Bridge monitoring using geophones: test and comparison with interferometric radar

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Abstract. More than 30% of European highway bridges present structural criticalities. Their continuous health monitoring is a priority. Conventional sensors are accurate and reliable, but they are often too expensive for continuous monitoring. Possible low-cost alternative equipment are the geophones, that are able to detect the displacement of structures by integrating in time their response. They can be easily installed and can provide continuous health monitoring by transmitting the data to a remote server.

The aim of this paper is to assess the capability of a geophone sensor to provide continuous, accurate and reliable data about the dynamic loads of a bridge. In order to validate its performance, it has been experimentally compared with an interferometric radar. As preliminary test the geophone has been fixed to a horizontal steel plate. The radar has been positioned under the steel plate in order to detect the same displacement component. The steel plate has been excited with controlled pulses. Finally a network of geophone sensors, provided with its control and transmission electronics, has been installed on a well-known bridge in Florence, Italy (the “Amerigo Vespucci” bridge). The interferometric radar has been installed under the deck close to an abutment. The obtained results both in controlled environment and in the in-field test are in good agreement, although the geophone appears less sensible to impulsive stimulus than the radar.

Keywords: Geophone sensor, Vespucci bridge, interferometric radar, bridge monitoring.

1 Introduction

The recent Morandi bridge disaster (Genova, Italy) increased attention on large structures health problems. Indeed about 30% of European highway bridges present structural criticalities [1]. Moreover the age of many bridges is more than 60 years, as an America study of 2013 highlights [2]. In this context continuous monitoring of dynamic properties of bridges is a priority and a challenge for civil and electronic engineers.

The conventional sensors (radar, total station, accelerometer) are accurate and reliable, but often they are too expensive for continuous monitoring. Furthermore a sensor network can be more appropriate to monitor the whole structure [3-6].

The aim of this paper is to assess the capability of a geophone sensor to provide continuous, accurate and reliable data about the dynamic loads of a bridge. This device is able to detect the displacement of structures by integrating in time their response and it can operate in a network by sending the measurement results of different devices to a remote server.

In detail a particular device made with an analog compensated geophone has been created by the joint venture between Move Srl and Studio Micheloni Srl.

The performance of the geophone sensor has been experimentally compared with an interferometric radar [7-10] in a controlled environment and during a test on Vespucci bridge, Florence, Italy.

2 The geophone sensor

A block scheme of the geophone sensor is shown in Fig. 1. The geophone is able to measure the speed-changing of a structure in the gravity direction. Its response is integrated to obtain the displacement using an analog integrator. The displacement is digitized by a 10 bit A/D converter. The control unit provides a 100 Hz clock to A/D converter and it manages the buffer and the communication with the server. The device is able to send data to a remote server via LoRaWAN network or via USB cable. A battery unit provides the power supply for each device and it ensures an operating time of one/two weeks. The battery unit can be recharged by a solar panel for operating indefinitely.

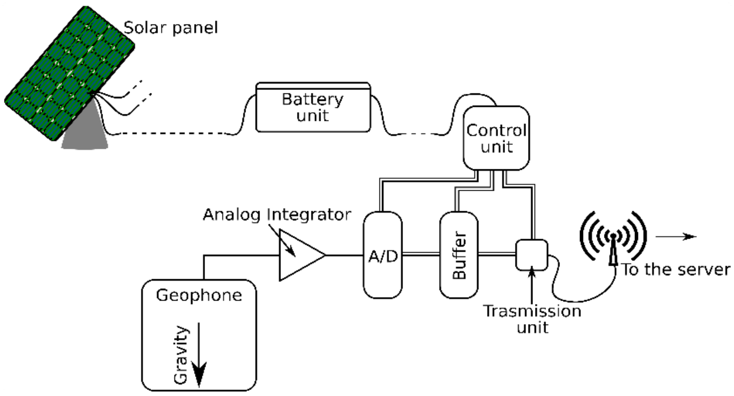

Fig. 1. Block scheme of geophone sensor

The geophone sensor is able to detect displacement in the band $1\ Hz - 20\ Hz$. The device can work in debug-mode or threshold-mode. In the debug-mode, the device is able to provide a continuous measurement and it sends all recorded data via USB. The debug-mode can be used for laboratory test or in a controlled environment. The threshold-mode is used for in-field operations. In this case the control unit checks the last value of the measurement and if it is larger than a fixed threshold, it sends a packet with $40\ s$ data ($20\ s$ before and $20\ s$ after threshold) to a remote server. The threshold can be adjusted for different applications.

The server is able to manage thousands devices installed also in different structures and the final user can access to the main data of the structure of interest.

The performance of geophone sensor has been compared with an interferometric radar. A radar is a remote sensor able to detect targets in its field of view by sending an receiving an electromagnetic wave. The interferometric radar is able to measure small displacements by measuring the differences of phase between the sending and receiving electromagnetic wave. The radar operated a Continuous Wave – Step Frequency signal in K_u band and it allows to detect the natural frequencies in the band from DC to more than $100\ Hz$, by applying the Fourier transform to the displacement. In Table 1 is reported a brief comparison between the performance of both sensors.

Table 1. Comparison between performance of geophone and interferometric radar.

	Geophone sensor	**Interferometric radar**
$f_{Acquisiton}$	$100\ Hz$	$(25-300)\ Hz$
f_{min}	$1\ Hz$	DC
f_{max}	$20\ Hz$	$>100\ Hz$
Acquisition time	$40\ s$	$>1\ hour$

3 The Amerigo Vespucci bridge, Florence, Italy

The Vespucci bridge was built in 1957 after WWII. The bridge replaces an older bridge destroyed by German mines and its design win a national contest for its originality and innovation. During 2017 some strong deteriorations were found on the structure, with particular reference to erosion under one pier (Fig. 2). For this reason, in 2018 the Municipality of Florene commissioned an extensive monitoring campaign and possible restoration works.

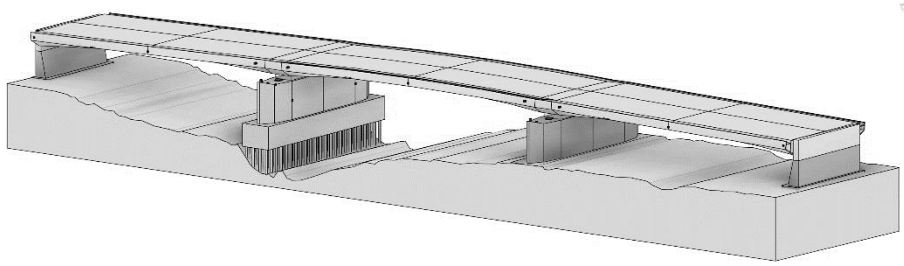

Fig. 2. Design of Vespucci bridge with erosion under left pier

The bridge was built with prestressed reinforced concrete and it is composed by three spans over two piers that are holding a four carriage roadway. Each span is a flat arch designed to do not interfere with the skyline of the old town.

In order to reinforce the arches a counterweight system was inserted the structures. As Fig. 3 shows a comb of cables was included in each arch and it is plugged inside the piers. This comb stiffs the structure during the static load and changes the dynamic properties of the bridge.

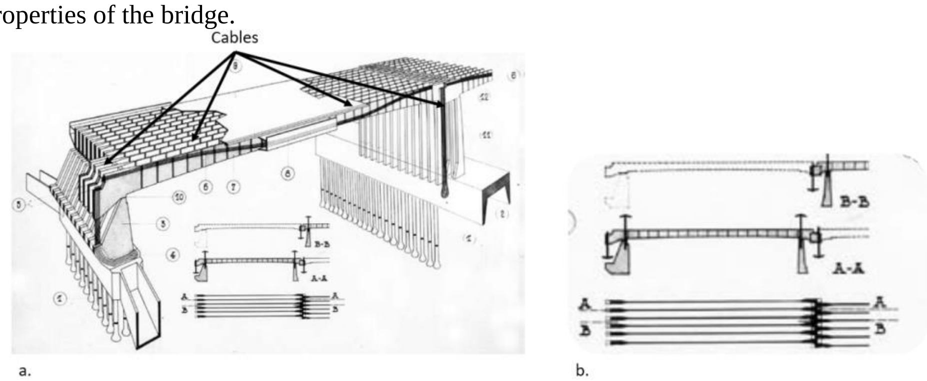

Fig. 3. Design of counterweight system of Vespucci bridge (a.). Detail of comb of cables (b.) [11].

Given this particular and original configuration of the bridge structure, it is very important to adopt an accurate monitoring system, which can correctly capture the dynamic behavior of the bridge.

4 Experimental results

The geophone sensor and the interferometric radar were preliminary compared in a controlled environment and finally during a dynamic test of Vespucci bridge, Florence, Italy.

4.1 Test in controlled environment

As preliminary test a geophone sensor in debug-mode has been fixed on a steel plate (Fig. 4). The steel plate was 2 m long, 0.5 m large and 2.5 mm height. It was cantilevered at 3 m height over a wall. The interferometric radar was positioned under the steel plate in order to detect the same displacement component of the geophone. The steel plate vibrated exited by short pulse stimulus.

Fig. 4. Experimental setup of controlled environment

Fig. 5 reports the comparison between the displacements measured by both sensors. Radar appears to be more sensitive to the impulsive stimulus than geophone, indeed the two displacements become more similar after 1 *s* by the stimulus.

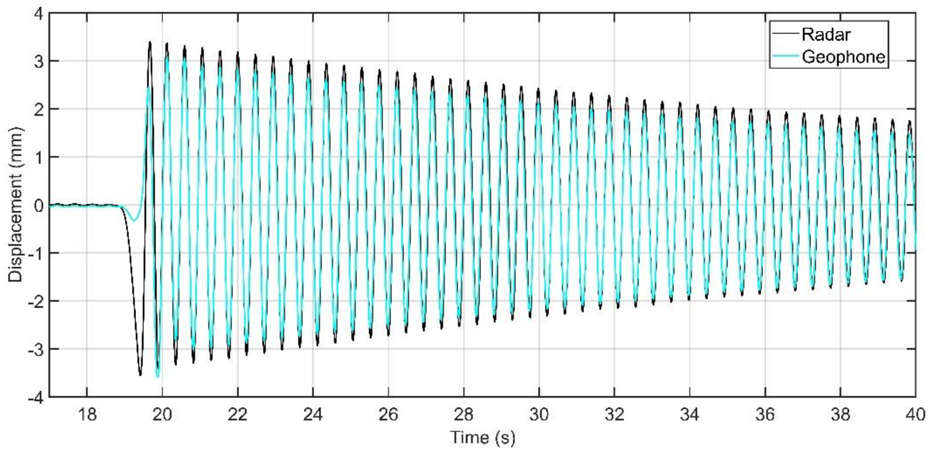

Fig. 5. Comparison between displacements measured by interferometric radar (Black) and by geophone system (Cyan).

The natural frequency of steel plate was measured with both sensors by calculating the Fourier Transform of the displacement. The comparison between the spectra is showed in Fig. 6. The frequency measured was $(2.131 \pm 0.007)\ Hz$ for both sensors.

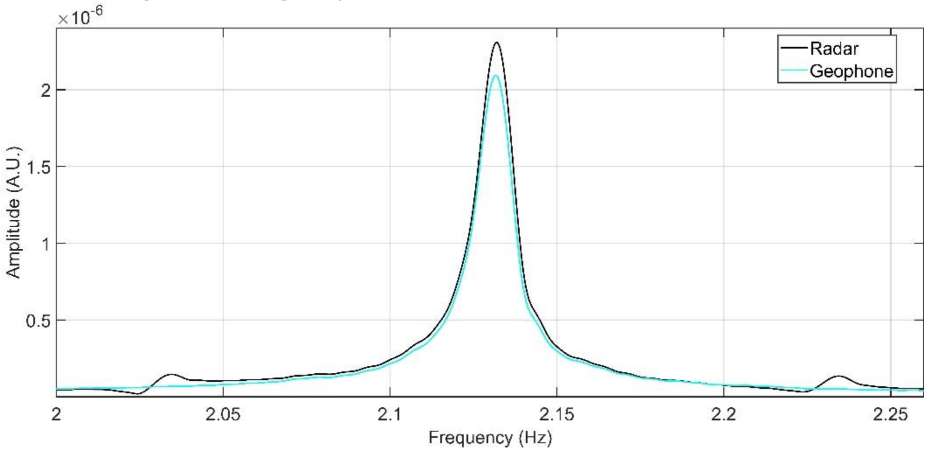

Fig. 6. Comparison between frequencies measured with interferometric radar (Black) and geophone system (Cyan).

4.2 In-field test: Vespucci bridge, Florence, Italy

A network of six geophones, operating in threshold-mode, was installed under the spans of Vespucci bridge in order to provide continuous monitoring during the renovations works. When the works will be finished, the sensors will allow to monitoring the bridge under the road live load. One single geophone has been used for the comparison with the radar.

With reference to Fig. 7 the geophone was located under the south span on the right side of carriageway. A standard target (corner reflector) for the interferometric radar was fixed close to the geophone. The radar was installed on a concrete platform $3.15\ m$ under the bridge. A $10000\ kg$ truck was exploited as stimulus to test the bridge. The truck went up on a $0.2\ m$ step. When the track dropped from the step, the bridge was excited by an impulsive stimulus.

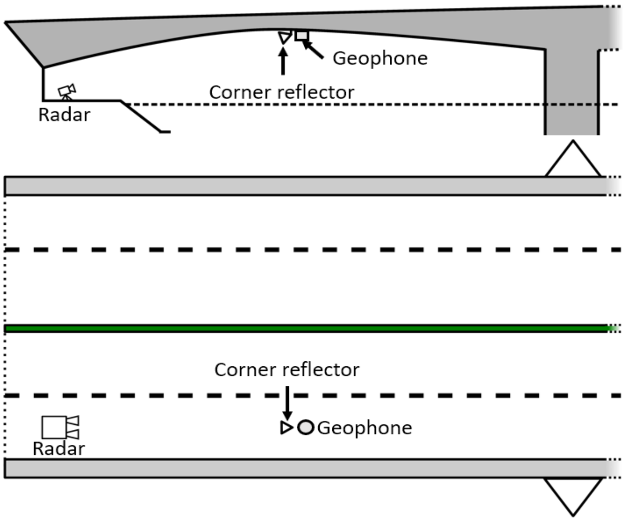

Fig. 7. Measurement setup during the dynamic test of Vespucci bridge.

The displacement measured by the radar is shown in Fig. 8. This displacement has been projected on vertical axis to be comparable with the geophone measurement. The comparison between geophone and radar is shown in Fig. 9. As Fig. 8 and Fig. 9 show, the radar has been able to detect the slow movement of the bridge. This slow movement can be the result of the counterweight system of Vespucci bridge.

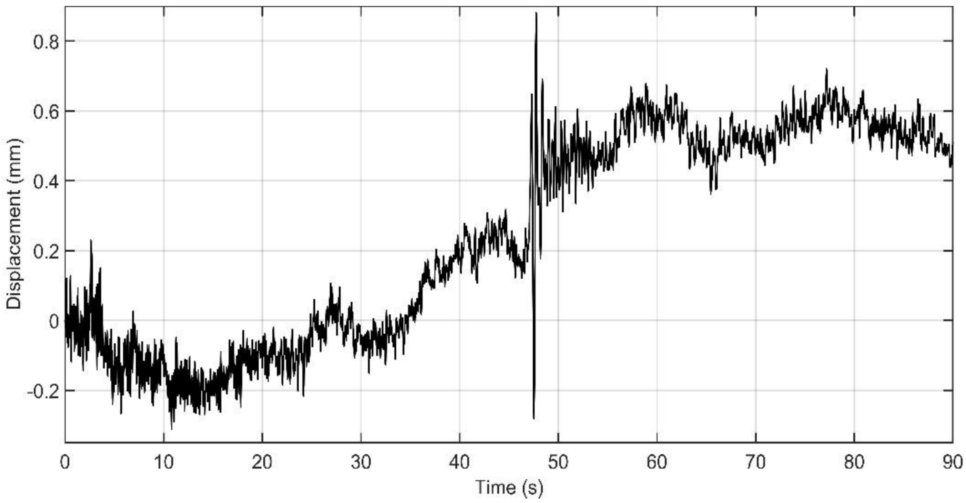

Fig. 8. Displacement measured by interferometric radar.

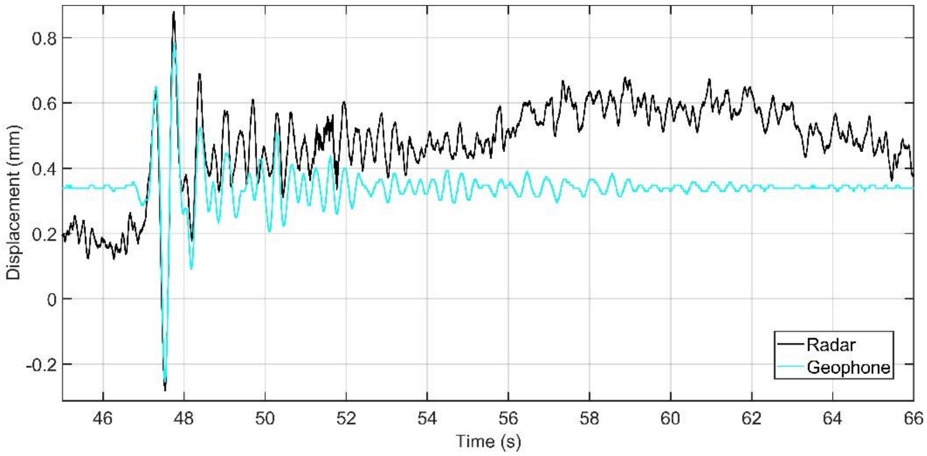

Fig. 9. Comparison between displacements measured by the interferometric radar (Black) and the geophone system (Cyan) zoomed on the stimulus by using their own bandwidths.

It is important to note that this comparison was performed by using their own bandwidths of both sensors. Comparison by using the same band can be more appropriate. Therefore a high-pass filter ($f_{LOW} = 0.5\ Hz$) was applied to both the measurements (Fig. 10). The two plots appear to be in good agreement.

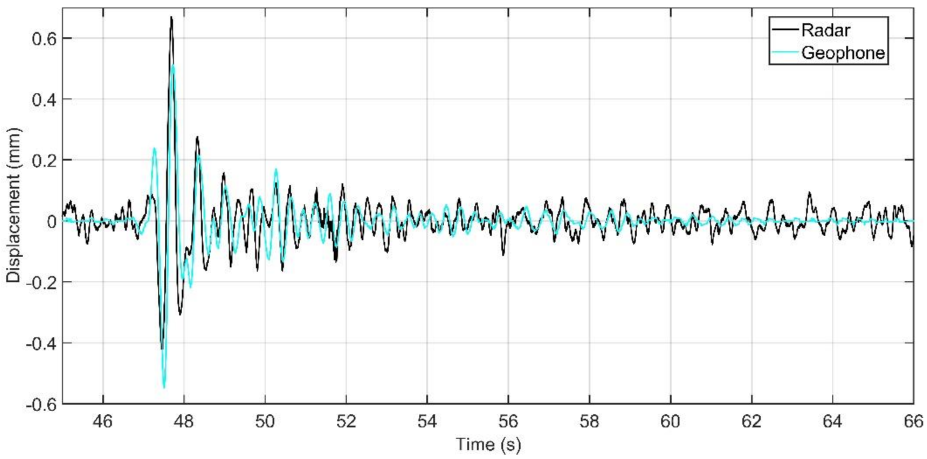

Fig. 10. Comparison between displacements in a common bandwidth of interferometric radar (Black) and geophone system (Cyan).

The spectra of the two sensors are shown in Fig. 11. The frequencies detected by radar have been $f_1 = (2.37\ \pm 0.05)\ Hz$, $f_2 = (3.12\ \pm 0.05)\ Hz$. The frequencies detected by geophone have been $f_1 = (2.40\ \pm 0.05)\ Hz$, $f_2 = (3.11\ \pm 0.05)\ Hz$ and $f_3 = (2.78\ \pm 0.05)\ Hz$. The frequencies f_1 and f_2 are in good agreement, while f_3 is not detected by interferometric radar.

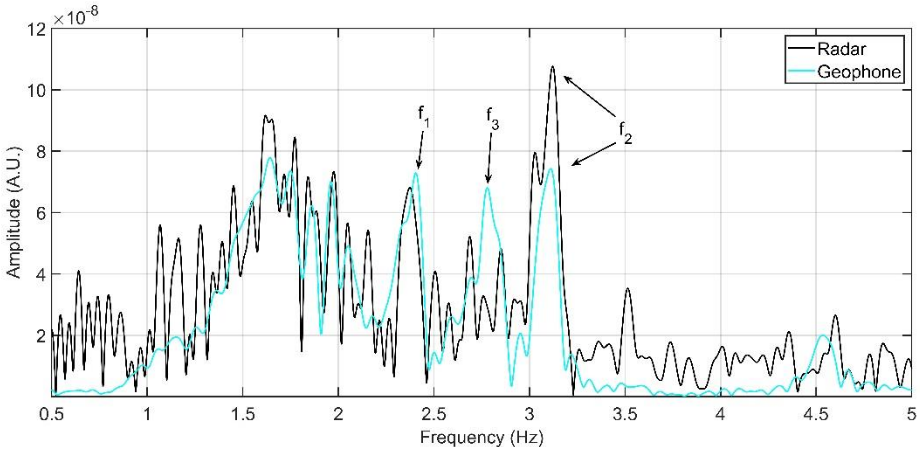

Fig. 11. Natural frequencies of Vespucci bridge measured with radar (Black) and geophone (Cyan)

5 Conclusions

A geophone sensor has been tested and its performance has been experimental compared with an interferometric radar. The test were performed both in a controlled environment and during the dynamic test of the Vespucci bridge, Florence, Italy. The displacements measured are in good agreement for the two sensors both in controlled environment and during an in-field test, as well as the natural frequencies.

The geophone appears to be less sensitive to the impulsive stimulus. However it can be used in most cases and it can provide continuous, and accurate monitoring of large structures.

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