Structural health monitoring of stay cables using the microwave interferometry

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ABSTRACT: The paper addresses the application of microwave remote sensing to the vibration response measurement on the stay cables of cable-stayed bridges. The investigation, carried out on the stays of various bridges, clearly highlights: (a) the accuracy of the results provided by the microwave remote sensing; (b) the simplicity of use of the radar technique (especially when compared with conventional approaches) and its effectiveness to simultaneously measuring the dynamic response of all the stay cables of an array; (c) the repeatability of the test with Structural Health Monitoring purposes.

1 INTRODUCTION

Stay cables are one of the most critical structural components in modern cable-stayed bridges and measurements of cable vibration are currently performed with different objectives, such as: (1) the experimental identification of local natural frequencies and damping ratios; (2) the evaluation of cable tensions, either to check the correct distribution of internal forces in the bridge at the end of construction or to track the possible change of cable tensions in time for Structural Health Monitoring (SHM); (3) the assessment of potential fatigue problems in stay cables caused by long-term traffic loads; (4) the evaluation of the amplitude of cable vibrations.

Although accelerometers are generally used to measure the cable vibrations, the installation of these contact type of sensors requires significant effort, especially when dealing with a large number of stay cables, and might expose the test crew to hazardous conditions if the bridge is in service. For these reasons, the development and application of new experimental techniques to systematically measure the dynamic response on stay cables in a simple and safe way has drawn the attention of several researchers and the measurement of cable vibrations has become a standard benchmark for the application of innovative non-contact systems.

Examples of non-contact sensors successfully employed in the dynamic assessment of stay cables include Laser Doppler Vibrometer (Cunha and Caetano 1999, Mehrabi 2006) and vision-based systems using digital image processing techniques (Ji and Chang 2008). Furthermore, the microwave interferometry has recently emerged as a technology, suitable to remotely measuring the vibration response of large structures (Pieraccini et al. 2004, Gentile and Bernardini 2008, Gentile 2009, Gentile and Bernardini 2010) and, more specifically, of stay cables (Gentile 2010). The new radar technology, based on the combined use of high resolution waveforms (Wehner 1995) and interferometric principles (Henderson and Lewis 1998), was developed in the framework of the Project PARNASO-MATER (2001-2004, funded by the Italian Government), and implemented by the Italian company IDS (Ingegneria Dei Sistemi, Pisa, Italy) in a microwave interferometer, named IBIS-S (Image By Interferometric Survey of Structures).
The paper first describes the radar equipment and its technical characteristics in order to highlight advantages and potential issues of the microwave technology. Subsequently, the application of microwave remote sensing to the measurement of vibrations on the stay-cables of two different cable-stayed bridges are presented and discussed.

2 THE RADAR-BASED MEASUREMENT OF DEFLECTIONS

The microwave-based measurement of deflections consists of two main steps:
1. to employ a radar to take coherent and consecutive images of the investigated structure, with each image being a distance map of the radar echoes intensity coming from the reflecting targets detected on the structure;
2. to compute the displacement of each target by comparing the phase information of the back-scattered electromagnetic waves collected at different times.

At each sampling interval, Stepped Frequency Continuous Waveform (SF-CW, see e.g. Wehner 1995) is adopted to detect the position of different targets placed along the radar line of sight. According to the SF-CW technique, the radar continuously transmits bursts of N electromagnetic pulses, whose frequencies are increased from pulse to pulse by a constant frequency increment \( \Delta f \), so that large effective bandwidth of \( B=(N-1)\Delta f \) is attained. A large value of \( B \) is, in turn, highly desirable since the range resolution (i.e. the minimum distance between two objects along the line of sight, at which they can still be detected individually by the radar) \( \Delta r \) may be expressed as:

\[
\Delta r = \frac{c}{2B}
\]  

(1)

The magnitude of the IDFT of the received echoes at each time sample provides a synthetic image, or range profile, of the scattering objects in the space illuminated by the antenna beam, as function of their relative distance from the sensor. A range profile is simply a 1-D map of the intensity of the received radar echoes in function of the distance of the objects that generated those echoes; in other words, it represents a 1-D map of the scattering objects versus their distances.

It is worth underlining that SF-CW provides only 1-D imaging capabilities, i.e. different targets can be individually detected only if they are separated in range; hence, measurement errors may arise from the multiplicity of contributions to the same range bin, coming from different points placed at the same distance from the radar but not lying on the same axis (Gentile 2009, Gentile and Bernardini 2010).

While the magnitude of the IDFT of the received echoes provides the position in range of the different objects in the scenario, the displacement of each target is evaluated by analyzing the phase of the electromagnetic waves reflected by the targets at different time instants. According to microwave interferometry (see e.g. Henderson and Lewis 1998), two range profiles acquired at different time instants exhibit phase differences depending on the motion of the targets along the radar line-of-sight. Hence, the displacement along the radar line of sight \( d_r \) is simply computed from the phase shift \( \Delta \Phi \) as:

\[
d_r = -\frac{\lambda}{4\pi} \Delta \Phi
\]  

(2)

where \( \lambda \) is the wavelength of the electromagnetic signal. Since the interferometric technique (2) provides a measurement of the displacement along the radar line of sight, the evaluation of the actual displacement requires the prior knowledge of the direction of motion.

The radar technology, based on the combined use of SF-CW and phase interferometry, was implemented in the industrially engineered microwave interferometer (IDS, IBIS-S system) used in this work. The radar equipment (Fig. 1) consists of a sensor module, a control PC and a power supply unit. The sensor module is a coherent radar (i.e., a radar preserving the phase information of the received signal) generating, transmitting and receiving the electromagnetic signals to be processed in order to provide the deflection measurements. The equipment radiates at a central frequency of 17.20 GHz, so that the radar is classified as \( \text{K}_{\mu} \)-band, according to
the standard radar-frequency letter-band nomenclature from IEEE Standard 521-1984. The main technical and operational characteristics of the IBIS-S sensor are summarized in Table 1.

In addition to its non-contact feature, the interferometric radar provides other advantages including the simultaneous monitoring of several targets within the sensor applicable distance, independence of daylight and weather, high accuracy and spatial resolution, portability and quick set-up time. On the other hand, obvious issues are related to the 1-D imaging capabilities, not always easy localization of measurement points (geo-referencing of target points), and relative displacements in line of sight only.

Table 1: Technical and operational characteristics of the microwave interferometer.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum operational distance (with sampling frequency of 40 Hz)</td>
<td>500 m</td>
</tr>
<tr>
<td>Minimum range resolution</td>
<td>0.50 m</td>
</tr>
<tr>
<td>Maximum sampling frequency</td>
<td>200 Hz</td>
</tr>
<tr>
<td>Displacement accuracy</td>
<td>0.02 mm</td>
</tr>
<tr>
<td>System Setup time</td>
<td>10 minutes</td>
</tr>
<tr>
<td>Operative weather condition</td>
<td>All</td>
</tr>
</tbody>
</table>

3 RADAR-BASED MEASUREMENT OF VIBRATION ON STAY CABLES

In order to investigate the global integrity and structural safety of cable-stayed bridges, periodic dynamic measurements on stay-cables are generally aimed at identifying the local natural frequencies, evaluating the tension forces (that are predicted from natural frequencies) and monitoring the changes in these forces over time. If a linear correlation exists between the mode order \( n \) and the corresponding natural frequency \( f_n \) of a cable, the tension force \( T \) in this cable can be obtained from its natural frequencies using the taut string model (Irvine 1981):

\[
T = 4\rho L^2 \left( \frac{f_n}{n} \right)^2
\]

where \( \rho \) is the mass per unit length and \( L \) is the effective length of the cable. For tension members that deviate from a taut string, still the cable forces can be predicted using the identified natural frequencies with reference to more advanced formulations (accounting for the effects of both the sag and the bending stiffness on the dynamic behaviour of cables (Mehrabi 2006).

Application of the radar technique to the measurement of cable vibrations seems especially promising in order to perform systematic dynamic assessment of stay cables in a simple and quick way. Firstly, high accuracy has to be expected from radar-based measurements in terms of both natural frequencies and cable tensions (Gentile 2009, Gentile 2010). Furthermore, the
radar technique provides the deflection time-history of a cable, so that it could be used to directly evaluate the susceptibility of cables to large amplitude oscillations or the efficiency of devices (e.g. external dampers) adopted to prevent excessive vibrations. Finally, the microwave interferometry exhibits in principle some advantages with respect to other techniques of remote sensing, such as: (a) possibility of use also in case of fog or rain and in almost all weather conditions; (b) higher precision of the measured deflections; (c) possibility of simultaneously measuring the response of several cables.

In addition, the possible issues that may occur in the application of the radar technique to bridges and large structures (i.e. 1-D imaging capabilities, geo-referencing of target points and a priori knowledge of the direction of motion), can hardly affect the survey of an array of cables. More specifically:

1. the typical position of the sensor in the survey of an array of cables is inclined upward, as schematically shown in Fig. 2a; hence, the only targets encountered along the path of the electromagnetic waves are the stays itself and 1-D imaging capability is perfectly adequate to the test scenario;

2. it can be assumed that the in-plane motion of the cable is orthogonal to its axis, so that the actual deflection \(d\) can be expressed as:

\[
d = \frac{d_r}{\cos[\pi/2 - (\alpha_c + \alpha_s)]}
\]

where \(\alpha_c\) and \(\alpha_s\) are the slope of the cable and of the sensor, respectively (Fig. 2a). In other words, the prior knowledge of the direction of motion is available for cable systems, so that it is possible to evaluate the actual displacement from the radial one;

3. Fig. 2b shows that it is straightforward to predict the scenario under the radar beam, so that the inspection of the range profile allows to quickly verifying on site that the sensor positioning provides a correct image of the test scenario.

![Figure 2: (a) Displacement along the radar line of sight and actual (in-plane) displacement of a stay-cable; (b) typical range profile expected for an array including two cables.](image)

4. ON SITE APPLICATION TO CABLE-STAYED BRIDGES

4.1 Experimental verification

As previously pointed out, dynamic measurements on stay-cables are often aimed at identifying the local natural frequencies. In order to evaluate the reliability and the accuracy of microwave remote sensing, the radar technique was firstly applied to few stays of a cable-stayed bridge crossing the Adda River (Gentile 2010), simultaneously using piezoelectric accelerometers and the microwave interferometer, with validation purposes. More recently, extensive measurements were performed in operational condition (i.e. under traffic and wind induced excitation) on all stay cables of the curved cable-stayed bridge (Fig. 3) erected in the commercial harbour of Porto Marghera (Venice, Italy), again by using conventional accelerometers and microwave remote sensing.

The cable-stayed bridge belongs to a viaduct, including six spans (42 m + 105 m + 126 m + 30 m + 42 m + 42 m), that generally curves with a radius of 175 m. The two longer curved
spans are suspended by cable-stays from an inclined tower. Elevation, plan and typical cross-sections of the bridge are presented in Fig. 3.

The cable-stayed bridge consists of an inclined triangularly-shaped concrete tower, single-plane cables and a composite deck. The curved deck has a centreline length of 231 m, with two different side spans and 9 cables supporting each side span.

The cast-in-place inclined tower (Fig. 3) is a visually memorable landmark and played a determining role in the conceptual and executive design of the bridge. The tower is about 75 m high and is characterized by a complex geometric layout, where both the base and the height of the triangular cross section are varying along the inclined longitudinal axis.

Figure 3: View, elevation, plan and typical cross-sections of the cable-stayed bridge in Porto Marghera.

Figure 4: Dynamic survey of the array of stay cables on Mestre side: (a) accelerometers and radar position; (b) view of the radar vibrometer on site; (c) range profile of the test scenario.

Fig. 4a shows the accelerometers and radar position in the test of the stay cables on Mestre
The radar was placed at the cross-section of the deck that is vertically supported by the basement of the tower and inclined 55° upward (Fig. 4b); a similar set-up was adopted in testing the array of stay cables of the opposite (Venice) side of the bridge. In both tests, time series of 3000 s were simultaneously collected by the accelerometers and the radar sensor, at rate of 200 Hz.

Fig. 4a also shows the angle of transmission covered by the main lobe of the antenna in the vertical plane, with all the points inside the shadowed area of Fig. 4a being observable from the sensor. It is worth underlining that the sensor transmits electromagnetic waves also in the horizontal plane and that different transmission angles in the vertical and horizontal plane could be obtained by using different antennas. Due to the cone-shaped emission of the sensor, notwithstanding the slightly spatial arrangement of the cables of each array, all the cables are clearly detected and identified in the range profiles. Fig. 4c shows the range profile of the scenario on the Mestre side and is characterized by the presence of nine well defined peaks clearly identifying the position of the stay cables in the array.

Fig. 5 shows the auto-spectral densities (ASD) of the ambient responses acquired, by using the two measurement systems, on the longer cable of the Mestre-side array. Although the ASDs of Fig. 5 are associated to different mechanical quantities measured (displacement and acceleration) and to different points of the stay cable, the spectral plots clearly highlight that:

a) a large number of local resonant frequencies of the cables are identified from radar data and these natural frequencies are in excellent agreement with the ones obtained from accelerometer;

b) the number of frequencies identified from radar data is large enough to establish if the cables behave as a taut string or deviate from a taut string. Hence, accurate estimate of the cable tensions can be retrieved from the identified natural frequencies as well.

It is worth underlining that similar results, in terms of number and agreement of natural frequencies, have been obtained for all the stay cables of the two arrays, with the exception of the two shorter ones (cables 1-2 in Fig. 4a). For the shorter stays, the radar technique detected the lower 3-4 local natural frequencies only, whereas the accelerometers (probably as a consequence of their position) provided a larger number of cable frequencies.

Figure 5: Stay cable 9 on Mestre side: (a) Auto-spectrum of the acceleration data measured by the conventional sensor; (b) Auto-spectrum of the displacement data measured by the radar.

4.2 Dynamic monitoring of the forestays of the cable-stayed bridge crossing the Oglio River

Two ambient vibration tests were carried out on the forestays of the cable-stayed bridge crossing the river Oglio between the towns of Bordolano and Quinzano (Fig. 6a), about 70 km far from Milan. The tests, performed in November 2008 and in November 2009, were aimed at investigating the repeatability of radar survey with SHM purposes.
The investigated bridge consists of a steel-composite deck, double-plane cables and two inclined concrete towers. The deck, 70 m long, consists of a steel grid of 4 girders framed by 12 floor beams; girders and floor beams are all composite with a 30 cm reinforced concrete slab. The cast-in-place concrete towers are 35.65 m high and each consists of an inclined, varying width, concrete leg bearing an upper steel device providing the upper anchorage for the stay-cables; two arrays of 3 forestays and 3 backstays converge at the top of each tower.

The dynamic characteristics of the bridge were well-known since ambient vibration tests were conducted in Spring 2004 by the Vibration Laboratory of L’Aquila University (Benedettini and Gentile 2011) and in July 2007 by the ViBLAB (Laboratory of Vibrations and Dynamic Monitoring of Structures) of Politecnico di Milano; in these tests, 10 global modes of the bridge were identified in the frequency range 0–10 Hz.

The deflection response of the two arrays of cables to wind and traffic excitation was quickly and safely acquired by positioning the microwave interferometer on the basement of the upstream-side and downstream-side tower, as schematically shown in Fig. 6b.

The range profiles of the test scenarios in the two tests are presented in Figs. 7a-b. Since the test scenario on the two sides was practically the same in the two tests, the radar image profiles are very similar and each range profile exhibits three well defined peaks, occurring at the expected distance from the sensor (Fig. 6b) and clearly identifying the position in range of the cables.

For each array, 3000 s of radar data were acquired at a rate of 200 Hz in the two tests; the displacement time-history collected in the last test on stay-cable S2U is shown in Fig. 8.

Fig. 9 shows the ASDs of the deflection response of the upstream forestays. The spectral plots in Fig. 9 are a synthesis of the frequency content present on each cable in the tests performed in 2008 and 2009, and allowed the identification of several local resonant frequencies, marked with the vertical dashed lines, in the frequency range of analysis (0–25 Hz). The inspection of the ASDs in Fig. 9 clearly highlights that:

a) the local natural frequencies of each stay cable are practically equal in the two tests;
b) the natural frequencies of the corresponding cables on the opposite sides (S1U–S1D, S2U–S2D and S3U–S3D, see Fig. 11) are almost equal;

Figure 6: (a) View of the cable-stayed bridge between Bordolano and Quinzano; (b) Elevation view of the radar position in the test of forestays (dimensions in m).

Figure 7: Range profiles of the test scenarios (2008 and 2009) on: (a) upstream side; (b) downstream side.
Figure 8: Deflection measured by the radar sensor in November 2009 on the stay cable $S_{2U}$.

(a) Stay cable $S_{1U}$  
(b) Stay cable $S_{1D}$  
(c) Stay cable $S_{2U}$  
(d) Stay cable $S_{2D}$  
(e) Stay cable $S_{3U}$  
(f) Stay cable $S_{3D}$

Figure 9: Auto-spectra of the displacement data measured by the radar in the two tests of November 2008 and November 2009 on bridge forestays.

Figure 10: Experimental and taut-string based natural frequencies of: (a) upstream-side forestays and (b) downstream-side forestays.

(c) the response of each cable is characterized by a large number of equally spaced and well-defined peaks so that the tension forces can be computed from cable’s natural frequencies using the taut string model (3);

d) the peaks of the ASDs placed at 1.06, 2.18, 4.25 and 6.03 Hz correspond to the global natural frequencies of the bridge, identified in the previous dynamic survey of the structure (Benedettini and Gentile 2011).
The application of the taut string model (3) leads to values of cable tensions summarized in Table 2 and very close to the design values. Finally, Fig. 10 shows how close the experimental resonant frequencies obtained from microwave remote sensing are to the predictions of taut string model.

Table 2: Tensions in the forestays of the cable-stayed bridge obtained from radar measurements.

<table>
<thead>
<tr>
<th>Stay cable</th>
<th>$T(f_1)$ (kN)</th>
<th>$T(f_2)$ (kN)</th>
<th>$T(f_3)$ (kN)</th>
<th>$T(f_4)$ (kN)</th>
<th>$T(f_5)$ (kN)</th>
<th>$T(f_6)$ (kN)</th>
<th>$T(f_7)$ (kN)</th>
<th>Average (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{1U}$</td>
<td>2704</td>
<td>2692</td>
<td>2712</td>
<td>2716</td>
<td>2722</td>
<td>2716</td>
<td>2715</td>
<td>2711</td>
</tr>
<tr>
<td>$S_{1D}$</td>
<td>2655</td>
<td>2654</td>
<td>2671</td>
<td>2670</td>
<td>2674</td>
<td>2662</td>
<td>2657</td>
<td>2663</td>
</tr>
<tr>
<td>$S_{2U}$</td>
<td>2923</td>
<td>2943</td>
<td>2924</td>
<td>2924</td>
<td>2939</td>
<td>2945</td>
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<td>2933</td>
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<tr>
<td>$S_{2D}$</td>
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<td>2982</td>
<td>2949</td>
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</table>

5 CONCLUSIONS

The paper is focused on the application of microwave remote sensing to the measurement of dynamic deflections on the cables of two cable-stayed bridges. The radar technique allows to simultaneously measuring the dynamic response of several stay-cables and provides a powerful and easy-to-use form of systematic and accurate evaluation of natural frequencies and cable tensions. More specifically, the results presented in the paper clearly highlight that:
1. a large number of local resonant frequencies can be identified from radar data on each stay-cable of an array and these natural frequencies seems as accurate as that obtained with conventional accelerometers;
2. in the investigated case studies, the number of frequencies identified from radar data was large enough to establish if the cables behave as a taut string or deviate from a taut string, so that accurate estimate of the cable tensions can be retrieved from the identified natural frequencies as well;
3. the radar survey seems especially suitable to SHM of the stay cables.

Furthermore, microwave remote sensing provides the deflection time-history of a stay-cable and could be used to directly evaluate the susceptibility of cables to large amplitude oscillations or the efficiency of devices (e.g., external dampers) adopted to prevent excessive vibrations.

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