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SHM of Vibrating Stay-cables by Microwave Remote Sensing

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Abstract. A radar equipment was used to measure the deflection response of bridge stay-cables induced by ambient and traffic excitation. After a concise description of the radar equipment and a summary of advantages and potential issues of the microwave technology, the paper focuses on the experimental tests performed on all stay-cables of the curved cable-stayed bridge erected in the commercial harbor of Porto Marghera, Venice, Italy. The bridge consists of an inclined concrete tower, single-plane cables and a composite deck; the curved deck has a centerline length of 231 m, with two different side spans and 9 cables supporting each side span.
Three series of ambient vibration tests were performed (on July 2010, April 2011 and October 2019) on the two arrays of cables of the bridge by using conventional accelerometers and microwave interferometer. The availability of simultaneously collected radar and accelerometer data (which are usually regarded as reference data in dynamic tests) allowed to investigate the accuracy of the radar technique (in terms of natural frequencies and tensile force estimated from natural frequencies) and the errors/uncertainties in radar results. Furthermore, the tests allowed to verify the repeatability of radar survey, with SHM purposes.

Keywords: Dynamic Testing, Microwave Remote Sensing, Radar, Stay-cable, Structural Health Monitoring.

1 Introduction

Microwave remote sensing is probably the most recent experimental technique suitable to the non-contact measurement of deflections on large structures, in static or dynamic conditions (see e.g. [1]). The main ideas of the microwave-based measurements of deflection are: (i) using a radar to take consecutive images of the investigated structure, with each image being built as an intensity distance map of the reflecting targets; (ii) evaluating the displacement response of each target by analyzing the phase of the back-scattered microwaves collected at different times [2].

Structural Health Monitoring (SHM) of cable-stayed bridges often involves periodic dynamic measurements of the stay-cables. The use of accelerometers is commonly employed in this kind of engineering practice because these sensors are very accurate with a relatively low cost. Unfortunately, the installation process is generally not easy, time-consuming and problematic when the bridge is in service and in the case of adverse weather conditions.

Remote sensing by microwave interferometer seems very promising in the SHM of cables because it exhibits various advantages, when compared to other techniques: (a) independence on daylight and weather conditions; (b) high accuracy; (c) possibility of simultaneously measuring the dynamic response of all stay-cables belonging to an array; and (d) simple, quick and safe installation process [3].

The dynamic measurements periodically performed on stay-cables are mainly aimed at monitoring the changes of the natural frequencies over time and, indirectly, at evaluating the evolution of the tension forces estimated from natural frequencies.

Using the taut string model theory, when a linear relationship exists between the mode order n and the corresponding natural frequency f_n of a stay-cable, the tension force T in the cable is calculated by the following [4]:

$$T = 4\rho L^2 \left(\frac{f_n}{n}\right)^2 \tag{1}$$

where ρ is the mass per unit and L is the effective length of the cable. In the case of deviation from the taut string model theory, the tension force T might be estimated by the following relationship [5-6]:

$$T = 4\rho L^2 \left(\frac{f_n}{n}\right)^2 \left[1 + \frac{2}{\xi} + \left(4 + \frac{n^2\pi^2}{2}\right)\frac{1}{\xi^2}\right]^{-2} \tag{2}$$

$$\xi = L\sqrt{\frac{T}{EJ}} \tag{3}$$

where E and J are the Young's modulus and the inertia moment of the stay-cable, respectively.

The paper describes the three series of ambient vibration tests performed in July 2010, April 2011 and October 2019 on the two arrays of cables of a curved bridge by using microwave interferometer and conventional accelerometers (which are usually regarded as reference data in dynamic tests). In Section 2, the analyzed curved cable-stayed bridge in Porto Marghera (Venice, Italy) is described. In Section 3, the experimental investigations are described and the comparison in terms of natural frequencies and tension forces is addressed. Section 4 concludes the paper.

2 The curved cable-stayed bridge in Porto Marghera (Venice, Italy)

The curved bridge is composed by a continuous deck, 387.80 m long and 23.70 m wide. The steel-concrete composite bridge includes six spans (42.80 m, 105 m, 126 m, 30 m, 42 m, and 42 m) with a curvature radius of 175 m and connects the municipality of Venice with the municipality of Mestre. The two largest spans are suspended by 18 cable stays (9 for each span) anchored along the central axis of the deck to the top of concrete tower, transversally inclined and 75 m high (Fig. 1) [8]. The cast-inplace inclined tower is a meaningful landmark of the surrounding landscape, and forms an essential part of the architectonic design of the bridge with its complex geometry, characterized by a triangular cross section that varies along the inclined longitudinal axis.

Fig. 1 Views of the curved cable-stayed bridge in Porto Marghera (Venice, Italy).

3 Ambient vibration tests

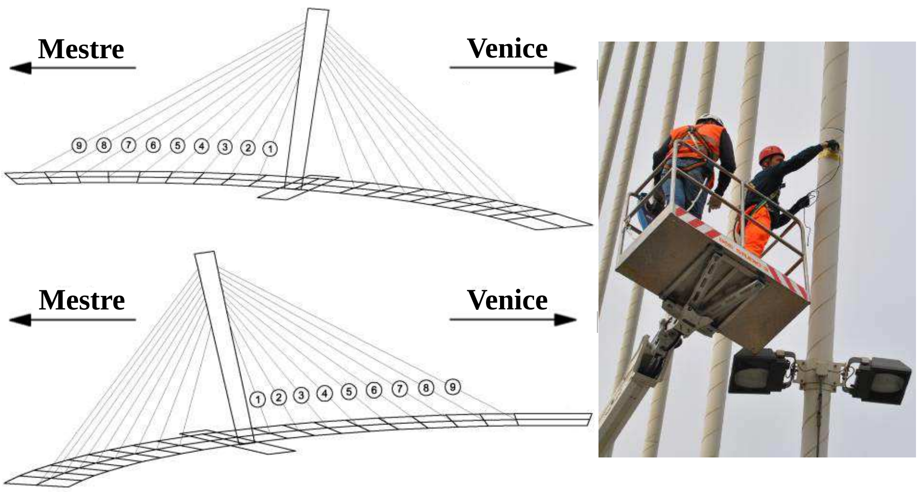
As previously pointed out, the dynamic measurements on the cables were performed to identify the local natural frequencies. In order to evaluate the accuracy and repeatability of the microwaves remote sensing, the radar data was compared with the data simultaneously recorded by the accelerometers. For both accelerometer and radar data, the modal identification was carried out applying the Frequency Domain Decomposition (FDD) technique [8].

Three series of ambient vibration data (July 2010, April 2011 and October 2019) were collected and analyzed in detail for SHM purposes.

In the case of ambient vibration tests by accelerometers, the structural response of the stay-cables to ambient and operational excitation was acquired in eighteen horizontal measuring positions according to the sensors layout shown in Fig. 2a during two different setups (with the first setup involving the Mestre side cables, and the second setup involving the Venice side cables) at an altitude of about 10 m from the bridge deck. For each setup, nine high-sensitivity uniaxial accelerometers (WR 731A, 10 V/g sensitivity and ±0.50 g measuring range) connected to WR P31 power units/amplifiers were used; in turn, each amplifier was wired to a multi-channel acquisition system with 3 DAQ modules (NI 9234, 24-bit resolution, 102 dB dynamic range and anti-aliasing filters). Each stay was instrumented by a unique sensor (Fig. 2b). The structural response was acquired at a sampling frequency of 200 Hz and a sampling time of 3000 s.

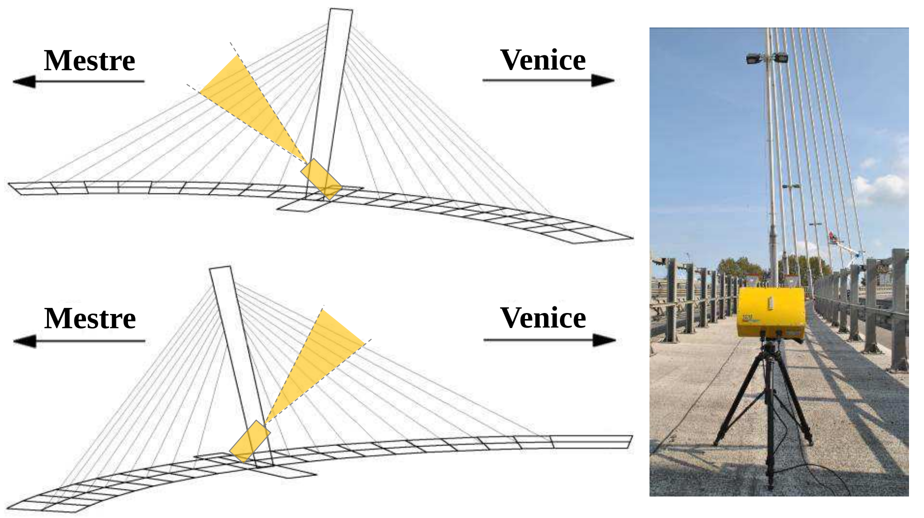
In the case of ambient vibration tests by radar, the structural response of the stay-cables to ambient and operational excitation was acquired in two different setups (Fig. 3a). In each setup, the vibrations of all the stay cables on one array were recorded at the same time. In the first setup, the IBIS-S radar points towards the Mestre side stay cables, in the second setup towards the Venice side stay cables. In both setups, the IBIS-S radar (maximum sampling frequency of 200 Hz, radiofrequency bandwidth of

17.2 GHz, maximum operational distance of 500 m, and displacement accuracy of 0.02 mm) was installed in a central cross-section of the bridge, 12 m from the first cable of each array, with an inclination of 55° upward (Fig. 3a). Finally, the structural response was acquired at a sampling frequency of 200 Hz and a sampling time of 3000 s.



(a) (b)

Fig. 2 Ambient vibration tests by accelerometers: (a) positioning of the accelerometer sensors during the test, and (b) installation process.



(a) (b)

Fig. 3 Ambient vibration tests by radar: (a) positioning of the radar during the test, and (b) radar pointing towards the stay-cables of Venice side.

3.1 Dynamic measurements on stay cables

For sake of brevity, the validation of the results obtained by the microwave interferometer is shown herein for two stay-cables of the bridge only.

Fig. 4 shows the auto-spectra density (ASD) associated to the ambient responses measured in 2019 on stay-cable n. 4 of Mestre side (Fig. 2a) and on stay-cable n. 9 of Venice side (Fig. 2a); each plot in Fig. 4 shows the ASD estimated from both acceleration and displacement data. Even if the ASDs of Fig. 4 are associated to different mechanical quantities (displacement and acceleration) and to different measured points of the cables, the spectral plots clearly show similar results between accelerometers and radar: the frequency content is characterized by nine (see Fig. 4a for stay-cable n. 4 of Mestre side) and fifteen (see Fig. 4b for stay-cable n. 9 of Venice side) well-defined peaks in the frequency range 0-16 Hz, respectively.

It should be noticed that microwave remote sensing generally provides the identification of a large number of cable frequencies and those frequencies are as accurate as those obtained with convention accelerometers. This aspect is crucial in order to establish if the cable behaves as a taut string or deviate from a taut string, and consequently, to accurately estimate the cable tension.

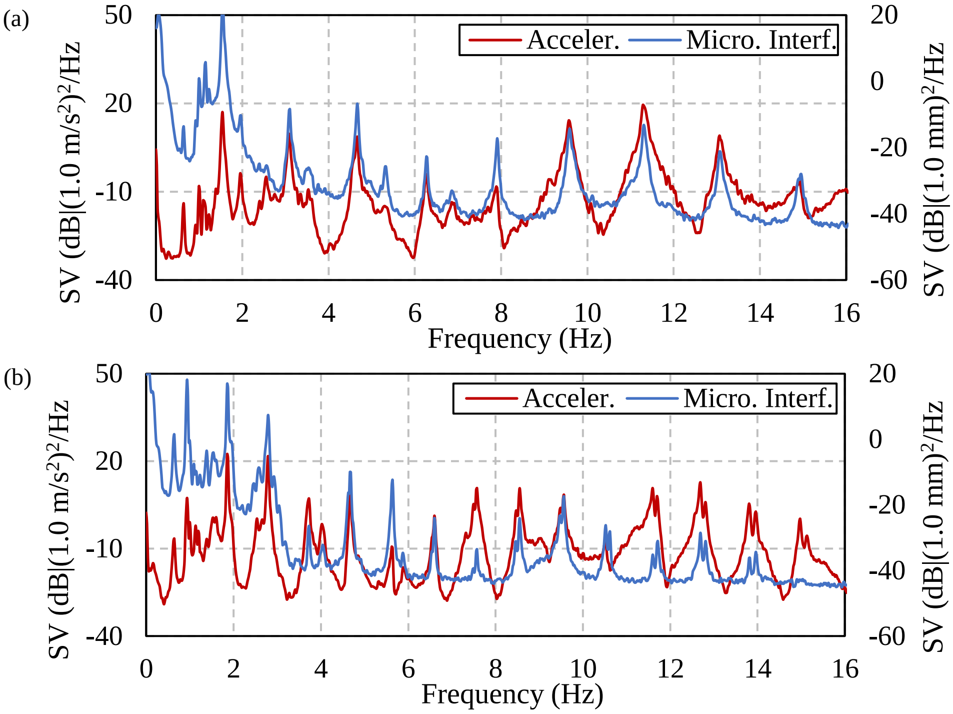


Fig. 4 Auto-spectra of acceleration and displacement data measured in 2019 on: (a) stay-cable n. 4 of Mestre side, and (b) stay-cable n. 9 of Venice side.

Very good results are obtained by the radar for all the stay-cables of the two arrays in all the tests except for the shortest cables (cable n.1 and n.2 of each array). In this case, accelerometers provide a much better identification of the natural frequencies in comparison with the microwave interferometer (Table 1). The reason of this poor performance is probably due to the presence of a worse electromagnetic reflectivity of the protective sheath of the shorter cables and their slope with respect to radar line of sight.

Table 1. Mestre side stay-cables: identified frequencies (2019) from accelerometer and radar data.

Stay-cable	*Sensor type*	f^{2019} (Hz)								
		n=1	n=2	N=3	n=4	n=5	n=6	n=7	n=8	n=9
1	accelerometer	1.191	2.383	3.613	4.961	6.484	8.027	9.727	11.580	13.380
	radar	–	–	–	–	–	–	–	–	–
2	accelerometer	1.211	2.383	3.672	5.020	–	8.086	9.766	11.600	13.550
	radar	–	–	–	–	–	–	–	–	–
3	accelerometer	1.641	3.262	4.883	6.680	8.418	10.210	12.070	14.000	–
	radar	1.641	3.281	4.902	6.699	8.438	10.230	12.090	–	–
4	accelerometer	1.543	3.086	4.668	6.270	7.891	9.570	11.290	13.070	14.900
	radar	1.543	3.105	4.668	6.270	7.910	9.590	11.310	13.070	14.94
5	accelerometer	1.387	2.754	4.160	5.547	7.070	8.555	10.060	11.680	13.300
	radar	1.387	2.773	4.160	5.547	7.109	8.594	10.100	11.680	–
6	accelerometer	1.289	2.578	3.887	5.195	6.504	7.832	9.180	10.570	–
	radar	1.289	2.578	3.887	5.195	6.523	7.852	9.199	10.570	11.970
7	accelerometer	1.250	2.480	3.711	4.941	6.250	7.500	8.770	10.020	11.390
	radar	1.250	2.480	3.711	4.961	6.250	7.500	8.770	10.040	11.390
8	accelerometer	1.094	2.188	3.281	4.395	5.508	6.621	7.715	8.887	10.060
	radar	1.094	2.188	3.301	4.395	5.508	6.641	7.754	8.887	10.040
9	accelerometer	0.957	1.914	2.871	3.828	4.785	5.742	6.738	7.715	8.691
	radar	0.957	1.914	2.871	3.828	4.785	5.742	6.758	7.715	8.711

3.2 Radar interferometer results

In order to investigate the accuracy and repeatability of radar survey, the results of July 2010, April 2011 and October 2019 are compared. Fig. 5 shows the auto-spectra of displacement data measured in 2010, 2011 and 2019 on the stay-cable n. 4 of Mestre side and on the stay-cable n. 9 of Venice side.

Fig. 5 shows a good overlap of the three spectral plots, indicating a high accuracy and repeatability of radar survey over the years (even if not all the dominant peaks are detected in all the setups, see Fig. 5b). The summary of the identified frequencies for the stay-cables n. 4 during the radar experimental investigations of 2010, 2011 and 2019 are presented in Table 2, and frequency variations of less than 1% were found. Furthermore, a slightly increase of all the local natural frequencies in the 2019 tests is observable in the spectral plots of Fig. 5.

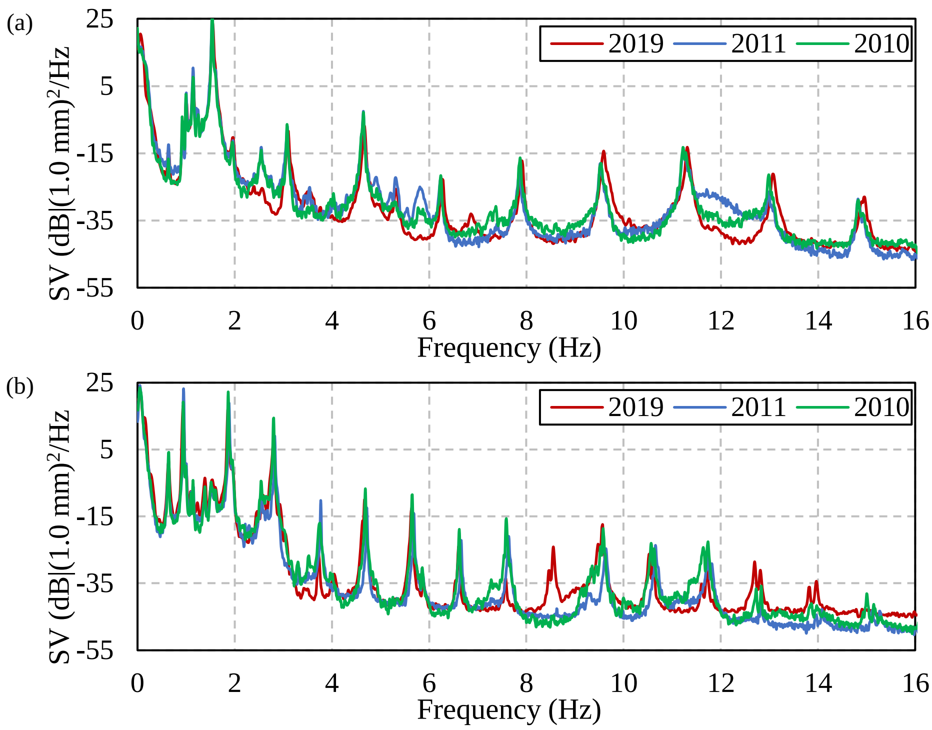


Fig. 5 Auto-spectra of displacement data measured in 2010, 2011 and 2019 on: (a) stay-cable n.4 of Mestre side, and (b) stay-cable n.9 of Venice side.

Table 2. Identified frequencies of the stay cables n.4 (radar data collected in 2010, 2011 and 2019).

	Mestre side					Venice side				
n	f^{2019} (Hz)	f^{2011} (Hz)	Δf_A (%)	f^{2010} (Hz)	Δf_B (%)	f^{2019} (Hz)	f^{2011} (Hz)	Δf_A (%)	f^{2010} (Hz)	Δf_B (%)
1	1.543	1.533	0.65	1.543	–	1.543	1.553	0.65	1.553	0.65
2	3.105	3.076	0.93	3.076	0.93	3.125	3.115	0.32	3.125	0.00
3	4.668	4.648	0.43	4.648	0.43	4.707	4.697	0.21	4.707	0.00
4	6.270	6.240	0.48	6.240	0.48	6.309	6.309	0.00	6.309	0.00
5	7.910	7.861	0.62	7.871	0.49	7.949	7.959	0.13	7.979	0.38
6	9.590	9.512	0.81	9.541	0.51	9.629	9.619	0.10	9.639	0.10
7	11.310	11.230	0.71	11.220	0.80	11.370	11.350	0.18	11.380	0.09
8	13.070	13.000	0.54	12.990	0.61	13.160	13.170	0.08	13.170	0.08
9	14.940	14.820	0.80	14.830	0.74	15.060	15.030	0.20	15.040	0.13

$$\Delta f_A = 100\times \left| (f^{2019} - f^{2011}) / f^{2019} \right|$$
$$\Delta f_B = 100\times \left| (f^{2019} - f^{2010}) / f^{2019} \right|$$

3.3 Estimation of cables tension

The results in terms of identified frequencies (Table 1) allow to conclude that the stay-cables of the bridge slightly deviate from the taut string (Eqn. 1). As an example, Fig. 6 shows the not perfect linear relationship between the mode order *n* and the corresponding natural frequency f_n of the stay-cable n.4 of Mestre (Fig. 6a) and Venice side (Fig. 6b) in the 2010, 2011 and 2019 tests. For this reason, Eqn. 2 was chosen to estimate the cables tension.

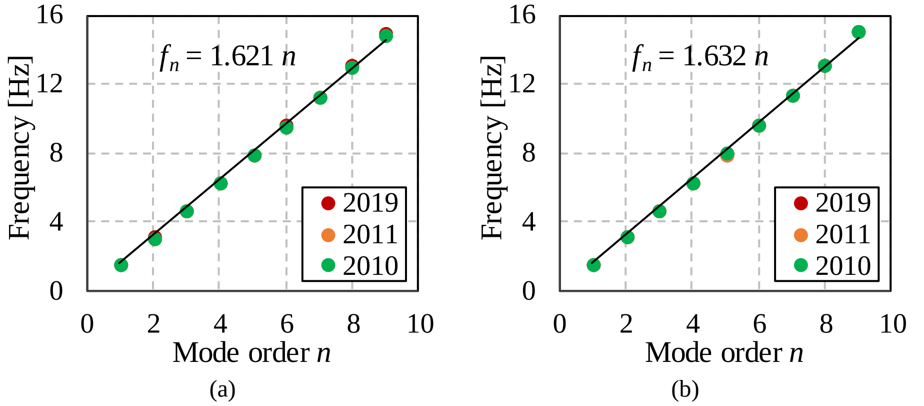


Fig. 6 Relationship between the mode order *n* and the corresponding natural frequency f_n of the stay cable n.4: (a) Mestre side, and (b) Venezia side.

The tension *T* of each cable was determined by minimizing the sum of the squares of the difference between the natural frequencies obtained by experimental tests and the predicted frequencies by Eqn. 2. For each cable, all the experimental identified frequencies were used.

Table 3 shows the cable forces of Mestre side stay-cables calculated by the data collected in 2011 and 2019. The results show a high similarity between the cable forces estimated using radar and accelerometer data and a slightly increase of the tension in 2019 test for the longest cables in comparison with the 2011 tests.

Table 3. Cable forces of Mestre side stay cables (experimental investigations of 2011 and 2019).

	Sensor type	*Mestre side stay-cables*								
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
T^{2019} (kN)	accelerometer	651	1159	2810	4344	4407	4592	5212	5761	5274
	radar	–	–	2767	4358	4351	4617	5222	5769	5274
T^{2011} (kN)	radar	524	925	2778	4222	4336	4532	5132	5761	5122

4 Conclusions

The paper describes the experimental investigation program carried out in July 2010, April 2011 and October 2019 on the cables of cable-stayed bridge in Porto Marghera (Venice, Italy). The dynamic deflections on the cables of the curved bridge were simultaneously measured in operational conditions by microwave remote sensing and traditional accelerometers to verify the repeatability of radar survey with SHM purposes.

The results discussed in the paper allow the following conclusions:

1. the radar technique is able to simultaneously measure the deflection of all the cables in an array, even in the case of a curved bridge;
2. the radar technique allows to establish if stay-cables behave as taut strings or deviate from a taut string;
3. the radar technique is able to identify a large number of natural frequencies for each cable, with an accuracy comparable to the one obtained with conventional accelerometers;
4. the radar technique allows an accurate estimation of the cable forces in operational conditions.

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