

DYNAMIC MONITORING OF CIVIL ENGINEERING STRUCTURES BY MICROWAVE INTERFEROMETER

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Abstract

This paper describes a non-contact vibrometer, designed for dynamic testing or monitoring of large structures. The new system, named *IBIS-S*, consists of a radar sensor apt to simultaneously measure the displacement response of several points belonging to a structure with accuracy of the order of hundredth of millimetres. In addition to its non-contact feature, the new vibration measuring system provides other advantages including quick set-up time, a wide frequency range of response and portability. In the paper, the radar-based sensor and its working principles are first described; afterwards, application to the measurement of ambient vibration response of a full-scale bridge is summarized. The test of the bridge included extensive comparison between the time series acquired by the radar and conventional sensors, with the comparison involving several points of the structure, for about 3000 s. Furthermore, resonant frequencies and mode shapes of the bridge, that were identified from the radar signals, are compared to the corresponding quantities estimated from the accelerometer's records.

Keywords: Ambient vibration, bridge, interferometric technique, *SF-CW* technique, radar.

1. Introduction

The modern conceptual design of civil engineering structures often includes the specification of the tests required for the Structural Health Monitoring (*SHM*) of the structure and sometimes the design of permanently installed monitoring system. Among the different techniques of experimental testing and monitoring, ambient vibration tests have recently become the main experimental method available for assessing the dynamic behaviour of full-scale structures.

Ambient vibration testing of full-scale structures is generally performed using piezoelectric or force-balanced accelerometers since these sensors are relatively inexpensive and accurate and have adequate signal-to-noise ratio, bandwidth, sensitivity and other technical characteristics. However, these devices exhibit well-known problems, especially related to mounting and hardwiring from the transducer to the data acquisition system so that, when the structure is very large, the effort associated with mounting and wiring the accelerometers is typically the most time-consuming task associated with the test. Furthermore, accelerometers do not provide a direct measurement of displacement, which is often of interest for the *SHM* of a structure in operational conditions.

Within this context, the use of innovative non-contact systems for vibration measurement appears to be very attractive and especially applications of laser-based systems (see e.g. [1], [2]) are reported in the literature.

Furthermore, a non-contact system using microwaves was described by Farrar et al. [3] and used to detect the overall vibration of the well-known I-40 bridge [4]; this sensor did not provide any range resolution, i.e. was not capable to detect different targets in the scenario illuminated by the microwave beam.

Recently, based on interferometric [5] and wide band waveform [6] principles, a novel radar system was developed, capable of measuring the dynamic response of several points of a structure with about $0.01\div 0.02$ mm displacement sensitivity [7]. The new microwave-based system, named *IBIS-S*, was developed by the IDS company in collaboration with the Department of Electronics and Telecommunication of the Florence University.

Subsequently, a joint research started between IDS and the Department of Structural Engineering of the Milan Polytechnic, mainly aimed to validate the results of the radar system and to assess its performance in dynamic testing of full-scale structures. During the ongoing research, the radar system was used in ambient vibration testing (*AVT*) of different R.C. bridges and the results of the last tests are summarized in this paper. In the test, the correspondence between the signals simultaneously acquired from radar and accelerometers in correspondence of several target surfaces was extensively investigated; furthermore, the modal parameters (resonant frequencies and mode shapes) identified with the radar system are compared to the corresponding quantities estimated with conventional accelerometers.

2. Sensor description and basic principles

The *IBIS-S* radar system consists of a sensor module, a control PC and a power supply unit.

The sensor module (Fig. 1) is a coherent radar generating, transmitting and receiving the electromagnetic signals to be processed in order to compute the displacement time-histories of the investigated structure. The sensor module, including two horn antennas (Fig. 1) for transmission and reception of the electromagnetic waves, exhibit a typical super heterodyne architecture. The base-band section consists of a Direct Digital Synthesis (*DDS*) device to obtain fast frequency hopping. A tuneable sine wave is generated through a high-speed D/A converter, reading a sine lookup table in response to a digital tuning word and a precision clock source. The radio-frequency section radiates at a central frequency of 16.75 GHz with a maximum bandwidth of 300 MHz; hence, the radar is classified as *K_a*-band, according to the standard radar-frequency letter-band nomenclature from IEEE Standard 521-1984 [8]. A final calibration section provides the necessary phase stability; design specifications on phase uncertainty are suitable for measuring short-term displacements with a range uncertainty lower than 0.01 mm.

The sensor module is installed on a tripod equipped with a rotating head, allowing the sensor to be orientated in the desired direction, as shown in Fig. 1. The module has an USB interface for connection with the control PC and an interface for the power supply module.

The control PC is provided with the software for the system management and is used to configure the acquisition parameters, store the acquired signals, process the data and view the initial results in real time.

Finally, the power supply unit provides power to the system through a 12 V battery unit.



Figure 1: View of the new *IBIS-S* sensor

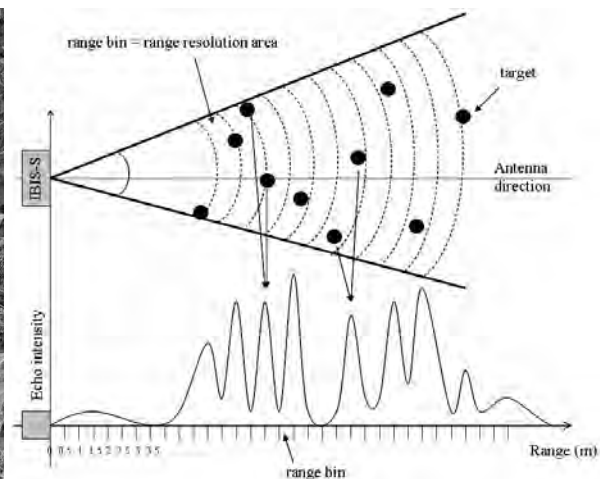


Figure 2: Range resolution concept

The ability to determine range (i.e. distance) by measuring the time for the radar signal to propagate to the target and back is surely the distinguishing and most important characteristic of radar systems. Two or more targets, illuminated by the radar, are individually detectable if they produce different echoes. The *resolution* is a measure of the minimum distance between two targets at which they can still be detected individually. The *range resolution* refers to the minimum separation that can be detected along the radar's line of sight.

Differently from the sensor described in [3], the *IBIS-S* system is capable of providing range resolution, i.e. to distinguish different targets in the scenario illuminated by the radar beam. Peculiarly, this performance is reached by using the Stepped-Frequency Continuous Wave (*SF-CW*) technique (see e.g. [5]).

Pulse radars use short time duration pulses to obtain high range resolution. For a pulse radar, the range resolution Δr is related to the pulse duration τ by the following [5]:

$$\Delta r = \frac{c\tau}{2} \quad (1)$$

where c is the speed of light in free space. Since (see e.g. [9]) $\tau = 1/B$, the range resolution (1) may be expressed as:

$$\Delta r = \frac{c}{2B} \quad (2)$$

Eq. (2) highlights that range resolution increases (corresponding to a smaller numerical value of Δr) as the frequency bandwidth of the transmitted electromagnetic wave increases; hence, closely spaced targets can be detected along the radar's line of sight. The *SF-CW* technique exploits the above concept to provide the *IBIS-S* sensor with range resolution capability.

The *SF-CW* technique is based on the transmission of a burst of N monochromatic pulses, equally and incrementally spaced in frequency (with fixed frequency step of Δf), within a bandwidth B :

$$B = (N - 1)\Delta f \quad (3)$$

The N monochromatic pulses sample the scenario in the frequency domain similarly to a short pulse with a large bandwidth B . In a *SF-CW* radar, the signal source dwells at each frequency $f_k = f_o + k\Delta f$ ($k=0,1,2, \dots, N-1$) long enough to allow the received echoes to reach the receiver. Hence, the duration of each single pulse (T_{pulse}) depends on the maximum distance (R_{max}) to be observed in the scenario:

$$T_{pulse} \geq \frac{2R_{max}}{c} \quad (4)$$

In the *IBIS-S* sensor, the *SF-CW* radar sweeps a large bandwidth B with a burst of N single tones at uniform frequency step, in order to obtain a range resolution of 0.50 m; in other words, two targets can still be detected individually by the sensor if their relative distance is greater than 0.50 m. The range resolution area is termed *range bin*. The radar continuously scans the bandwidth at a rate ranging up to 100 Hz, so that the corresponding sweep time Δt of 10 ms is in principle well suitable to provide a good waveform definition of the displacement response for a civil engineering structure.

At each sampled time instant, both in-phase and quadrature components of the received signals are acquired so that the resulting data consist of a vector of N complex samples, representing the frequency response measured at N discrete frequencies. By taking the Inverse Discrete Fourier Transform (*IDFT*) the response is reconstructed in the time domain of the radar: each complex sample in this domain represents the signal (echo) from a range (distance) interval of length $cT_{pulse}/2$. The amplitude range profile of the radar echoes is then obtained by calculating the magnitude of each bin of the *IDFT* of acquired vector samples. This range profile gives a one dimensional map of scattering objects in the viewable space in function of their relative distance from the equipment.

The concept of range profile is better illustrated in Fig. 2, showing an ideal range profile obtained when the radar transmitting beam illuminates a series of targets at different distances and different angles from the system. Fig. 8 refers to the application of the *SF-CW* technique in the dynamic testing of a full-scale bridge and shows the typical range profile of the bridge. The peaks in the plot of Fig. 8 correspond to "good" measurement points and the sensor can be used to simultaneously detect the displacement and the transient response of these points.

Once the image of the scenario illuminated by the radar beam has been determined at uniform sampling intervals Δt , the displacement response of each target detected in the scenario is evaluated by using the Differential Interferometry technique (see e.g. [6]); this technique is based on the comparison of the phase information of the back-scattered electromagnetic waves collected in different times.

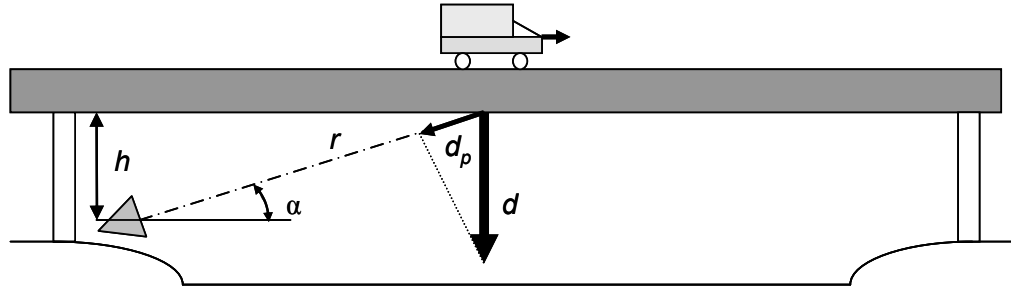


Figure 3: Radial displacement vs. projected displacement

Generally speaking, when of a target surface moves with respect to the sensor module (emitting and back-receiving the electromagnetic wave), at least a phase shift arises between the signals reflected by the target surface at different times. Hence, the displacement of the investigated object is determined from the phase shift measured by the radar sensor at the discrete acquisition times. The radial displacement d_p (i.e. the displacement along the direction of wave propagation) and the phase shift $\Delta\varphi$ are linked by the following:

$$d_p \propto \frac{\lambda}{4\pi} \Delta\varphi \quad (5)$$

where λ is the wavelength of the electromagnetic signal.

The sensor module emits a series of electromagnetic waves for the entire measurement period, and processes phase information at regular time intervals (up to 10 ms) to find any displacement occurring between one emission and the next. It is worth underlining that the interferometric technique (5) provides a measurement of the radial displacement of all the range bins of the structure illuminated by the antenna beam; once the radial displacement d_p has been evaluated, the vertical displacement d can be easily found by making some geometric projection, as shown in Fig. 3.

Finally, the main operational characteristics of *IBIS-S* system are summarised in Table 1.

Table 1: *IBIS-S* operational characteristics.

Parameter	
Maximum operational distance (for minimum 40Hz sampling frequency)	500.00 m
Maximum sampling frequency	100.00 Hz
Displacement sensitivity (accuracy)	0.01 mm
Operative weather condition	All

3. Application to ambient vibration test of a bridge

3.1 Description of the bridge

The investigated bridge crosses the Adda river between the towns of Capriate and Trezzo (about 50 km far from Milan). Elevation and view of the bridge are shown in Fig. 4. The bridge, dating back to the 60's, has a total length of 113.3 m and consists of two variable-depth R.C. balanced cantilevers (47.2 m long), connected by one simply supported drop-in girder (18.9 m long).

3.2 Experimental procedures and dynamic behaviour of the bridge

Two series of ambient vibration tests were conducted and the response of the bridge was measured at selected points using WR-731A piezoelectric sensors, each with a battery power unit. These sensors, allowing acceleration or velocity responses to be recorded, were used as conventional accelerometers in the first series of tests for operational modal analysis purposes. During the second series of tests, the radar sensor and the conventional sensors were simultaneously used, with the radar module being placed near the basement of the Trezzo-side pier.

The objective of the test of the radar system was two-fold. First, the correspondence between the time-histories evaluated from the radar and the ones recorded by conventional accelerometer was extensively investigated in correspondence of several target surfaces; peculiarly, the velocity time-histories directly recorded by the WR 731A sensor (in the second series of tests) were compared to the ones computed by deriving the displacement obtained by the *IBIS-S* sensor. Subsequently, resonant frequencies and mode shapes of the bridge, identified from the radar signals, were compared to the corresponding quantities estimated from the accelerometer's records.

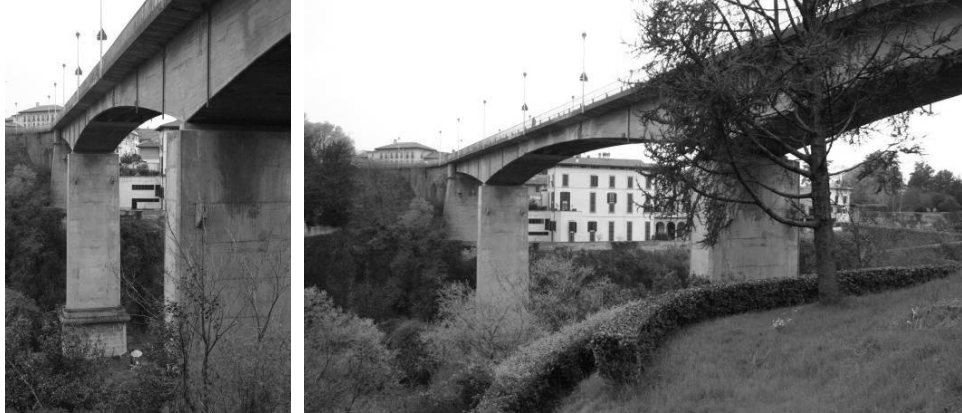
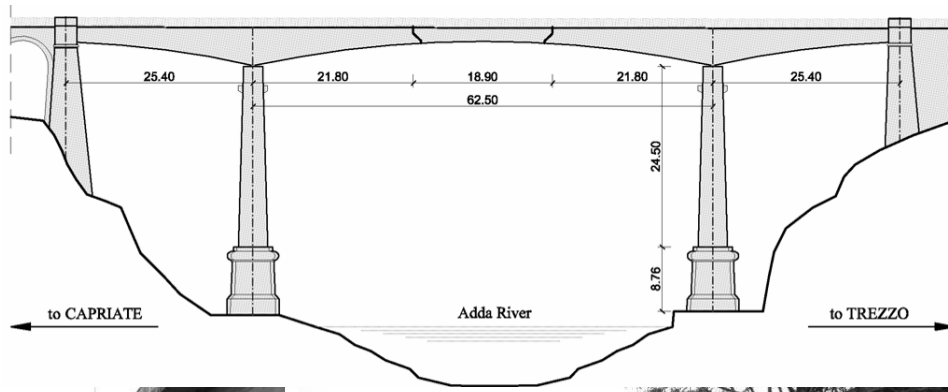


Figure 4: Elevation (dimensions in m) and view of the bridge in Capriate (Italy) from upstream side

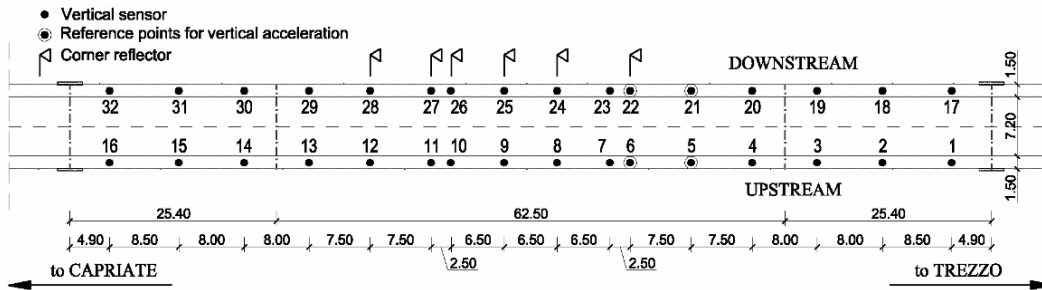


Figure 5: Sensor layout during the tests of the Capriate bridge (dimensions in m)



Figure 6: Accelerometers and corner reflectors installed on the Capriate bridge

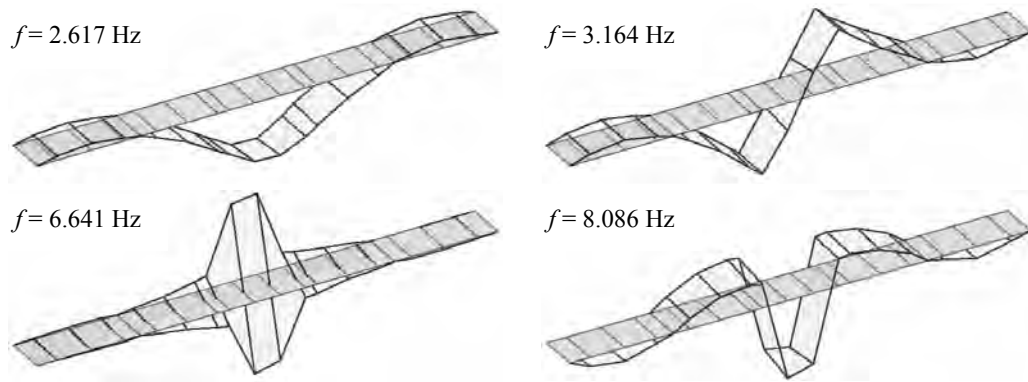


Figure 7: Mode shapes identified from conventional acceleration signals (*FDD*)

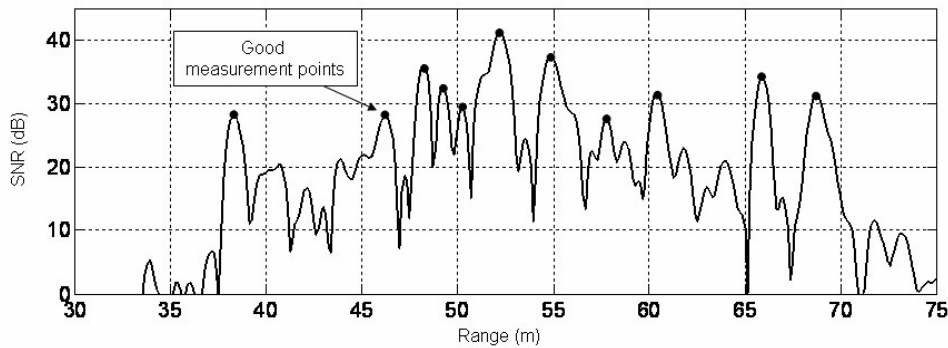


Figure 8: Typical range profile of the Capriate bridge

In both series, the length of the time window acquired by the conventional sensors was 3000 s per channel, at a sampling rate of 200 Hz. In the second series of tests, the control PC of the *IBIS-S* sensor has been configured to measure targets up to a distance of 100.0 m, with a scenario sampling frequency of 100 Hz.

Fig. 5 shows a schematic diagram of the vertical accelerometers layout. A series of three set-ups was required to cover all the measurement points, with the sensors placed at test points TP5-TP6, TP21-TP22 of Fig. 5 being used for reference measurements. In order to provide accurate comparison between the signals acquired from conventional sensors and radar system, simple passive radar reflectors or *corner reflectors* were placed as close as possible to the accelerometers on the downstream side of the deck, as shown in Figs. 5 and 6. It should be noticed that such simple passive reflectors, very quick and easy to mount, can be used in special cases, when the structure is not sufficiently reflective to electromagnetic waves or when the displacement of specific points on the structure need to be measured (as it happens in the present application).

Experimental modal analysis using data from the accelerometers was performed before beginning the simultaneous acquisition with the radar. The *Frequency Domain Decomposition (FDD)* [10] technique implemented in the *ARTEMIS* software [11] was used for modal identification and the results revealed 4 normal modes in the frequency interval of 0–10 Hz. Fig. 7 shows the identified vibration modes. The first vertical bending mode is symmetric, with a frequency of 2.62 Hz, while the second mode (3.16 Hz) involves out-of-phase bending of the two balanced cantilevers so that the central drop-in girder undergoes a nearly rigid motion; the first torsion mode is at 6.64 Hz and the corresponding mode exhibits one complete wave.

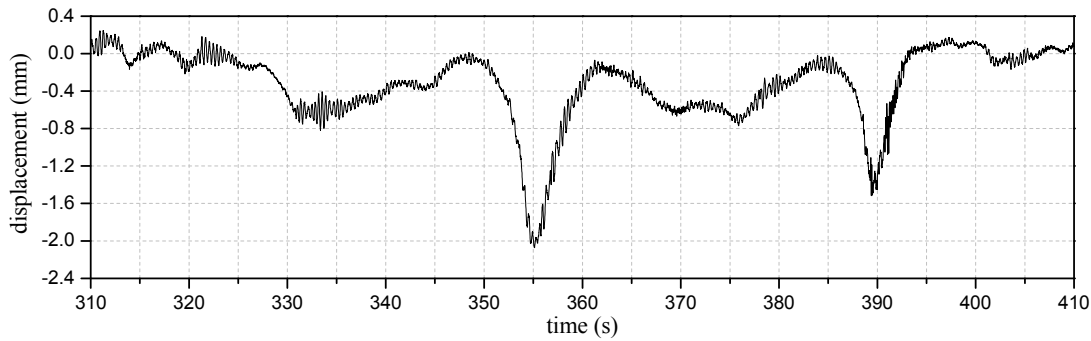


Figure 9: Typical displacement provided by the *IBIS-S* sensor at TP25

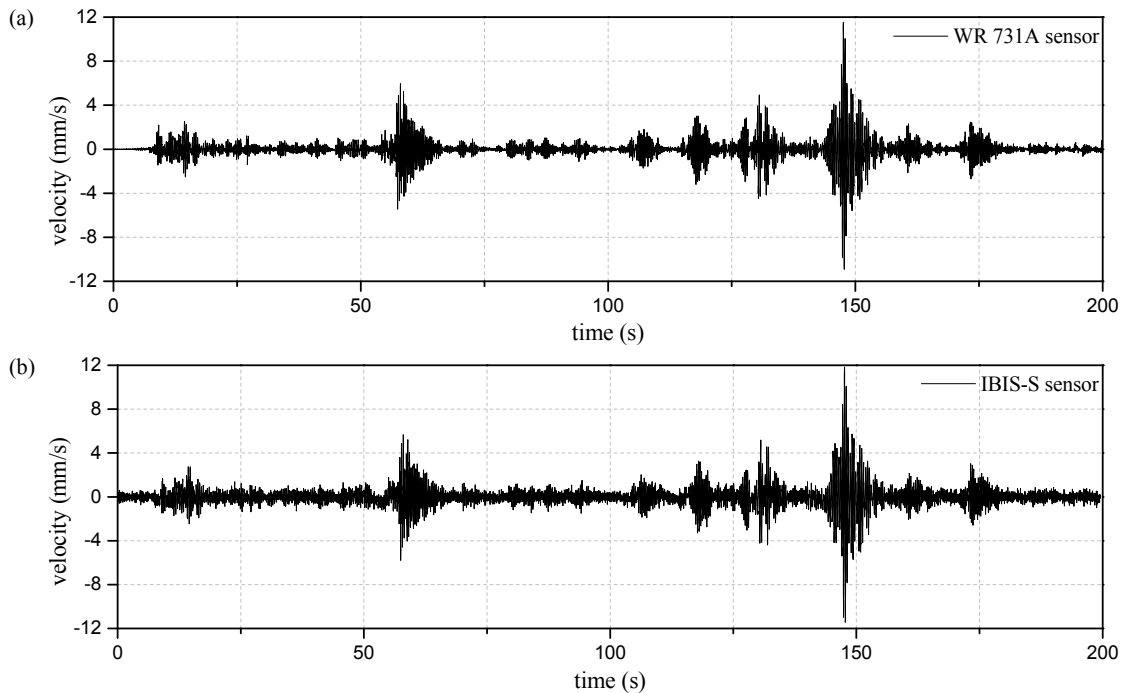


Figure 10: Typical velocity signal recorded at TP22 by: (a) WR 731A sensor and (b) *IBIS-S* sensor

3.3 Results obtained from the radar sensor

As previously pointed out, the second series of ambient vibration tests of the bridge included the installation of 6 corner reflectors on the downstream side of the deck, corresponding to test points TP22, TP24-TP28 (Fig. 5) in the close neighbourhood of the accelerometers (Fig. 6). Then, the displacement responses corresponding to corner reflectors and the velocity responses of the conventional sensors were simultaneously recorded for 3000 s.

Fig. 8 shows a typical range profile of the bridge, with several peaks clearly marking the positions of the corner reflectors and of other points of the structure characterized by a good electromagnetic reflectivity.

The analysis of the results provided by the radar sensor first included the qualitative inspection of the displacement measurements obtained by the radar-based vibrometer. Fig. 9 shows an example of displacement time-history measured at TP25; it should be noticed that the displacement signals are very similar to what expected, based on well-known theoretical models [12], i.e. composed by the superposition of a peak and damped harmonic functions. It is also marginally observed that the displacement signals provide the possibility either to count the travelling cars and trucks over the bridge or to obtain the statistical distribution of the displacement over short and long periods.

Afterwards, the velocity time-histories computed by deriving the displacement obtained from the *IBIS-S* sensor were compared to the ones directly recorded by the WR 731A sensors. Figs. 10(a) and

10(b) show an example of the recorded data at TP22 for a time period of 200 s; the first plot shows the conventional sensor measurement while the second plot refers to the velocity obtained deriving the displacement signal provided by the radar sensor. The inspection of Figs. 10(a) and 10(b) reveals a remarkable correspondence between the time series, although some differences are detected, basically related to the different signal-to-noise ratio of the two sensors.

Another example of comparison is given in Figs. 11(a)-(d); the figures refer to the signals simultaneously recorded at TP22, TP24, TP25 and TP26 over a short time period (10 s) and clearly show an excellent match between the data obtained from radar and conventional sensors. A similar match was obtained for all corner reflectors along 3000 s of acquired time window, provided that the displacement response exceeds $0.01 \div 0.02$ mm.

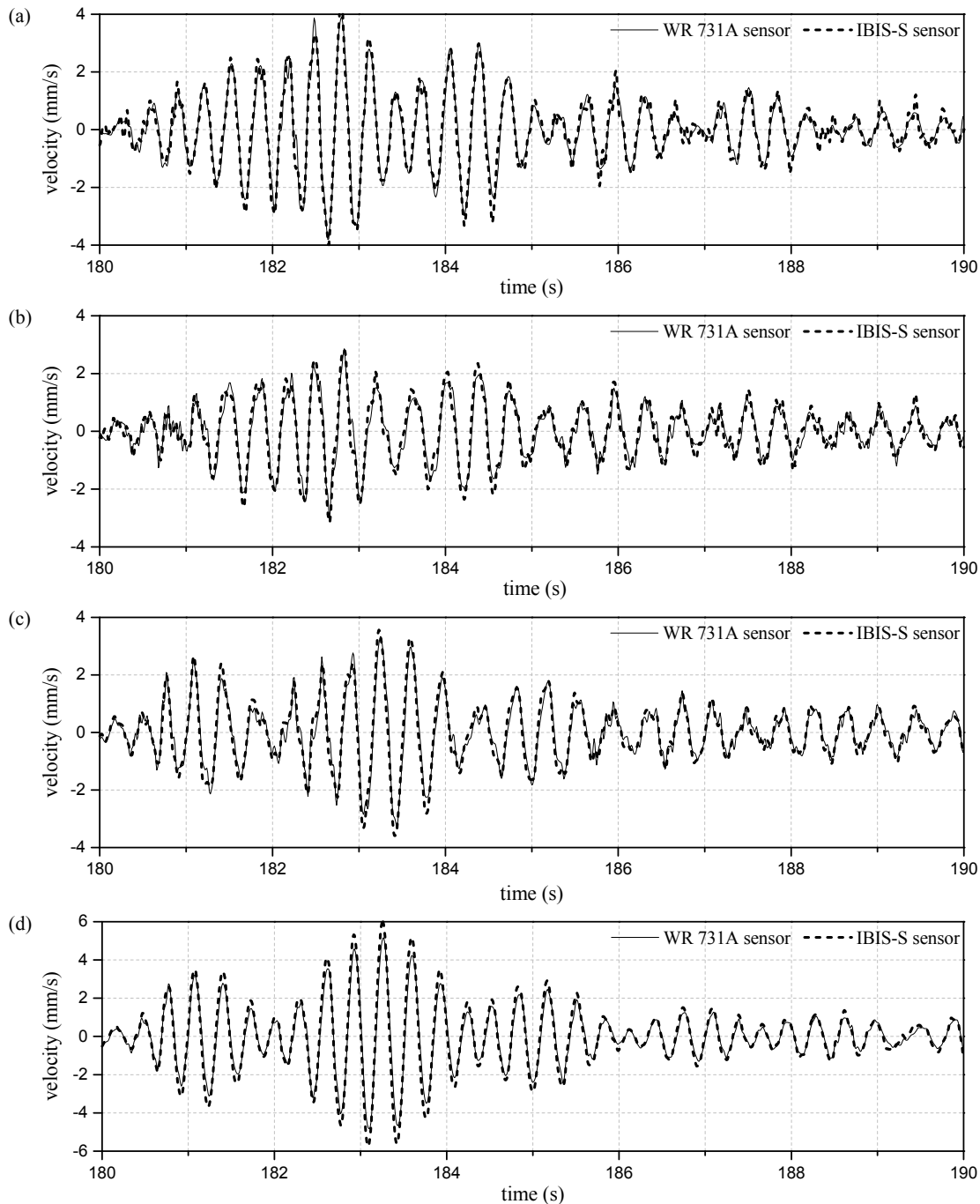


Figure 11: Typical comparison between the velocity signal recorded by WR 731A and IBIS-S sensors at different test points of the deck: (a) TP22; (b) TP24; (c) TP25; (d) TP26

Finally, resonant frequencies and mode shapes, identified from the radar signals, were compared to the corresponding modal parameters previously estimated from the accelerometer's records. The evaluation of the modal parameters from the radar signals was first carried out by applying the *FDD* technique to all available velocity records obtained by the radar sensor. The identified natural frequencies turned out to be practically equal to the values obtained from operational modal analysis of the ambient acceleration (with the frequency discrepancy being less than 0.90%, see Fig. 12); furthermore, also the modal displacements exhibit very good agreement, as shown in Fig. 12. It is worth mentioning that similar results were obtained also by using the displacement data directly provided by the radar.

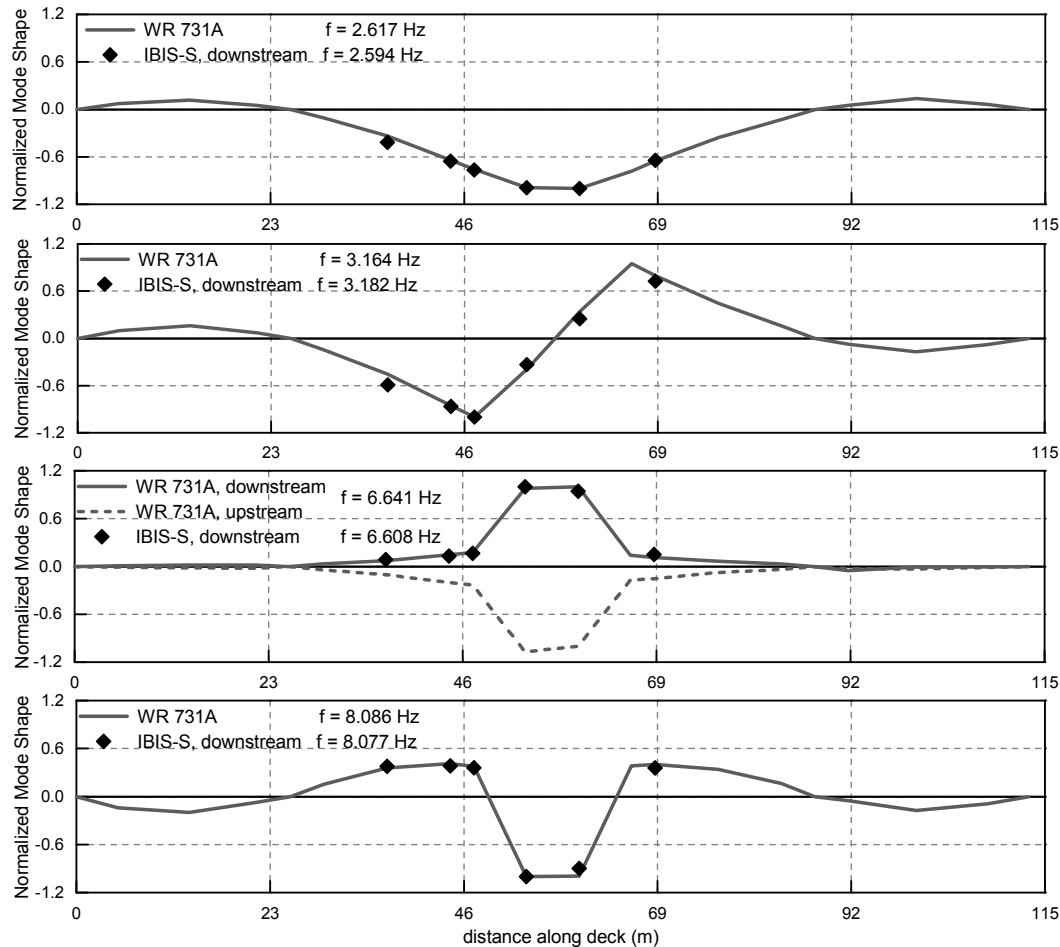


Figure 12: Mode shapes identified from WR 731A and *IBIS-S* signals.

4. Conclusions

An innovative radar-based measuring system, named *IBIS-S*, was developed for remote, non-contact displacement vibration measurements. In principle, the new microwave vibrometer exhibit several advantages:

- a. remote structural monitoring (remote sensing) can be performed without the need of accessing the structure to install sensors or optical targets. In special cases, when the structure is not sufficiently reflective to electromagnetic waves or when displacement of specific points on the structure must be measured, simple passive radar reflectors can be quickly and easily fixed;
- b. the microwave interferometer is quick and easy to install and can be used both day and night and in all weather conditions;
- c. although mode shapes of a structure are routinely estimated using conventional accelerometers or other sensors, these sensors do not provide a direct measurement of displacement, which is often of interest for the study of civil engineering structures in operational condition. On the contrary, the new radar system simultaneously measures the displacements of several points in the area illuminated by the antenna beam;

- d. the sensor can be used to detect either static displacements or the transient response in real time, thus avoiding diverted quantities.

The new radar sensor was applied to non-contact measurement of traffic-induced responses on a full-scale bridge and exhibited excellent stability of functioning, when used on site for long time intervals. Based on the analysis of the test results, including the inspection of the displacement responses obtained from the radar sensor and the comparison with the data recorded by conventional accelerometers, the following conclusions can be drawn:

1. the displacement measurements obtained by the radar sensor seem very similar to what expected, based on well-known theoretical models (see e.g. [12]);
2. the time-histories evaluated from the radar sensor generally exhibit excellent agreement with the ones recorded by conventional sensors;
3. the comparison of the modal parameters (resonant frequencies and mode shapes) identified from radar data to the modal parameters identified from data obtained with conventional accelerometers shows that the modal behavior obtained with the radar system is as accurate as that obtained with the conventional accelerometers.

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References

- [1] Cunha A., Caetano E. & Delgado R., Dynamic tests on a large cable-stayed bridge, *J. Bridge Engineering*, ASCE, **6**(1), 2001, 54-62
- [2] Kaito K., Abe M. & Fujino Y., Development of a non-contact scanning vibration measurement system for real-scale structures, *Structure & Infrastructure Engng.*, **1**(3), 2005, 189-205.
- [3] Farrar C.R., Darling T.W., Migliori A. & Baker W.E., Microwave interferometers for non-contact vibration measurements on large structures. *Mech. Syst. Signal Process.*, **13**(2), 1999, 241-253.
- [4] Farrar C.R. & Cone K.M., Vibration testing of the I-40 bridge before and after the introduction of damage, *Proc. 13th Int. Modal Analysis Conf. (IMAC-XIII)*, 1995, 203-209.
- [5] Taylor J.D. (Ed.), *Ultra-wideband radar technology*. CRC Press, 2001.
- [6] Henderson F.M. & Lewis A.J. (Eds.), *Manual of Remote Sensing. Principles and Applications of Imaging Radar*, 3rd Ed., Wiley & Sons, 1998.
- [7] Pieraccini M., Fratini M., Parrini F., Macaluso G. & Atzeni C., Highspeed CW step-frequency coherent radar for dynamic monitoring of civil engineering structures, *Electron. Lett.*, **40**(14), 2004, 907-908.
- [8] Skolnik M.I. (Ed.), *Radar Handbook*. McGraw-Hill, 1990.
- [9] Marple S.L. Jr., *Digital spectral analysis with applications*, Prentice-Hall, 1987.
- [10] Brincker R., Zhang L. & Andersen P., Modal Identification from Ambient Responses using Frequency domain Decomposition. *Proc. 18th International Modal Analysis Conference (IMAC-XVIII)*, 2000, 625-630.
- [11] ARTeMIS Program Overview, <http://www.svibs.com>, 2006.
- [12] Fryba L., *Vibration of solids and structures under moving loads*. 3rd Ed., 1999, Academia Prague.