STRUCTURAL CONTROL AND HEALTH MONITORING
Struct. Control Health Monit. 2008; **15**:283–298
Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/stc.252

Experimental utilization of interferometric radar techniques for structural monitoring

G. Bartoli[1], L. Facchini[1,*,†], M. Pieraccini[2], M. Fratini[2] and C. Atzeni[2]

[1] *Department of Civil Engineering, University of Florence, 3, V. S. Marta, 50139 Florence, Italy*
[2] *Department of Electronics and Telecommunications, University of Florence, 3, V. S. Marta, 50139 Florence, Italy*

SUMMARY

This paper presents a new surveying technique that can be employed with hardly reachable structures or extensive structures. The technique is based on an interferometric radar device, which can be positioned up to 2 km away from the structure to be examined and can record displacement measurements with a sampling frequency of up to 100 Hz and an accuracy of 0.1 mm. The results given by the radar are compared with those given by a set of three accelerometers on a test structure (namely, a steel cable-stayed footbridge) for three different loads: a symmetric dynamic load, an eccentric dynamic load and a symmetric quasi-static load. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: radar; remote sensing; interferometry; dynamic monitoring; accelerometer; structural testing

1. INTRODUCTION

Dynamic testing of structures is usually carried out by means of a large number of sensors installed on the structure itself. Recordings generally consist of accelerations measured at discrete points of the examined structure with a given sampling rate, usually in the range of at least 100 Hz.

Such an arrangement implies that, in order to monitor the motion of even a small amount of structural points, considerable networking (e.g. cables, equipment, sensors) is necessary. Moreover, the global motion of the structure cannot be recorded, but has to be evaluated by the introduction of suitable hypotheses and modeling.

So far, for large amounts of sensors, cables could be substituted by radio data transmission from sensors to the central acquisition system, but such an arrangement cannot generally enable high sampling rates and is limited by the possibility of radio communication: for example, if the

*Correspondence to: L. Facchini, Department of Civil Engineering, University of Florence, 3, V. S. Marta, 50139 Florence, Italy.
† E-mail: luca.facchini@unifi.it, luca@dicea.unifi.it

Contract/grant sponsor: MIUR, Italian Ministry for Education, University and Research

Received 29 January 2007
Revised 22 November 2007
Accepted 4 December 2007

Figure 1. A view of the tested cable-stayed pedestrian bridge.

sensors and the acquisition system are located on opposite sides of a thick concrete wall, then the communication may be poor or even impossible.

As an alternative to such conventional techniques, interferometric radar has been recently proposed as measurement instrument for testing and monitoring large structures, such as bridges, towers, buildings and dams. Some of the authors recently proposed a non-contact microwave sensor able to provide displacement measurements with sub-millimeter accuracy and sampling rate high enough to track the transient movements of an entire architectural structure. The sensor, an interferometric continuous wave step frequency (CWSF) radar, has been tested on bridges [1] and towers [2].

The interferometric radar employed in this experimentation is a step frequency continuous wave device, which provides complex range images of the illuminated scenario up to 2 km range. The image rate can be set up to 100 Hz, i.e. this instrument is able to sample the entire scenario in the view cone providing up to 100 images per second. Displacements between subsequent images can be measured with a better accuracy than 25×10^{-6} m.

The instrument is able to distinguish parts of the structure only if they are separated in range; therefore, scatters that are not rigidly moving at the same distance from the sensor can give signals whose rotation angle is not directly related to the displacement. This can result in a measurement error that has to be evaluated in operating conditions.

In this paper the authors report a direct comparison between the two measurement techniques (radar and network of accelerometers) employed during a field test on a steel cable-stayed pedestrian bridge, shown in Figure 1. As the two instruments measure different quantities (displacement and acceleration) a preliminary discussion about signals and noise is necessary. Finally, the experimental results are critically discussed.

2. DESCRIPTION OF THE INTERFEROMETRIC RADAR

The radar prototype that has been developed is shown in Figure 2. It consists of an extremely compact device weighing about 12 kg, which operates in *Ku* band. The system is made of the sensor, a portable PC and a battery pack.

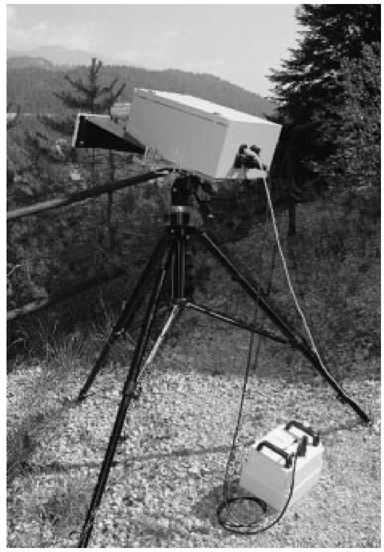

Figure 2. The interferometric radar.

Its compactness makes it easy to carry on any kind of terrain, and the installation of the sensor is analogous to that of a common camera on a tripod near the structure to be tested. The PC is dedicated to the control and storage of the acquired data by means of proper software, which also performs a first data analysis.

The sensor and the PC are connected by means of a USB 2.0 interface. The battery pack provides power for about 5–6 h.

The behavior of the radar depends heavily on the kind of desired measurement as well as on the operating conditions (namely, material and shape of the examined structure, surrounding scenario, etc.). Nevertheless, the performance of the radar may be summarized as follows:

- longest operating distance: 2 km;
- best image resolution: 40 cm;
- highest sampling frequency: 100 Hz (but depends on the furthest object to be measured);
- deflection measurement accuracy: better than 0.1 mm.

From the technical point of view, the device is a CWSF radar operating in the *Ku* frequency band. Its main characteristics are as follows:

- central frequency: 16.8 GHz;
- maximum bandwidth: 380 MHz;
- number of pulses (steps) in the band: 1–32 767;
- pulse duration: 10–218 μs;
- emitted RF power: ~4 dB m;
- sampling rate for the measurement: 1/(number of steps × pulse duration);
- power supply: 24 V;
- power: 25 W;
- maximum operative range: 2 km.

DOI: 10.1002/stc

More technical details can be found in literature [1–4]. The basic idea to employ a radar for the measurement of structural displacements and strains is to carry out several coherent and consecutive measurements of the examined structure. This can be done by positioning the device in such a way that the structure is completely contained in its visual cone. Each radar measurement can be considered as a distance map of the radar echoes intensity coming from the scenario. Each single discontinuity of the structural surface can potentially represent a source of reflection or diffusion of the electromagnetic waves coming from the radar itself and is therefore able to generate an echo, provided that its dimensions are comparable, or greater, than the wavelength of the device (in this case, roughly 16 mm).

Each single resolution cell containing an echo of sufficient intensity (in other words, distinguishable from the instrumental noise) will be taken into account and will become a virtual displacement sensor.

A structure with a rough surface will therefore be more easily surveyed than a perfectly smooth one. A regularly discontinuous structure will be spatially sampled with a rate given by the distance resolution δr. The displacements will be evaluated from the phase angle of the signals; owing to the 2π periodicity of the phase, an indetermination is introduced in the measurements. This means that only differential measurements can be carried out and not absolute ones. It is therefore necessary to precisely define the geometry of the structure before the experiment starts.

2.1. Measurement geometry

A fundamental parameter of the device is the distance resolution: in other words, two distinct objects whose relative distance is less than the distance resolution appear as one to the device. Moreover, only the radial displacement component (that is, parallel to the ideal line which goes from the radar to the examined object) can be measured.

Therefore, it is a good rule to position the radar in such a way that different points appear at different distances. Moreover, it seems proper that the points of the structure not be positioned at the same distance from the device, and in the case of undesired objects lying in the visual cone, that their distance from the radar be different from the structural points to be surveyed. The visual cone must therefore be oblique with respect to the structure, and in the case of a bridge a possible arrangement is shown in Figure 3.

The position of the radar is often heavily influenced by the surrounding terrain: in the case study that will be shown in the following paragraphs, the height h (see Figure 3) varies from about 2.8 to 3.2 m, since the examined bridge is slightly arched. The view angle γ (namely the

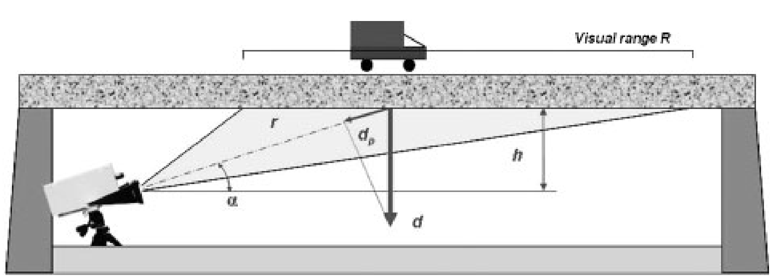

Figure 3. A possible arrangement in the case of the survey of a bridge vertical deflection.

DOI: 10.1002/stc

angle of the cone where the radar signal lies) is currently about 13°. The optimization of the view range R is carried out by adjusting the vertical inclination α of the radar.

In the case of a bridge with a smooth horizontal inferior surface (see Figure 3), we obtain that

$$R = \frac{h}{\tan(\alpha - \gamma/2)} - \frac{h}{\tan(\alpha + \gamma/2)} \tag{1}$$

It is to be noted that such a position of the radar under the bridge implies that, even in the case of uniformly distributed discontinuities, such discontinuities will appear to the radar as denser in the furthest region of the visual cone and sparser in the nearest ones.

2.2. Measurement of actual displacements

The radar is able to determine only the radial component of the displacement of the structural points (that is, the component d_p shown in Figure 3). In order to evaluate the correct value of the vertical displacement, a correction factor has to be introduced as follows (see Figure 3):

$$\begin{array}{l} d_p = d \sin\alpha \\ \sin\alpha = h/r \end{array} \Rightarrow d = \frac{r}{h} d_p \tag{2}$$

This means that, for a given deflection d of a point of the bridge, the measurement d_p given by the radar will be smaller for increasing values of the distance r until the measurement will be confused with the noise of the device.

To summarize, two effects must be taken into account when positioning the radar: on the one hand, if the height h is pronounced, the measurements will be more accurate, but the distribution of the discontinuities will be sparse. Lowering h implies a denser distribution of discontinuities, but the accuracy of the measurements will be reduced as well.

2.3. Primary information provided by the radar

- Range profile plot: this plot describes the intensity of the received echoes as a function of the distance from the radar. Since it reports the intensity of the received signal, the plot is affected by the attenuation due to the wave propagation in the space and the reflectivity of the structure.
- Movie of the structural deflection, velocity and acceleration in time: the deflection plot is obtained as the phase difference, represented in millimeter scale, of each radar measurement with respect to the first one of the series, as a function of horizontal distance and time. The structural deflection can be fully evaluated only if the initial configuration is known. The velocity plot is obtained from the previous one. In this case it is not necessary to determine the initial configuration of the structure. The acceleration plot is obtained in turn from the previous one.
- Time history and spectral analysis of the deflection of selected points on the structural surface: such plots show the time history of the deflection (or velocity or acceleration) of selected points on the surface of the structure. The time history can be Fourier transformed in order to obtain its spectral density function.

DOI: 10.1002/stc

3. DESCRIPTION OF THE CASE STUDY

In order to assess the performance of the radar device, some load tests were carried out on a cable-stayed pedestrian bridge in the center of Tuscany, Italy, shown in Figures 1 and 4. The bridge seemed a good case of testing structure for the device, as the bridge deck is made of steel beams supporting a mixed steel–concrete deck. Such beams are discontinuities of the inferior surface of the deck and represent very good sources for echoes to be generated, as the range profile plot represented in Figure 5 shows.

Figure 6 shows a view of the inferior surface of the bridge deck. It is evident that the best sources of echoes are the crossbeams, which generate the peaks of the range profile shown in Figure 5.

The bridge has been instrumented by means of the radar coupled to three accelerometers in the positions shown in Figure 4. The accelerometers were glued to the upper surface of the longitudinal beams supporting the deck; such an arrangement enabled one to evaluate the vertical deflections of two different sections along the bridge span and the torsional motion of one of them.

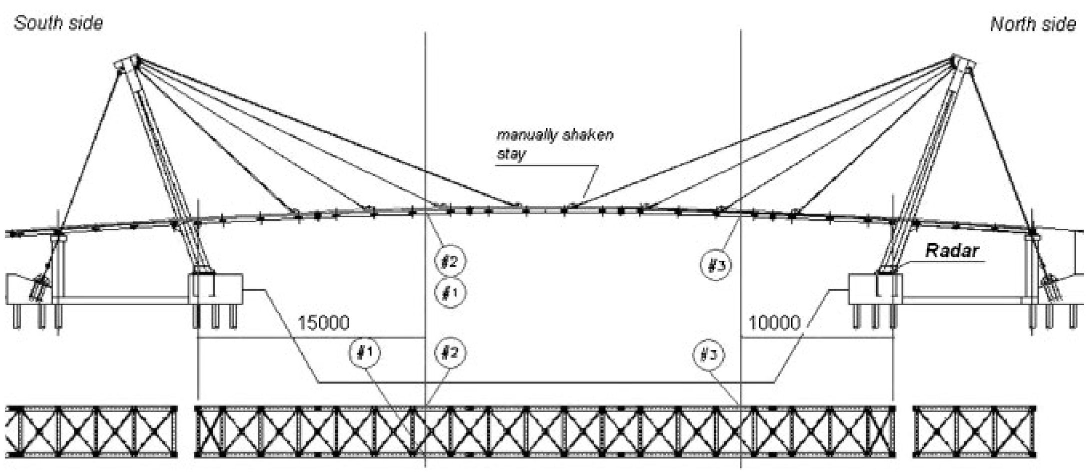

Figure 4. Elevation and plan view of the bridge; the numbers indicate the positions of the three accelerometers. The position of the radar is also indicated. Measures are in millimeters.

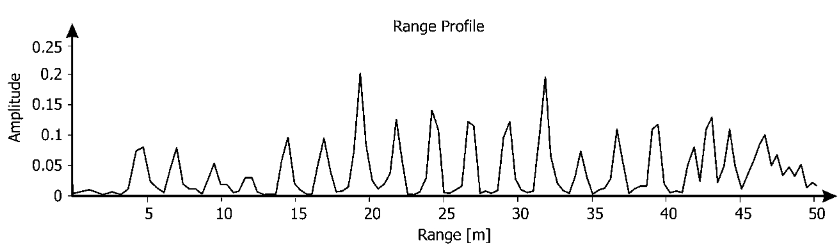

Figure 5. Range profile of the inferior surface of the bridge deck.

DOI: 10.1002/stc

Figure 6. The view of the bridge inferior surface from a position similar to that of the radar device.

Figure 7. An accelerometer installed on the bridge deck, together with a corner reflector.

Three corner reflectors were installed on the deck together with the accelerometers as shown in Figure 7 in order to generate a supplementary radar echo exactly in correspondence to the positions of the accelerometers, thus simplifying the comparison procedure.

4. DESCRIPTION OF THE TESTS

Eleven tests with different loads were carried out on the bridge. The first six tests were carried out with the radar positioned perfectly in the middle of the two pillars on the north side of the bridge. Unfortunately, no echo from the corner reflectors could be received by the radar in such

DOI: 10.1002/stc

position, so that another set of five tests was carried out with the radar positioned on the east side of the bridge, in order for the echoes generated by the corner reflectors to be received by the radar itself.

More precisely, the tests were:

- Walk and run of an adult along the center line of the bridge deck; in this case, no torsional motion of the deck was excited.
- Manual shaking of four different stays: vertical deflections as well as torsional motions of the bridge deck were excited.
- Slow motion of a compact type car along the bridge deck: no torsional motion of the deck was excited.

The sampling rate of the accelerometers was as high as 1 kHz, so that spectral densities up to 500 Hz could be evaluated; on the other hand, the radar sampling rate was as high as 75 Hz, so that a Nyquist frequency of 37.5 Hz was obtained. Each test lasted for 160 s.

As a matter of fact, the accelerometers and the radar provide two different kinds of measurements: accelerations and relative displacements of the examined structure.

The displacement measurements provided by the radar are affected by an indeterminate offset, while, if the accelerations provided by the accelerometers are integrated twice, the result will be affected by an indeterminate linear trend, as the initial values of displacements and velocities are unknown.

Consequently, from a theoretical point of view, the best strategy to compare the results of the two systems seems to differentiate twice the displacements measured by the radar and then compare them with the accelerations provided by the accelerometers.

In practice, at least three effects have to be taken into account, and precisely the presence of noise in the measurements which affects the measurement accuracy, the presence of constant or slowly varying instrumental offsets (due, for instance, to thermal effects) and, last but not the least, a more or less pronounced variation of the frequency response of the accelerometers.

The effect of noise on the measurements can be conveniently described in the frequency domain. The noise of both the radar device and the accelerometers system can be sensibly described as a white noise, with a constant intensity at each frequency.

Since the Fourier transform of the derivative of a time-dependent function is equal to the Fourier transform of the function times $-\mathrm{i}\omega$, it is obtained that

$$F[\dot{d}(t)] = -\mathrm{i}\omega F[d(t)] \tag{3}$$

$$F[\ddot{d}(t)] = -\mathrm{i}\omega F[\dot{d}(t)] = -\omega^2 F[d(t)] \tag{4}$$

This means that the higher frequency components of the noise are greatly enhanced by a double differentiation, which can cause complex troubles in the comparison.

On the other hand, the integration of a time-dependent function (such as the accelerometer signal) implies dividing its Fourier transform by a factor $-\mathrm{i}\omega$, which enhances the lower frequency components of both signals and noise.

A possible compromise is the comparison of the velocities of the monitored points of the structural surface: this implies a single integration of the accelerometer signals and a single differentiation of the radar signal.

The integration enhances the noise at the lower frequencies, introduces a constant offset in the result and, if an offset or a low-frequency calibration is present in the accelerometer signal, its

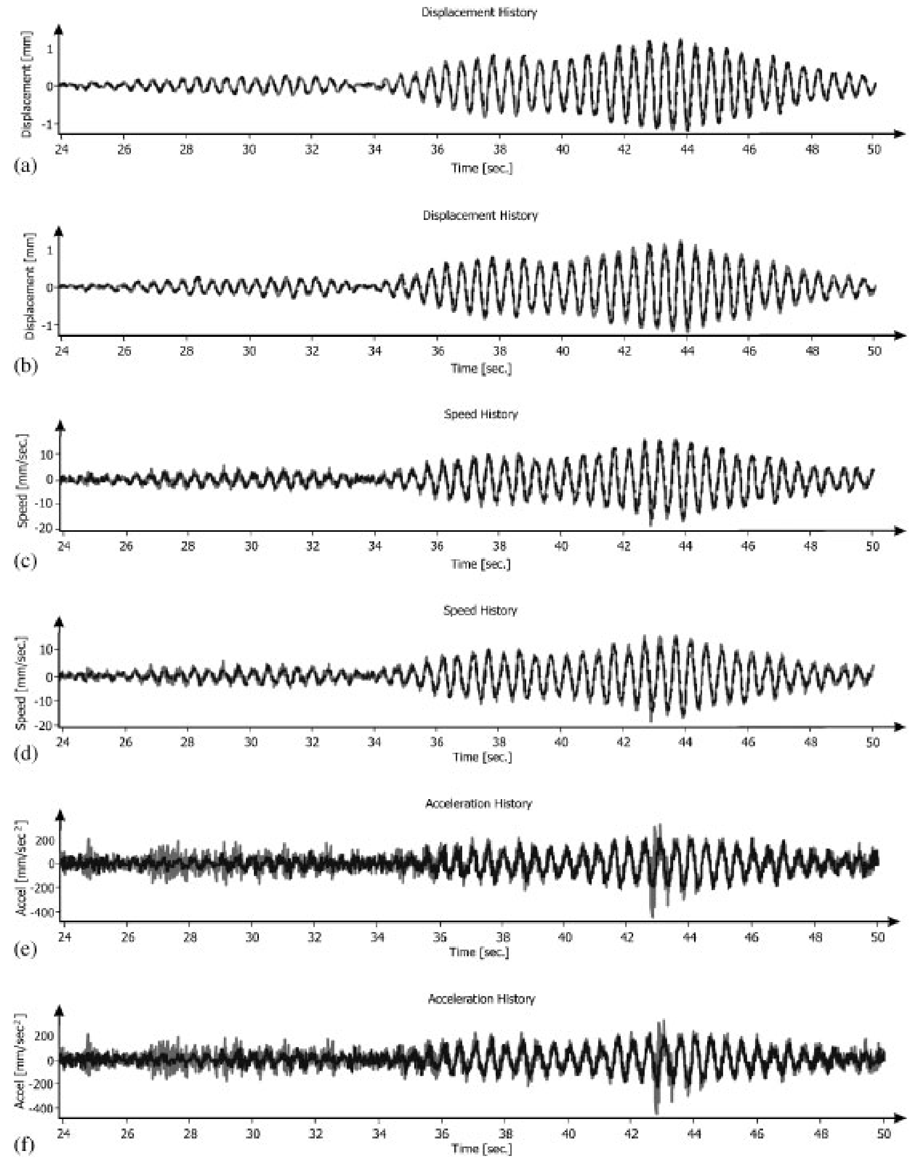

Figure 8. From above downwards: portions of (a) and (b) displacement; (c) and (d) velocity and (e) and (f) acceleration time histories starting from 24″ until 50″. Black line (dotted or continuous): accelerometer #1 (pictures (a), (c) and (e)) and accelerometer #2 (pictures (b), (d) and (f)). Gray line: radar.

integration causes a pronounced deviation from the actual velocity of the structure. Such inconvenience can be removed by means of a high-pass filtering of the accelerometer signal, with a relatively low cut-in frequency, in order for the structural frequencies to be retained by the filtered signal.

DOI: 10.1002/stc

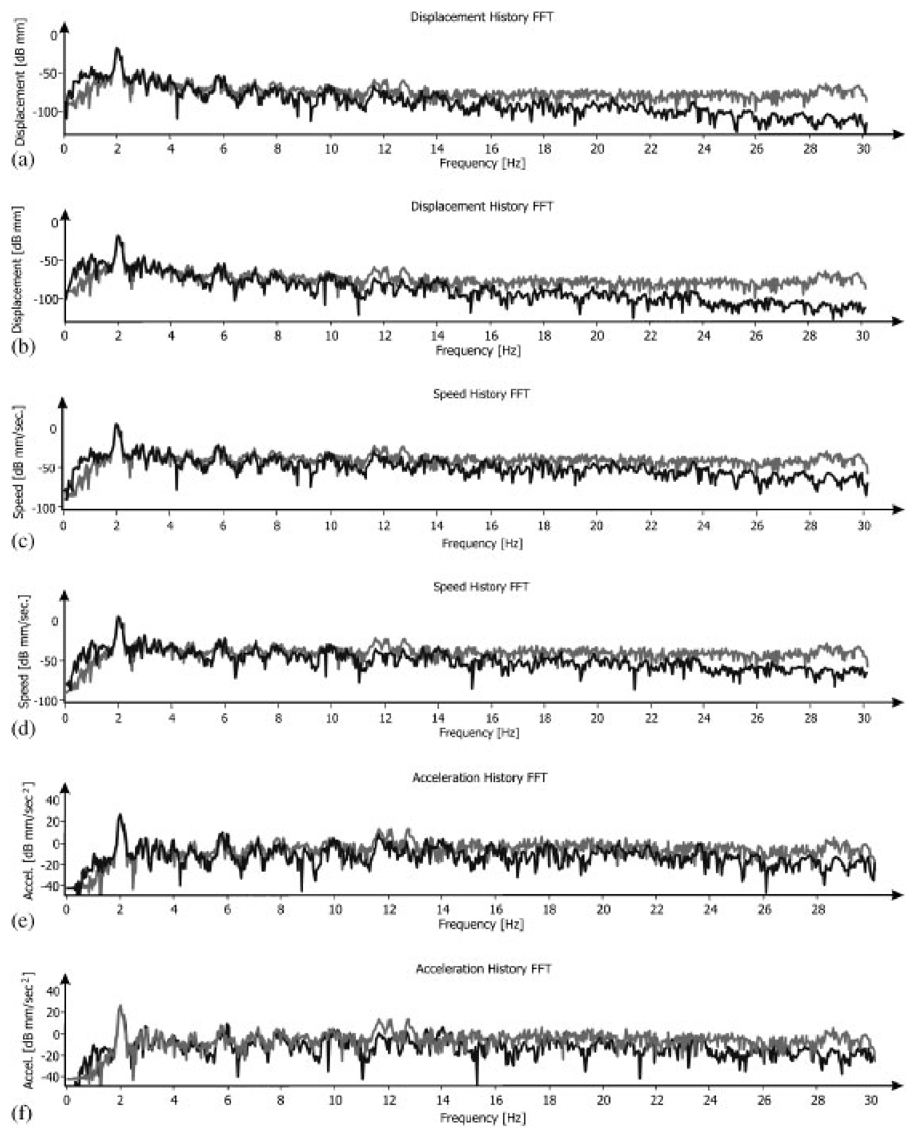

Figure 9. FFT of the previous signals in logarithmic scale: displacements FFT is expressed in dB mm, velocities in dB mm/s, accelerations in dB mm/s^2. Black line: accelerometer #1 (pictures (a), (c), and (e)) and accelerometer #2 (pictures (b), (d) and (f)). Gray line: radar.

The differentiation of the radar signal implies the removal of the indetermination on the displacements and the higher frequency components of the noise to be enhanced. On the other hand, the natural frequencies of the civil engineering structures are located in the low to middle frequencies range; hence, a low-pass filtering of the radar signal should not affect its structural frequency content.

DOI: 10.1002/stc

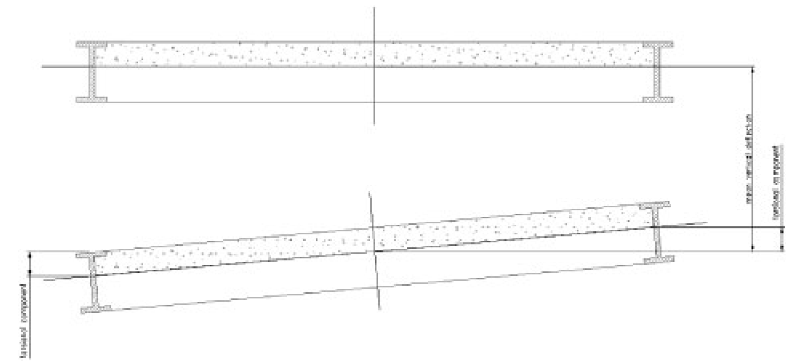

Figure 10. Sketch of the bridge deck motion during the examined tests.

To summarize, a band-pass, fifth-order Butterworth digital filter was utilized to pre-filter both the accelerometer and radar signals. The cut-in frequency was as low as 0.9 Hz and the cut-off frequency as high as 30 Hz. Such a filter exhibits an extremely flat frequency response, while the phase angle deviates from linearity near the cut-in and cut-off frequencies. Such a deviation, on the other hand, affects the data in the same fashion and enables the results to be compared.

Such filtering eventually enables three comparisons to be carried out: the comparison of the displacements, velocity and accelerations of the monitored points of the structure: the indetermination on the displacements provided by the radar measurement is in fact compensated by the low-pass filtering. The comparison between the acceleration histories appears the hardest to be performed owing to the great enhancement of the instrumental noise.

4.1. Walk and run of an adult along the center line of the deck

During this test, an adult walked and subsequently ran along the bridge deck along its center line, in a way that no torsional motions of the bridge deck were excited.

The dynamic load is constituted by a series of pulses with varying frequencies (during the walk the gap between consecutive pulses was approximately half a second, during the run approximately half as much).

Although the excitation intensity was not too strong, it has been possible to record motions of the bridge deck by means of both radar and accelerometers.

Figure 8 shows a window of the time histories of displacement, velocity and accelerations recorded by accelerometers #1 and #2 and the radar device. Since both the time histories of the accelerometers nearly coincide with the radar one, it is clear that no torsional motion of the structure was excited during this test. Furthermore, as the vertical deflection evaluated from the radar recording practically coincide with the double integral of the accelerometer signals, it is clear that the structural motion is essentially constituted by vertical deflections.

The comparison of displacements and velocities is excellent, while the time history of the acceleration evaluated by means of a double time derivative of the radar signal is strongly affected by noise enhancement. The comparison is even better in the frequency domain, as Figure 9 shows.

DOI: 10.1002/stc

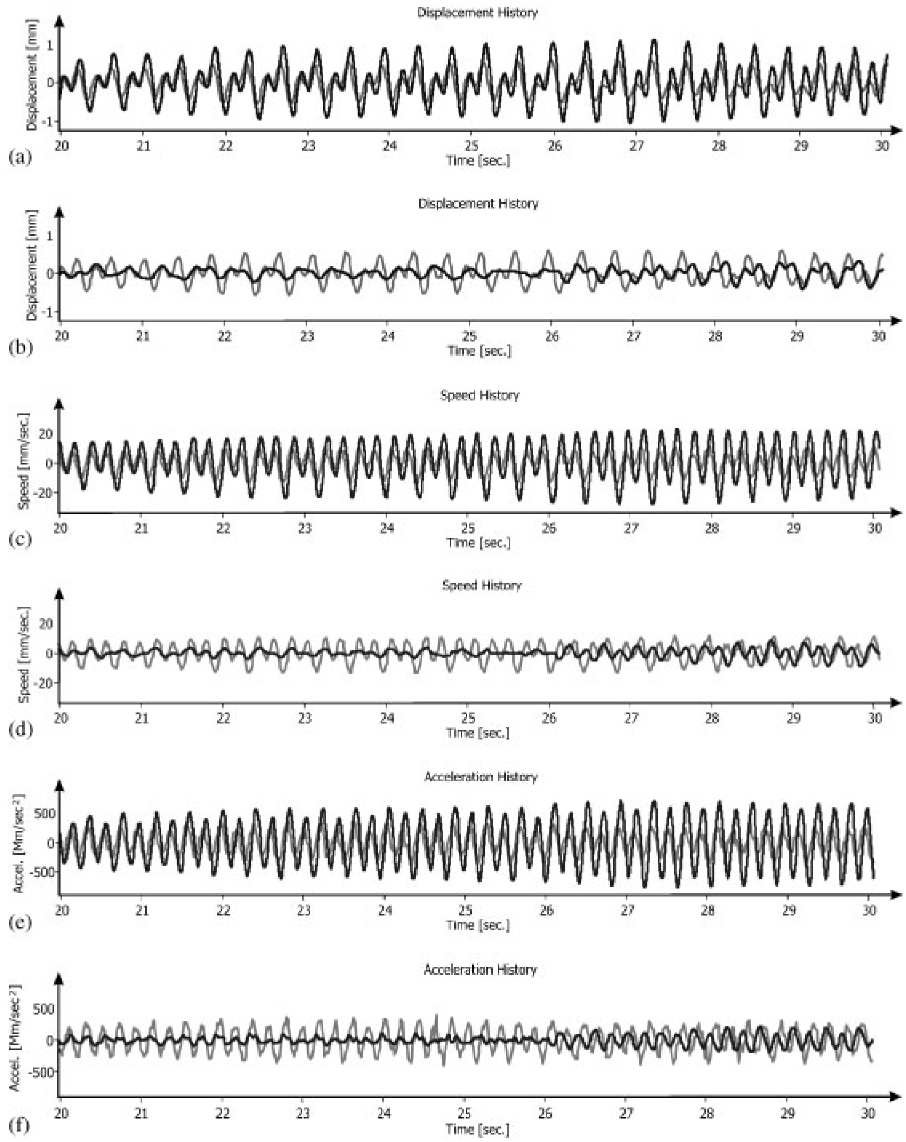

Figure 11. Windows of the time histories of the displacements, velocities and accelerations evaluated from the signals of accelerometer #1, accelerometer #2 and radar. Black line: accelerometer #1 (pictures (a), (c), and (e)) and accelerometer #2 (pictures (b), (d) and (f)). Gray line: radar.

4.2. Manual shaking of a stay

The second set of tests was constituted by the manual shaking of four different stays; as the results obtained for each test are similar to each other, only the ones obtained in the case of the fifth stay on the left side will be discussed in the following.

DOI: 10.1002/stc

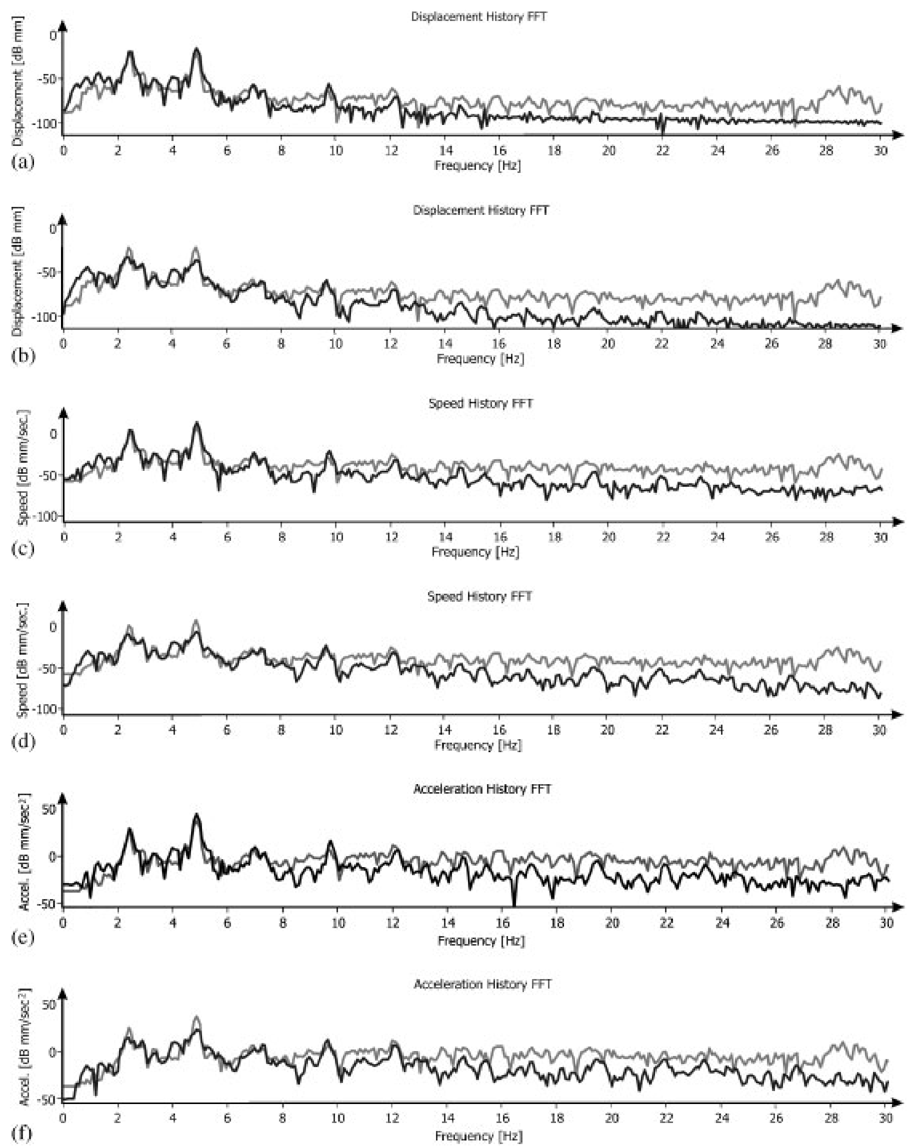

Figure 12. FFT of the previous signals in logarithmic scale: displacements FFT is expressed in dB mm, velocities in dB mm/s, accelerations in dB mm/s^2. Black line: accelerometer #1 (pictures (a), (c), and (e)) and accelerometer #2 (pictures (b), (d) and (f)). Gray line: radar.

From the time histories of the accelerometer and radar signals, a difference in intensity is clear.

More precisely, such an excitation caused a motion of the bridge deck, which can be decomposed into a vertical deflection component and a torsional component. While the vertical

DOI: 10.1002/stc

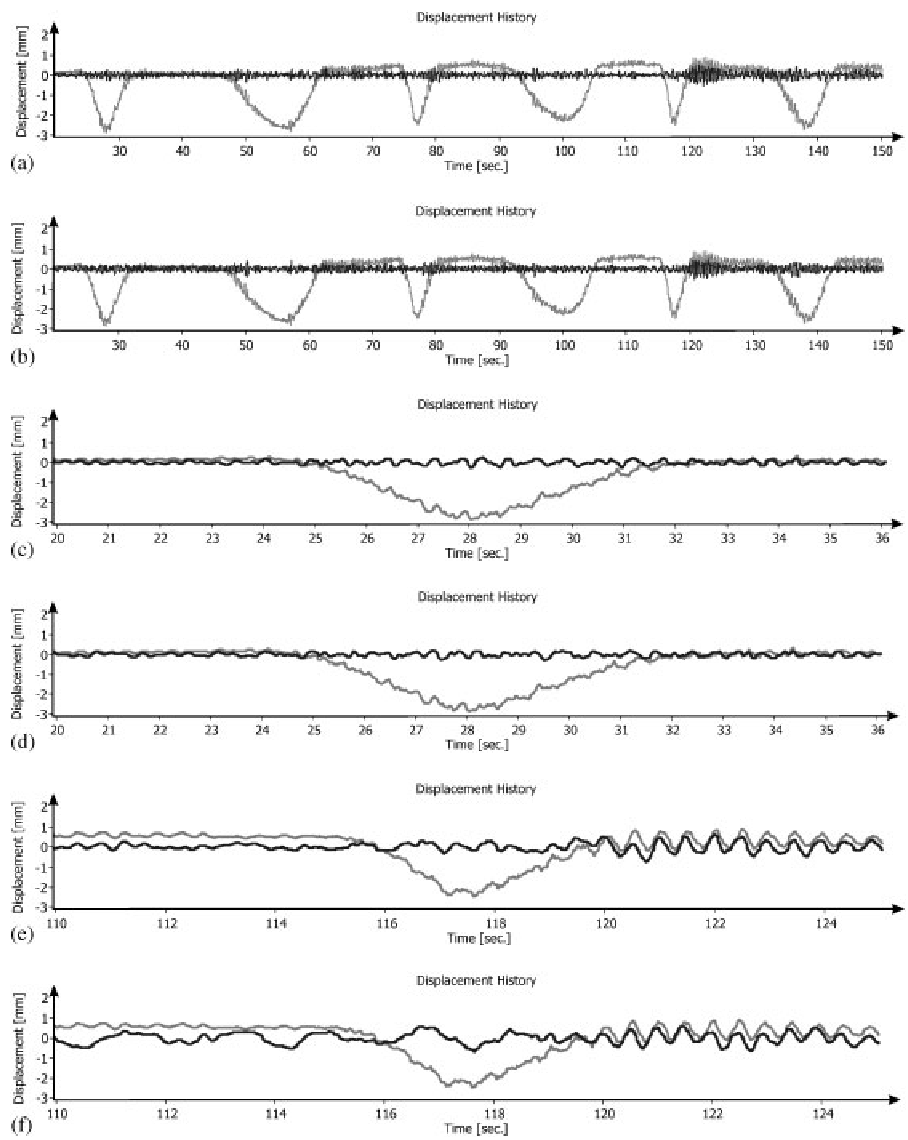

Figure 13. Time histories of the deck deflection caused by the compact car. Black line: accelerometer #1 (pictures (a), (c), and (e)) and accelerometer #2 (pictures (b), (d) and (f)). Gray line: radar.

deflection causes equal deflections on both sides of the bridge deck, the torsional one causes opposite deflections of the bridge deck (Figures 10 and 11).

It is nevertheless interesting that the frequency content was not altered by the averaging introduced by the radar measurement, as shown by Figure 12.

4.3. Slow motion of a compact type car along the bridge deck

During this last test, a small car (compact type) was driven back and forth along the bridge deck. Since the motion of the car was slow, it did not cause pronounced dynamic amplifications of the bridge deflection but rather quasi-static displacements.

In this case, only the time history of the displacements is reported (see Figure 13) along the whole duration of the test and in two interesting windows.

The accelerometer record had to be high-pass filtered owing to the presence of instrumental drifts, while the radar record did not need any high-pass filtering. Both signals were low-pass filtered with a cut-off frequency as high as 30 Hz.

As a consequence, the very low-frequency deflection caused by the car passing by the accelerometer positions cannot be shown in the plots. As a matter of fact, accelerometers are not adequate instruments to catch the bridge behavior under almost quasi-static excitations, while on the other hand the radar device still exhibits a good behavior.

The apparent out-of-phase behavior of the radar and the accelerometer signals is due to the fact that such harmonic is extremely near to the cut-off pole of the high-pass digital filter.

5. SUMMARY AND DISCUSSION OF THE OBTAINED RESULTS

An interferometric radar technique for the remote survey of civil structures has been presented and critically discussed on the basis of comparisons with results given by a set of accelerometers for a series of dynamic and quasi-static loading tests on a cable-stayed pedestrian bridge.

The comparisons were established in the time domain (comparison between the time histories of displacement, velocity and acceleration of key points on the structure) and in frequency domain (comparisons between the FFT of the before-mentioned time histories).

Very good agreement was found in the case of a dynamic load acting along the longitudinal axis of the bridge deck: in this case, only vertical deflection arouse and no torsional motion of the deck was observed.

A scarce behavior of the radar was observed in the case of an eccentric dynamic load, such as the manual shaking of a stay; since the device has no angular resolution, it can only measure displacements along the line r from the examined point on the surface to the radar itself. In the case of a bridge, this implies that only those deflections that cause a non-zero component d_p along the line r can be detected by the radar. In the case of a torsional motion of the deck, two points at the same distance from the device give rise to two different displacements: the device can only measure the mean of such displacements, thus averaging out the torsional motion.

In the case of a slowly moving car on the bridge deck, the radar showed a much better behavior than the accelerometers, as the latter instruments are completely inadequate for quasi-static testing. On the other hand, the radar device proved to be adequate for both quasi-static and dynamic measurements.

ACKNOWLEDGEMENTS

The grant from MIUR, Italian Ministry for Education, University and Research, granted in the framework of the PRIN 2004 research project '*VINCES*: *Vibrations IN Civil Engineering Structures*: *source of damage and discomfort*, *diagnostic and safety assessment tool*' is gratefully acknowledged.

REFERENCES

1. Pieraccini M, Fratini M, Parrini F, Macaluso G, Atzeni C. High-speed CW step-frequency coherent radar for dynamic monitoring of civil engineering structures. *Electronics Letters* 2004; **40**(14):907–908.
2. Pieraccini M, Fratini M, Parrini F, Pinelli G, Atzeni C. Dynamic survey of architectural heritage by high-speed microwave interferometry. *IEEE Geoscience and Remote Sensing Letters* 2005; **2**(1):28–30.
3. Pieraccini M, Tarchi D, Rudolf H, Leva D, Luzi G, Atzeni C. Interferometric radar for remote monitoring of building deformations. *Electronics Letters* 2000; **36**:569–570.
4. Pieraccini M, Luzi G, Mecatti D, Fratini M, Noferini L, Carissimi L, Franchioni G, Atzeni C. Remote sensing of building structural displacements using a microwave interferometer with imaging capability. *NDT&E International* 2004; **37**:545–550.

DOI: 10.1002/stc