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Monitoring Wind and Vibrations at Movable Scaffolding System

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ABSTRACT: This paper reports the work in the context of the SMART_OPS project, which aims to develop a monitoring solution for large movable scaffolding systems (LMSS) with Organic Prestressing System (OPS).
The SMART_OPS project includes 2 sets of monitoring systems installed on a Movable Scaffolding System (MSS) for deck spans up to 70m. The MSS built 12 spans near Bratislava between May 2019 and February 2020. In the first stage, it was used a commercial system to get knowledge of the variables under study with state-of-the-art equipment. In the second stage, a customized monitoring system is under development. The monitoring scheme included 2 sonic anemometers, 29 strain gauges and 3 triaxial accelerometers in the first stage. This paper describes the results obtained with commercial equipment to demonstrate in a full-scale MSS under normal operation the advantages and challenges of monitoring. This first experience was also crucial to define the main characteristics of the customized monitoring system.

KEY WORDS: Movable Scaffolding Systems (MSS); Large MSS (LMSS); Organic Prestressing System (OPS); Structural Monitoring; Operational Modal Analysis (OMA).

1 INTRODUCTION

The construction of prestressed concrete bridge decks with Movable Scaffolding Systems (MSS), a three-dimensional steel lattice structure that supports the formwork, used to construct one entire span of the bridge deck, that additionally has the ability to self-launch between adjacent spans, is typically used in the 40-60 m span range. Until the last few years, bridges with 70-90 m deck spans were usually built with precast solutions, metallic solutions or by balanced cantilever method. However, over the last few years, experiences have been made and new solutions have been developed for the 70-90m span range, usually referred as LMSS – Large MSS [1]. These experiences in large scale MSS were partly supported by the OPS use. The OPS technology is an active control system for static or quasi-static loadings, where prestress cables and hydraulic jacks become part of the structure as structural members [2]. The hydraulic pressure in the jacks is controlled by an algorithm based on the mid-span deflection of the MSS. When the mid-span deflection reaches a predetermined threshold, the OPS algorithm transmits instructions to the hydraulic jacks which compensate the deflection (the algorithm induces force increment with increasing deflection).

Unlike a permanent structure, MSS must undergo several operations with very different characteristics, namely:

- Static phase (usually called Concreting): suspension of the deck concrete weight while the deck is not self-supporting. The concrete weight is substantially bigger than the MSS weight. During this phase the MSS deformation is kept small by the OPS in order to achieve a bridge deck with the desired geometry;
- Movable phase (usually called Launching): movement of the MSS between adjacent spans facing an evolving structural system (the MSS moves above supports that run through the entire MSS length).

This already highly technological MSS machines will be equipped with the SMART_OPS monitoring system that will permit to monitor online the forces transmitted to the supporting structure, the evolution of its response to strong winds and the tracking of its modal properties, with particular attention to the natural frequencies tracking, as a mean to detect structural anomalies and variations along MSS typical working cycle. The data supplied by the SMART_OPS also provides additional information to improve the safety and risk management in bridge construction.

The commercial monitoring system installed on the MSS represented in Figure 1 includes three subsystems, comprising 2 sonic anemometers, 3 triaxial accelerometers, 14 linear strain gages and 5 rectangular rosette strain gages.

Figure 1. Monitored MSS over Danube river with Bratislava on the background [3]

This paper includes preliminary results from the data collected by the anemometers and accelerometers. The accelerometers collected information between 28/04/2019 and

04/03/2020. The anemometers were installed later, operating between 13/09/2019 and 12/02/2020.

2 SENSORS LAYOUT

The monitoring plan included 2 sonic anemometers, one installed near the front end of the MSS (Anemometer 1, see Figure 2) and other installed near the MSS highest point (Anemometer 2, see Figure 2)
The sonic anemometers provided information about 4 variables related with wind and temperature: Wind Speed, Wind Azimuth, Wind Elevation and Sonic Temperature. The anemometers sampling rate was around 28Hz, then adjusted in post-processing to 25Hz to ensure homogeneity. The results from both anemometers are similar, with minor differences in wind speed and wind direction. Therefore, in this work, only the data from anemometer 2 is detailed.

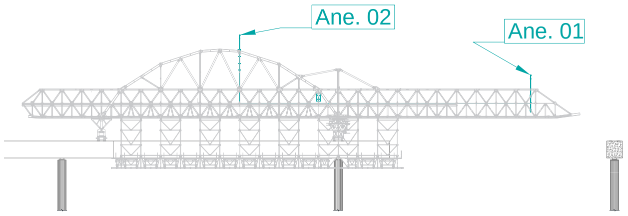

Figure 2. Anemometers positions

The mean wind speed for 10-minute periods reached a maximum of 16.6m/s on 04/02/2020 between 9:20 and 9:30 GMT (see Figure 3).

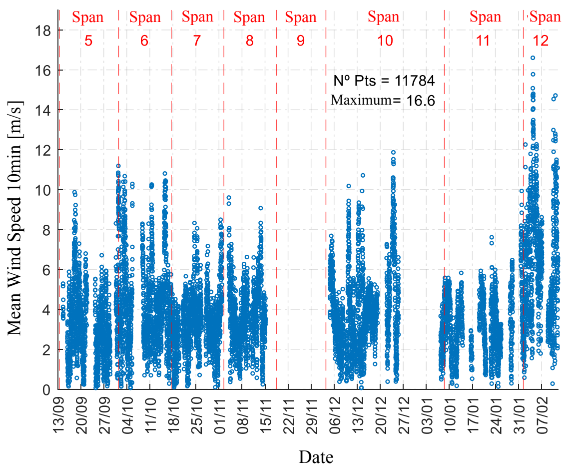

Figure 3. Mean wind speed for 10-min periods

The wind data did not change significantly from span to span, which was expected, because the distance to the ground and the surroundings are similar for all spans. This paper does not account for these minor differences between spans.

The wind occurred in several plan directions, from which 3 were preponderant (see Figure 4). The most frequent direction, around 70º with the North, is the one with lower wind speeds. This direction is nearly the direction of the bridge deck and is possible that this wind direction is related with the preparation for bridge construction (the tree removal in the deck alignment created a channel of wind).

The most relevant direction is around 330º with North. This direction combines the highest speed winds and a direction nearly perpendicular to the MSS, which is usually the critical direction for the MSS (the exposed area to transversal winds is significantly higher than for vertical and longitudinal winds).

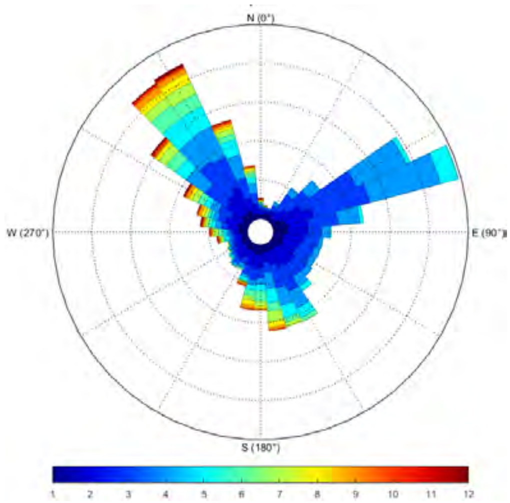

Figure 4. Mean wind speed for 10-min periods

2.1 Accelerometers

After some analyses on the MSS numerical model to find the most suitable positions for the accelerometers, an ambient vibration test was performed onsite on a similar MSS (the viaducts on both sides of the bridge were built by similar MSSs). Finally, the elected positions include one at the tip of the front cantilever (102), one near the middle of central span (103) and one at one-third of central span (104) (see Figure 5).

Each of the 3 points is instrumented with a triaxial accelerometer measuring with a sampling rate of 50Hz (longitudinal, transversal and vertical accelerations were recorded).

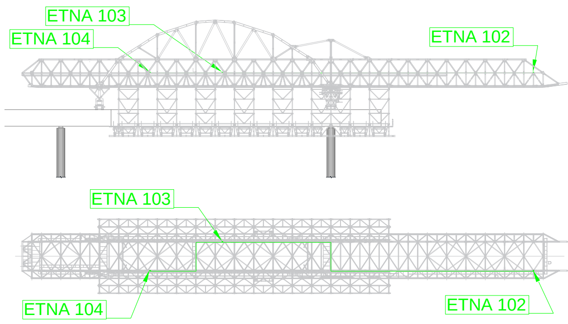

Figure 5. Accelerometers positions

3 VIBRATION LEVELS

The vibration levels of the MSS along the bridge deck construction are very inconstant, depending essentially on the existence and magnitude of the most important sources of excitation. The most important sources are the work onsite, the wind, foundation microtremors and water movement on the Danube river. The work on the MSS is particularly relevant for the vibration level, being possible to identify even the working hours, the lunch and middle-morning breaks and the change from daylight saving time to standard time on 27/10. In Figure 6 it is represented the RMS of the vertical accelerations for periods of 5 minutes, as a function of the date (in the horizontal axis) and the GMT hour (in the vertical axis). The areas in red are associated with higher accelerations.

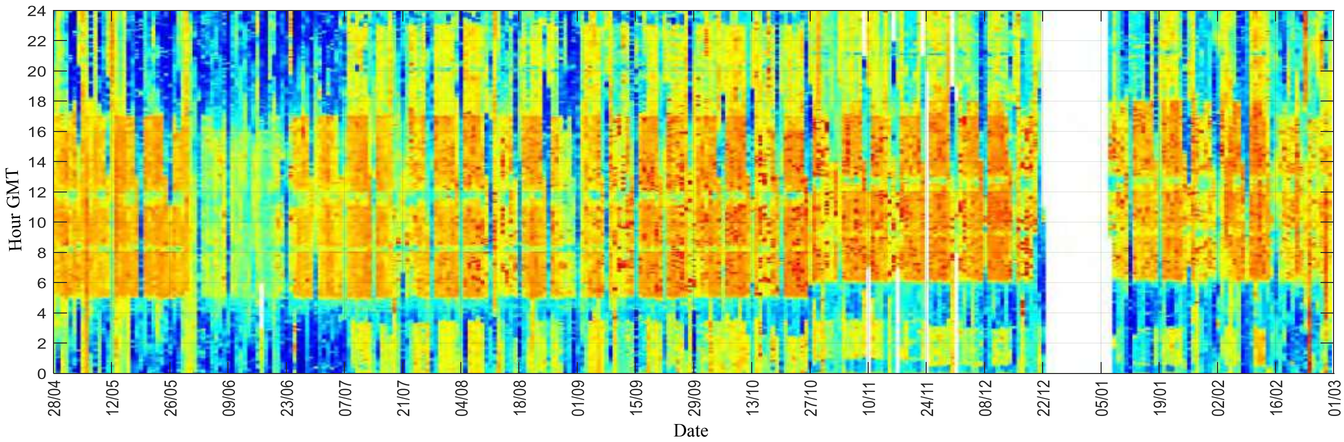

Figure 6. Vibration levels on the MSS during the bridge construction (the vibration level increases from blue to red)

The wind also plays a vital role in the excitation of the MSS. The acceleration response to wind is governed by buffeting (see Figure 7). Since it is much more flexible, the influence of wind on the front cantilever (Etna 102, see Figure 5) is higher than on the central span (Etna 103 and Etna 104, see Figure 5).

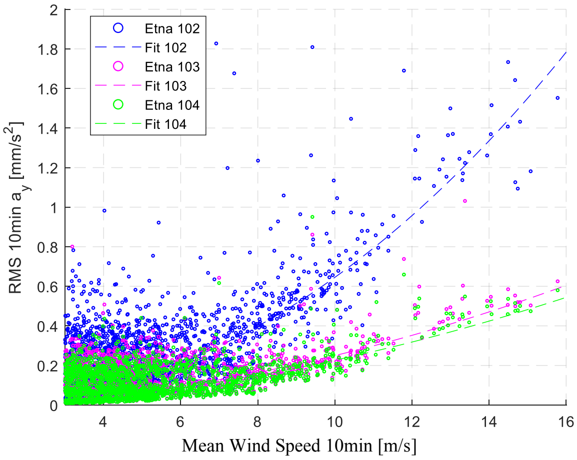

Figure 7. Relation between mean wind speed and the RMS of transversal acceleration, both for 10 minute periods

4 AMBIENT VIBRATION TESTS

For comparison with the numerical model and to obtain a higher spatial definition of the modes, an ambient vibration test was performed during the construction of the 5th deck span. The Etna 102 on its original position was used as reference during all setups (see Figure 5). All other points of the MSS (represented in blue in Figure 9) and the points on the bridge deck (represented in magenta in Figure 9) were instrumented only in 1 setup.

For modal identification, it was used the peak picking method. The averaged normalized spectrum (ANPSD) for transversal and vertical directions is represented in Figure 8 for all points (in green), for the points on the MSS (in blue) and for the points on the bridge deck (in magenta).

On the spectrum associated with the points on the MSS (blue line) 9 peaks were identified, marked by red lines in Figure 8.

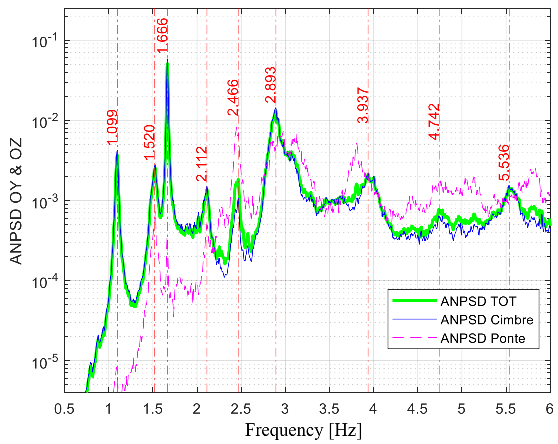

Figure 8. ANPSD for transversal and vertical directions

The more prominent peaks are related with the front nose modes, the peak with frequency around 1.099Hz with transversal bending and torsion of the nose (see Figure 9 on the left) and the frequency around 1.666Hz with the vertical bending of the front nose (see Figure 9 on the right).

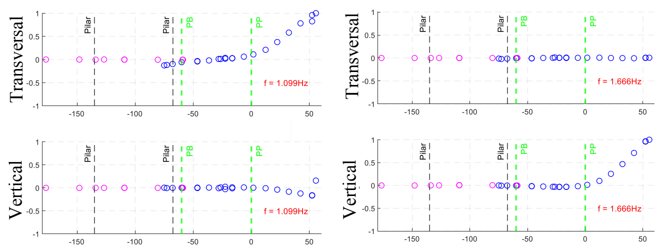

Figure 9. Mode shapes for f=1.099Hz (on the left) and f=1.666Hz (on the right)

5 MODAL IDENTIFICATION

After removal of long-term trends and decimation to 25Hz, each one-hour transversal and vertical time series were subjected to a modal identification process using the Enhanced Frequency Domain Decomposition method (EFDD) [4].

Since the modes are well-spaced, it was considered only the 1st singular value of the decomposition. The peaks of the spectra were grouped into modes with similar characteristics (frequency, damping and modal configuration) and compared with the modes obtained with the ambient vibration test. The more relevant modes are included in Figure 10.

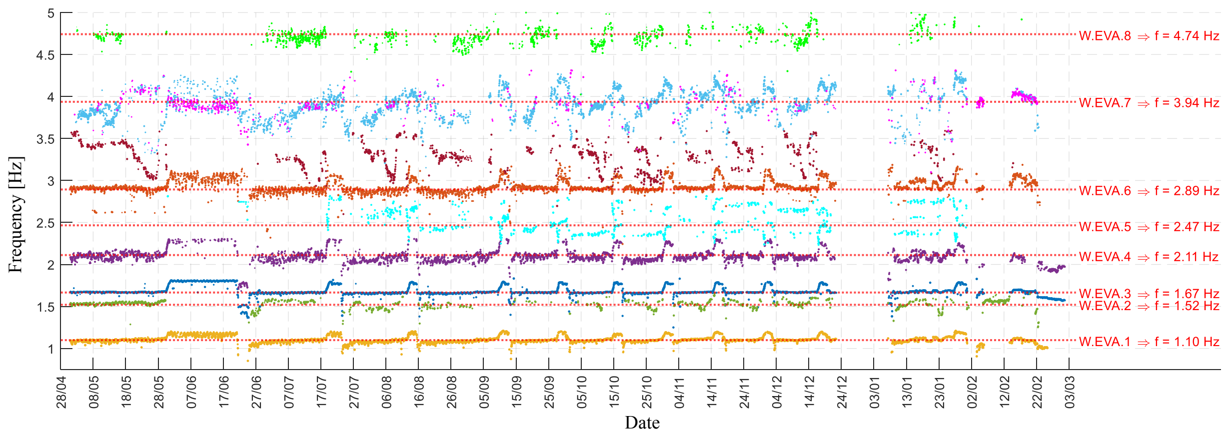

Figure 10. Identified modes using EFDD grouped by color and compared with ambient vibration tests (in red, on the right)

The natural frequencies identified with the ambient vibration test (numbered from W.EVA.1 to W.EVA.8 on Figure 10) and afterwards with the continuous monitoring data are nearly the same.

The modal configurations obtained with EFDD are compared with the ones estimated with the ambient vibration tests in Figure 11. Figure 11 includes the information presented in Figure 9, together with the results delivered by the EFDD method (in red). The outcomes from both methods agree.

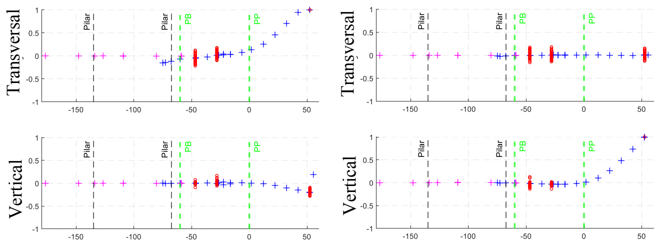

Figure 11. Mode shapes for f=1.098Hz (on the left) and f=1.668Hz (on the right)

The mean characteristics of the modes identified with EFDD are detailed in Table 1. Comparing the mode characteristics, 5 of the modes identified recurrently by the EFDD were also identified with the ambient vibration test:

- FDD.1 ≈ W.EVA.1
- FDD.2 ≈ W.EVA.2
- FDD.3 ≈ W.EVA.3
- FDD.4 ≈ W.EVA.4
- FDD.6 ≈ W.EVA.6

Table 1. Modes identified with EFDD.

Modo	Freq. [Hz]	ξ [%]	Modal Configuration					
			102_OY	103_OY	104_OY	102_OZ	103_OZ	104_OZ
FDD.1	**1.098**	0.91%	1.00	0.00	-0.06	-0.19	-0.01	0.00
FDD.2	**1.538**	0.28%	0.14	0.90	1.00	0.00	-0.02	0.02
FDD.3	**1.668**	0.27%	0.01	0.00	0.00	1.00	-0.03	-0.02
FDD.4	**2.089**	1.46%	-0.26	0.21	-0.11	1.00	-0.01	0.01
FDD.5	**2.517**	0.84%	0.06	-0.02	-0.01	1.00	0.36	0.38
FDD.6	**2.911**	0.87%	0.80	-0.35	-0.07	1.00	0.10	-0.05
FDD.7	**3.296**	1.36%	0.04	-0.05	-0.02	0.98	1.00	0.71
FDD.8	**3.906**	2.12%	1.00	0.21	0.28	0.29	0.00	0.00
FDD.9	**3.927**	2.36%	1.00	0.29	0.37	0.59	0.04	0.01
FDD.10	**4.713**	2.65%	0.39	0.10	0.64	1.00	-0.01	-0.03

The other modes identified with the ambient vibration tests have also a correspondent mode on the continuous monitoring, but their appearance is not so frequent, eventually because they are related with specific conditions of excitation or particular conditions of the MSS.

6 CONCLUSIONS

The monitoring system installed on the MSS consisting on anemometers and accelerometers proved successful on collecting information on wind characteristics and on modal identification of the main modes in the [0 5Hz] frequency range. The use of peak peaking and EFDD methods revealed similar results, parametric methods for more robust tracking of the modal properties are under implementation.

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