which can read and elaborate the data transmitted from the tag, as well as providing energy to the tags .

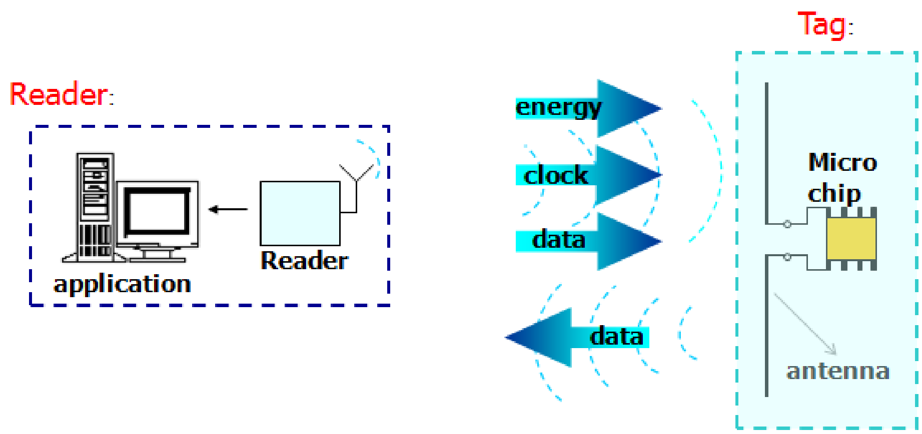

Figure 1. scheme of an RFID system, comprising the reader and the tag(s).

Various kinds of data and first of all a unique identification code (ID) can be wireless transferred to the reader by means of radio-frequency electromagnetic signals.

The tags could be **passive**, harvesting energy from the interrogating system, **semi-active** when a battery is included only to feed sensors or microcircuitry on-board the tag, or **fully active** where a local source directly feeds a microcontroller as well as the transmitting radio.

For SHM purposes, passive RFID tags can become particularly interesting as enabling platforms for a series of sensing activities. In particular, in our case, tags will be thought of not only as radiotransponders, but also as sensors, capable of monitoring their mutual distance and, hence, the strain occurring in an engineering structure.

A possible modelling framework for such proposed system can be the theory of RFID grids [2-3], recently introduced and experimented by the authors. A grid of RFID tags can be thought of as a close displacement of antennas, which has to be considered as a unique electromagnetic interconnected system having specific properties.

Physical information about the Grid, and about its interaction with the structure on which it is placed on, can be extracted from the Analog IDentifier AIDn of the nth tag, independently on the reading modalities. The analog identifier has been

defined in [2] as a function of the turn-on power P_n^{to} of the nth microchip, e.g. the minimum power driving the reader for which the nth microchip starts responding, and of the corresponding backscattered power emerging from
the grid, when the nth microchip is performing impedance modulation, and afterward collected by the reader ($P_{R\leftarrow T,n}$).

For a typical ASK modulation protocol, the analog identifier may be written in a very compact form:

$$AID_n = \frac{p_n}{\sqrt{P_{R\leftarrow T,n} P_n^{to}}} \propto R_{C,n} \left| Y_{G,nn} \right|$$

Where p_n is the chip sensitivity, $R_{c,n}$ is the nth chip resistance and $Y_{g,nn}$ is the nnth element of the grid admittance matrix.

The Analog Identifier has the interesting property of being independent from the measurement setup, i.e. distance and orientation of the reader from the tag. Therefore, it is particularly suited to conduct measurement in real-life environments, where the stability and repeatability of laboratory measurement setups is harder to guarantee. On the other hand, both turn on power and backscattered power collected at the reader will be recorded as well and can be fruitfully used for sensing if the measurement setup is guaranteed to stay the same over successive measurements.

The envisaged system is hence composed by a grid of RFID antennas (tags) properly placed over the structure and by a remote reader device, which wirelessly powers the sensing antennas and collects their responses.

The processing of the retrieved signals from each antenna of the grid will provide an aggregated information about the deformation of the grid itself, which if compared to a reference condition, will yield the displacement that the structure has undergone.

SENSING RATIONALE FOR GRIDS OF ANTENNAS

Antennas are inherently sensitive to the environment they are surrounded from. Common RFID tags design has been struggling with this problem for years, with the need to retune the antenna according to the material on which it would be positioned. However, such a property can also be seen as an intrinsic sensing capability: by changes in the environment of the antenna, its behaviour, i.e. the radiation properties, will change and therefore the variation of the environment can be remotely assessed.

Such capabilities are being exploited currently in a number of applications, for instance to monitor the dielectric properties of liquids or the gas/humidity concentration in the air (see for instance [4]). A similar approach can be used if grids of antennas are considered: in this case, the variation of the grid geometrical structure, due for instance to mechanical stress on the structure on which the grid is laying, will reflect once more into a change of radiation properties of the grid itself, giving a distributed information about the stress level the structure is experiencing.

This latter case will be analysed in this work: from an electromagnetical point of view, this can be interpreted as follows: if we have a mechanical structure on which a grid of tags is laid, a stress on such structure will cause strains along the structure itself and, consequently, on the RFID grid: the single tags will be deformed as well as their mutual distance will change, according to the level of stress / strain.

These two effects- namely, the single antenna deformation and the mutual distance variation- will have differently important effects on the overall performance of the grid and can be treated separately.

If we first assume antennas to be unshrinkable (i.e. their shape changes little with respect to the overall strain of the structure), the main factor of change will be the variation of the mutual distance between the tags of the grid, which causes variations in the mutual coupling of antennas, i.e. the mutual impedance.

Therefore, a remote estimation of such variation in the mutual coupling of the antennas could provide the basis for the wireless monitoring of surface deformations, provided that a grid of strongly coupled antennas is attached over the part of interest in the mechanical structure.

Furthermore, improvements in terms of sensitivity are expected to be experienced when also the single antennas are free to be deformed: such effect will be shown during the conference.

DEFORMATION PARAMETRIZATION

Before going into the details of the electromagnetic response of the grid when a deformation is taking place, a few concepts about the parametrization of the deformation will be given, to help the reader recall the parameters of interest [5].

- *Stress:* if F is the force acting on an elemental surface of area A, the stress is defined as

  $$S = \lim_{A \to 0} \frac{\bar{F}}{A}$$

  Stresses induce a deformation of the structure on which they act: this deformation may change the size or the shape of the structure. In any case, the shift of each point can be described by a displacement vector.
  Displacement can be seen as the presence of strain in the structure.
- *Normal strains* are defined as the incremental change in length divided by the original length. For instance, the normal strain along the x-axis is

  $$\varepsilon_x = \frac{\Delta dx}{dx}$$
- *Linear displacement model:* throughout the work, a linear displacement model will be assumed: this implies a linear relationship between stress and strain, as is the case in the elastic region of the deformations.

PARAMETRIZATION OF THE GRID RESPONSE

The deformation sensing through the RFID-grid is basically an inverse problem relating the measured variation of the AIDs to the unknown change of inter-element spacing.

Actually, the raw data available after each measurement will be a two-dimensional matrix with N x M entries, where N is the number of RFID tags (or microchips) involved, e.g. the sampling points, while M is the number of frequency samples. Hereafter $AID_{n,0}$ will indicate the state of the grid in a reference condition, for instance in absence of deformation. These data have to be processed in order to provide a relationship with the deformation suffered by the structure, in terms of displacement or strain .

For smooth variations of the grid topology, it is expected that the AID_n will mainly change by frequency shift and amplitude scaling and hence two integral indicators are extracted: the frequency shift τ_n of the peak value in the considered interrogation bandwidth and a normalized scale factor γ_n, defined as the difference between the value averaged over the bandwidth of the AID at a given deformation and at reference condition, normalized by the value of the reference condition.

Sensitivity and expected resolution

The achievable resolution in the data retrieval is expected to be mainly related to the sensitivity of the RFID reader, for what concerns the allowed control over the emitted power, and the sampling of the received backscattered signals emerging from the grid.
The sensitivity of the RFID GRID, when considered as a deformation sensor, can be defined as the ratio between the variation in the measured AID_n and the corresponding variation in the strain, e.g. the slope of the AID_n vs strain curve: $S_\varepsilon = \dfrac{\partial AID_n}{\partial \varepsilon}$.
This function depends on the particular deformation mechanism and hence will be calculated for every case.
Similarly, it is useful to introduce sensitivity parameters also for the integral indicators, e.g. $S_\tau = \dfrac{\partial \tau_n}{\partial \varepsilon}$. and $S_\gamma = \dfrac{\partial \gamma_n}{\partial \varepsilon}$.
The resolution $\delta\varepsilon$ is defined as the minimum variation of the strain that the system is able to detect. It is therefore linked to the minimum variation of measured data $\delta AID = \min(AID^{(1)} - AID^{(2)})$ which the system is able to discriminate. It can be expressed as

$$\delta\varepsilon = \delta AID / S_\varepsilon$$

It might be worthwhile to express the resolution in terms of relative resolution, i.e.

$$\delta\varepsilon / \varepsilon_0 = \delta AID / AID_0$$

Which is only dependent on the reader performance.
Just to have a numerical feeling, it is worth mentioning that, low-cost readers having 60dB of receiver's range and 8 bits would theoretically enable a relative resolution of 1%, while more sophisticated readers with 90dB range and 16bits ADC, would achieve a relative resolution of 0.01%.

EXAMPLES OF RFID GRIDS ANALOG IDENTIFIERS FOR CANONICAL DEFORMATIONS

- *Simple canonical antennas (Dipoles):* if we take into consideration a grid of 5 RFID tags, in which the antennas are dipole-like and are disposed side-by-side along direction x, and we perform a uniaxial stress along the same direction x, we obtain the analog identifier values shown in fig. 2. Please remember that in this case the single antennas are supposed to be unshrinkable and therefore only the variation of the mutual coupling will affect the response of the grid .

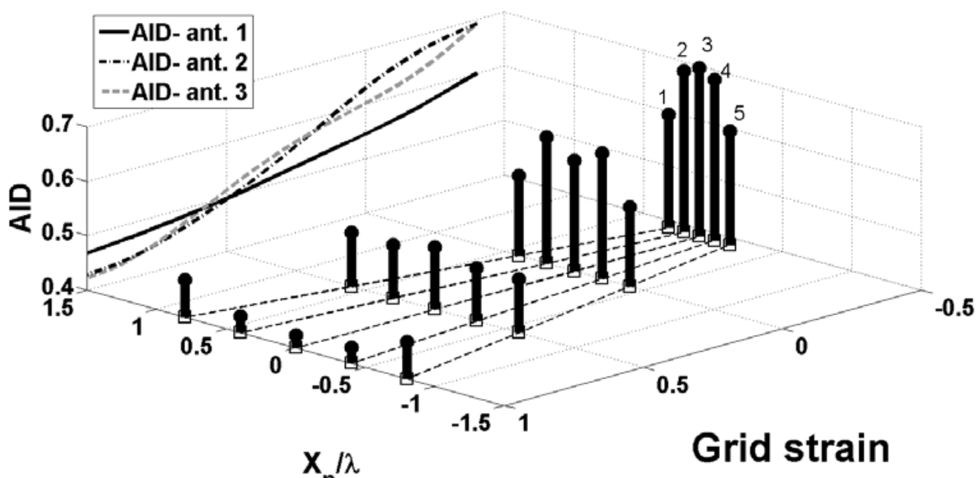

Figure 2. Histogram representation of the grid analog identifier profile at a given frequency versus overall grid strain and position of the sensor over the surface, for a grid of 5 dipoles.

The variation of the AID with strain is clear from the summarizing lines on the left wall of the graph: the behaviour is quasi-linear, exhibiting higher values when the grid is compressed (negative strain) and lower values when it is elongated (positive strain).
The integral metrics, i.e. the frequency shift and the normalized scale factor, are shown in fig. 3 for the central antenna. The sensitivities for τ_n and γ_n are respectively 26MHz/strain and 14%/strain .

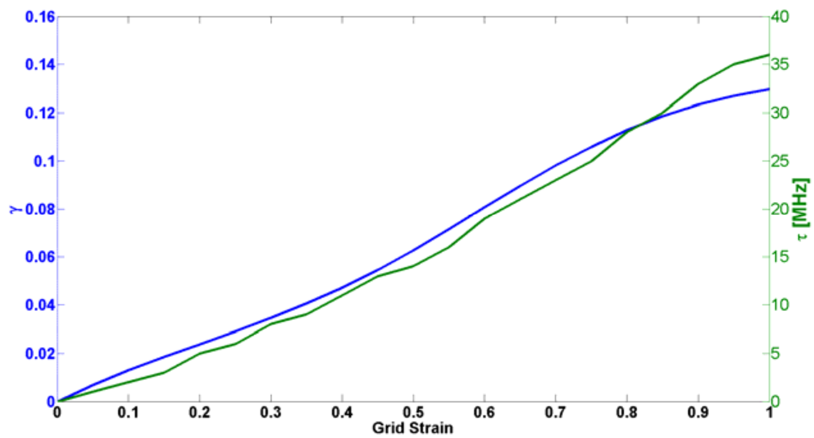

Figure 3. Frequency shift and normalized scale factor versus grid strain, for the central antennas of a grid of 5 dipoles.

CONCLUSIONS

In this contribution, we investigated RFID grids' capabilities, showing how they might be a useful instrument to estimate the overall amount of surface deformation, as well as to provide a local representation of the displacement.

It has been shown that, thanks to the intrinsic sensing characteristics of antennas, mutual coupling variations as well as deformation in the antenna shape can be remotely monitored. These two contributions have different weights and can be optimized, through material selection, antenna and grid design, in order to fulfill the requirements of the final application.

Many different parameters can be extracted from the grid: namely, the power metrics (turn on and backscattered power) as well as the analog identifier and several other indirect parameters, which would add into the quantity of information available.

Tests on real life structures have been done in the case of dipoles under uniaxial strain , with results comparable to the simulation and they will be shown during the conference. Further tests are now being planned for grids on metal:

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