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## Orientation Sensor Based on Harmonic Transponder

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### Abstract

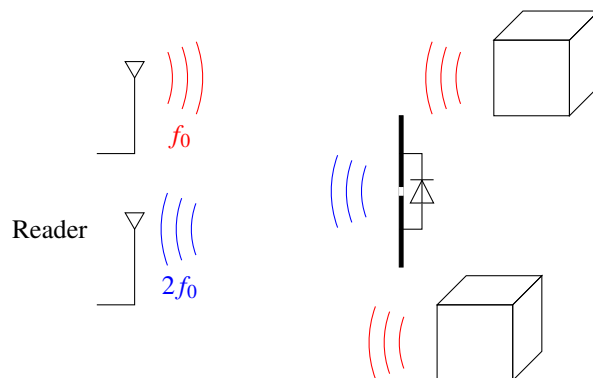
In this paper, we present an harmonic transponder based on a RECCO tag which can be used as a sensor to measure the orientation of the scatterer compared to the incident electric field. The procedure is based on a single reference measurement and can be applied in dynamic environment. Due to the non-linearity present in the transponder, this tag can be read at a distance which is significantly higher than the read range of a linear transponders (such as all chipless tags).

### 1 Introduction

Non-Linear transponders have the ability to generate new frequency components located at multiples of the incident fundamental frequency. This constitutes a fundamental difference compared to classical objects present inside the environment since the latter ones are generally perfectly linear and can only backscatter at the fundamental frequency. This property is classically used to easily detect the presence of the harmonic transponder in complex environments. Fig. 1 presents the basic concept of the harmonic reading system.

Thus an harmonic radar is composed by at least a transmitter at  $f_0$  and a receiver at  $nf_0$ . The non-linear transponder is based on at least one non-linear element. The fundamental objective of the non-linear transponder is to receive the highest power at  $f_0$ , to efficiently convert this power at  $nf_0$  thanks to the non-linear element and to backscatter this power at  $nf_0$  towards the reader. Despite this apparent complexity, a harmonic transponders can be composed by a single Schottky diode connected to a well designed antenna. Moreover, these transponders can be fully passive devices and can operate based only on the incoming energy sent by the reader. Thus harmonic transponders do not require the presence of a battery which significantly improves their usability and eases their maintenance.

Harmonic transponders and radars are not a recent paradigm and have been investigated for decades in the literature. Many applications have been addressed such as the detection of insects [1], improvement of 5G networks [2] and UHF RFID performance [3, 4, 5]. Commercial applications are also available, the RECCO system is based on harmonic transponders to detect victims in harsh environment at distances higher than 80 m in free-space and 20 m through packed snow.

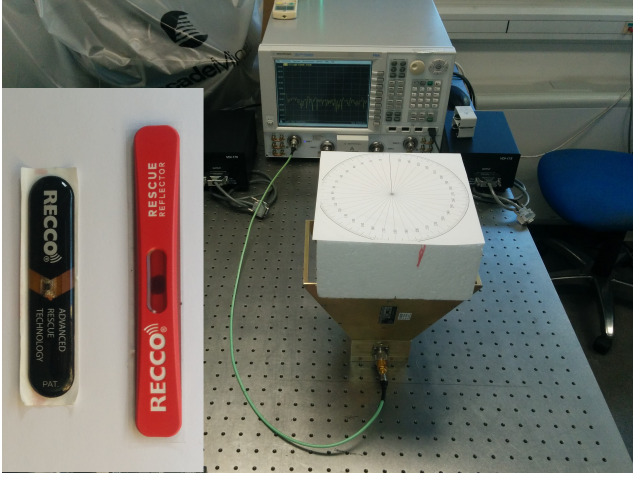


**Figure 1.** Principle of the harmonic reading system.

One of the most beautiful property of harmonic transponders is that they provide a natural robustness to clutter interference. Since all objects present inside the environment are linear systems, their responses to a continuous wave (CW) is only located at  $f_0$ . However, harmonic transponders are different since (a part of) their response is located at  $nf_0$ . Thus, this technique allows to easily separate the transponder response from the response of any object present inside the environment simply by tuning the receiver to  $nf_0$ . As a consequence, harmonic transponders provide a higher read range compared to linear time-invariant transponders used for example in the chipless technology.

One significant drawback of harmonic transponders is that the reflected signal does not contain any useful information. This fact deprives classical harmonic transponders from being identified (*i.e.*, encode an ID) and/or being used as a sensor (*i.e.*, to monitor physical quantities). Only few examples have been investigated such as [6] which combines harmonic backscattering and Doppler modulation to monitor respiration monitoring. Other interesting examples includes humidity sensing [7] and crack detection [8].

In this paper, we show that we can use classical harmonic transponders as a robust sensors. This paper addresses the problem of finding the orientation of the transponders based on the amplitude of its backscattered signal. The proposed technique is applied on two harmonic transponders (RECCO reflectors) and allows one to estimate the orientation of the harmonic transponders.



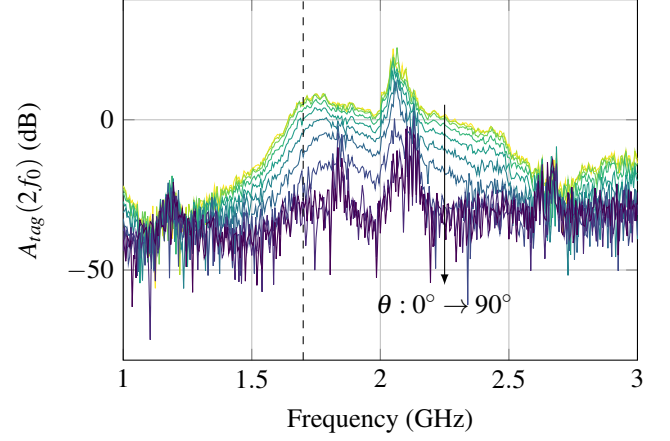
**Figure 2.** Measurement bench used in the study. Inset: Harmonic transponders (RECCO reflectors).

## 2 Results

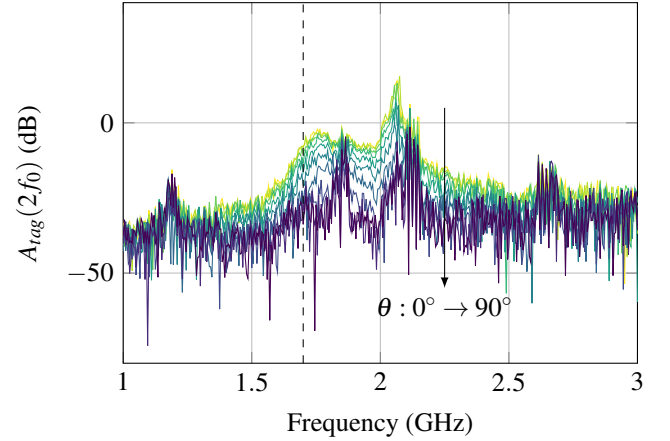
As in [5], the measurement bench is based on a Vector Network Analyzer (VNA) with frequency offset option. This method allows to uncouple the local oscillator used in the transmitter from the one used in the receiver. For measuring the response of an harmonic tag, the receiver frequency is set to 2 times the frequency used by the source. Note that, in this case, the resulting plot does not correspond anymore to a  $S$ -parameter but to the signal directly seen by the receiver (without normalization by the reference).

For the study, we consider two harmonic transponders based on RECCO reflectors. These transponders are also available on Ebay or Amazon for few dollars and can be directly integrated into clothes. Note that these transponders are classical harmonic transponders and have not been optimized to be used as sensors. Measurement bench used to characterize the transponders is presented in Fig. 2 and is composed of a PNA 5222A connected to a linearly polarized UWB antenna A.H. Systems, inc. SAS-571. Harmonic transponders are presented in the inset of Fig. 2 and are placed (one at a time) at a distance of 20 cm from the antenna. Transmitted power has been set to 0 dBm and the sweep for the fundamental frequency is between 500 MHz and 1.5 GHz. Thus the corresponding frequency of the receiver starts at 1 GHz and ends at 3 GHz. Tags are measured by placing each transponders on the foam at different angles from 0 to 360 degrees by steps of 10 degrees. Note that all the tags are measured in real environment.

Note that if the system (instrument and environment) is purely linear, the power at  $nf_0$  should strictly equal to 0. However, due to the instrument imperfections, a significant power at  $nf_0$  is present on the receiver when the transmitter operates at  $f_0$  due non-linearities present in both emission and reception. Fortunately, this power (which depends on  $f_0$ ) can be easily characterized and compensated. Thus in order to isolate the tag response, a first measurement is



**Figure 3.** Received power at the second harmonic for the red tag with  $\theta = [0; 90]$  degrees.



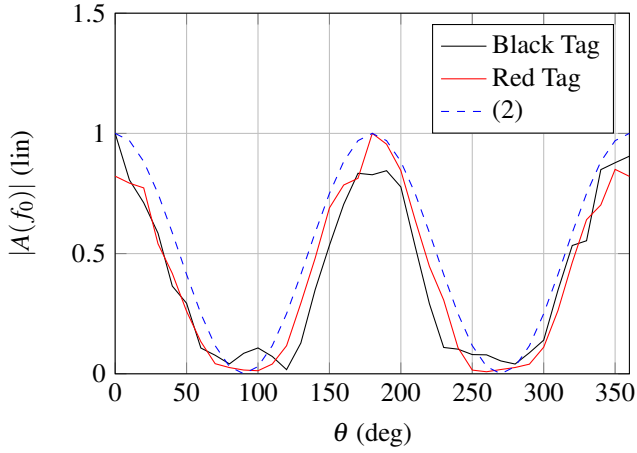
**Figure 4.** Received power at the second harmonic for the black tag with  $\theta = [0; 90]$  degrees.

done without the harmonic tag. The response of the tag is obtained with the simple formula:

$$A_{tag}(2f_0) = A_{raw+tag}(2f_0) - A_{raw}(2f_0) \quad (1)$$

Even if (1) looks like to the empty environment procedure used in chipless [9], note that  $A_{raw}(2f_0)$  does actually not depend on the environment (which is linear and only reflects power at  $f_0$ ) but only on the instrument imperfections. Thus, environment can be changed without affecting  $A_{raw}(nf_0)$  which provides a natural robustness to the approach compared to the classical methods used in chipless even in dynamic environments.

Signals backscattered by the harmonic tags at the second harmonic for different orientation are presented in Fig. 3 and 4 for the red and black tag respectively. First, note that the detection of the harmonic transponders can easily be done by remarking that the received power is higher when a transponder is placed in front of the antenna compared to the case where no transponder is present. Second, the amplitude of the backscattered signal at  $2f_0$  is a function of the tag orientation. This property will be used to transform



**Figure 5.** Normalized harmonic backscattered power at 1.7 GHz as a function of the orientation.

simple harmonic transponders into an orientation sensors.

In the following, since the efficiency of each scatterer depends on the frequency, we select a single frequency of 1.7 GHz for both scatterers. Note that similar results can be obtained for other frequencies (with a scaling of the backscattered signal). At this specific frequency, the magnitude of the backscattered signal has been plotted as a function of the orientation for  $\theta = [0; 360]$  by step of 10 degrees. Results are presented in Fig. 5 for both transponders. We can see that the backscattered power at the second harmonic is maximum when the orientation of the tag is parallel to the incident E-field and that this backscattered power is equal to 0 when the tag is perpendicular to the E-field. Experimental results can be fitted with the expression:

$$A_{ref}(\theta) = A_0 \cos^2 \theta \quad (2)$$

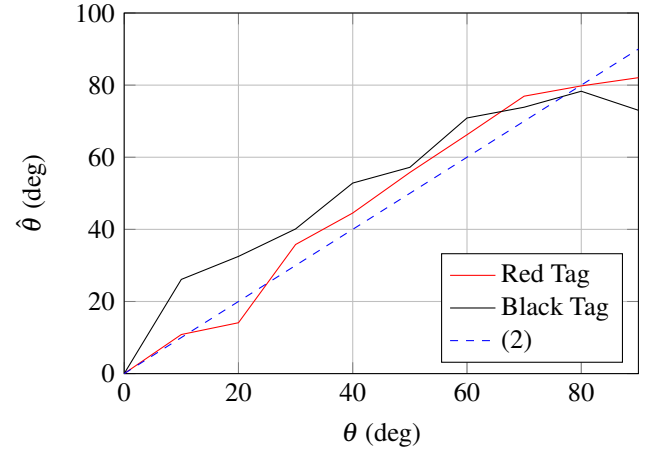
which is also plotted on the same figure. Note that measurements and empirical model are in good agreements for both transponders. Note that this agreement can not be valid for all harmonic scatterers.

Model presented in (2) can then be used to easily estimate the orientation of the harmonic scatterer as:

$$\hat{\theta} = \arccos \left( \sqrt{\frac{A_m}{A_0}} \right) \quad (3)$$

Note that this estimation requires one reference measurement  $A_0$  where the orientation of the scatterer is known at a given distance.  $A_m$  corresponds to the measurement at the same distance in the unknown orientation. Note that a single reference measurement can be used for multiple orientation estimations (as long as the distance is kept constant).

Fig. 6 presents the estimation of the orientation  $\hat{\theta}$  as a function of the true orientation of the sensor. Due to the symmetry of the structure  $\theta$  should belong in the interval  $[0; 90]$  to avoid ambiguity during the determination of  $\hat{\theta}$ .



**Figure 6.** Response of the orientation sensor.

Fig. 6 shows that the accuracy of the sensor on the range  $[0; 90]$  is in average equals to 4.4 and 9.2 degrees for the red and black tag respectively. The maximum error over the same domain is equal to 7.9 and 17 degrees for the red and black tag respectively. Moreover, the sensors present a good linearity over the entire interval. Finally, note that these sensors can be used in dynamic environments since  $A_0$  and  $A_m$  are not affected by the modification of the linear environment.

### 3 Conclusion

In this paper, two harmonic transponder based on RECCO reflector are used to determine the orientation of the tag. The proposed method require a single reference measurement at a known distance and offer a good robustness in complex environment due to the properties of the backscattered signal. The sensor provide an accuracy of 10 degree over a range of 90 degrees. Finally, the read range achieved by these transponders can outperform similar chipless sensors.

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