INTERNATIONAL SYMPOSIUM CONSTRUCCIONS - STRUCTURES

Title
Operational Modal Analysis of railway bridge km. 9578, track “La Ceniza”, Santa Clara, Cuba

Título
Análisis Modal Operacional del Puente ferroviario km. 9578, vía “La Ceniza”, Santa Clara, Cuba

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Abstract: This paper deals with the structural monitoring of the steel railway bridge km. 9578, via "La Ceniza", Santa Clara, Cuba, in the framework of the international collaborative project TEAM-VLIR "Vibration-based evaluation of civil engineering structures (VIBRAS)" between the Catholic University of Leuven, UCLV and CUJAE. It describes the acceleration measurements on the bridge girders. The objectives of the vibration measurements are to validate a bridge model, by updating the model, and the identification of bridge damage, although this work does not include these applications.

The measurement system and vibration measurements were performed in March 2019, by a team consisting of KU Leuven professors from the Department of CE Guido de Roeck, Geert Lombaert, and Kristof Maes, UCLV professors, CUJAE, Civil Engineers from the Centre Bridge Testing Station. The paper describes the sensor configuration for the measurements and the results of the operational modal analysis, including the measurement process, the main data acquisition, the system identification for the 5 configurations, and the results of the developed identification procedures and the identified modal parameters, as well as the main conclusions derived from that process.

Resumen:
En el presente trabajo se aborda el monitoreo estructural del puente ferroviario de acero km. 9578, vía "La Ceniza", Santa Clara, Cuba, en el marco del proyecto de colaboración internacional TEAM-VLIR "Evaluación de estructuras de ingeniería civil basada en vibraciones (VIBRAS)" entre la Universidad Católica de Leuven, la UCLV y la CUJAE. En el mismo se describen las mediciones de aceleración en las vigas del puente. Los objetivos de las mediciones de vibración son validar un modelo de puente, mediante la actualización del modelo, y también la identificación de daños en el puente, aunque este trabajo no incluye estas aplicaciones.
El sistema de medición y las mediciones de vibración se realizaron en marzo de 2019, por un equipo compuesto por los profesores de la KU Leuven del Departamento de CE Guido de Roeck, Geert Lombaert, y Kristof Maes, profesores de la UCLV, CUJAE, Ingenieros Civiles de la Estación Comprobadora de Puentes del Centro. En el trabajo se describe la configuración de sensores para las mediciones y los resultados del análisis modal operativo, el proceso de medición, la adquisición de datos principales, la identificación del sistema para las 5 configuraciones, y los resultados de los procedimientos de identificación desarrollados y los parámetros modales identificados, así como las principales conclusiones derivadas de dicho proceso.
Keyswords: Modal Analysis, bridge structural monitoring, system identification, parameter estimation, sensor configuration, vibration measurements.

Palabras Claves: *Análisis Modal, Monitoreo estructural de puentes, identificación de sistemas, Estimación de Parámetros, configuración de sensores, mediciones de vibración.*

1. Introduction

This report describes monitoring and modal analysis processes: setups, field data acquisition, signal processing, system identification and parameter estimation for several applications (model updating and damage identification) of steel railroad bridge km. 9578, track "La Ceniza", Santa Clara, Cuba (see Fig. 1.1), in the frame of TEAM-VLIR project "Vibration-based assessment of Civil Engineering Structures (VIBRAS)" (project ZEIN2016PR419-01 funded by Flanders Inter-university Council VLIR, 13/03/2016 – 31/12/2019). They consist of acceleration measurements on the bridge girders, strain measurements at the bridge girders flange plates. Aims of the vibration measurements are to validate a bridge model, via model updating, and also bridge damage identification.

Installation of measurement system and vibration measurements were performed on March 2019, by a team composed of KU Leuven Professors of CE Department Guido de Roeck, Geert Lombaert, and Kristof Maes, professors of UCLV

This report describes the measurement setups and the results of the operational modal analysis.

Fig. 1 General overview of the bridge "La Ceniza".

Principal bridge characteristics are summarized in Table no. 1.

Table 1 Principal bridge characteristics

Year of Construction:	1906
Type of bridge:	Steel (Top desk).
Bents:	Edge walls
Piles:	-
Total length:	19.20m.
Number of spans:	one
Distance between axes:	2.14 m
Type of sleepers:	Mexican hardwood and Russian pine.
Total number of sleepers:	64 u
Type of lanes:	Main P-50
Guard-rail and Guards:	80 lb./y
Section to which it belongs:	Santa Clara Station – "La Ceniza".
Mass of the Bridge	47.32 ton.
Supports	Pinned at Santa Clara side, simple supported in "La Movida" side.
Coordinates of Center of Mass	$X_{CM} = 9{,}21\ m, \quad Y_{CM} = 1{,}524\ m, \quad Z_{CM} = 1{,}183\ m$

2. Methodology

The measurement system consists of the following components:

Table 2 Equipment and items used during measurements

No.	Item	Qt.	No.	Item	Qt.
1	8 slot data acquisition unit (NI cDAQ 9188)	1	9	Large impact hammer (PCB 086D50)	1
2	4 channel ICP DAQ module (NI 9234)	4	10	Low noise microdot to BNC cable 6 m	12
3	4 channel strain DAQ module (NI 9237)	2	11	Military pin to BNC cable 3 m	12
4	Power generator 7000 W	1	12	1 slot data acquisition unit (NI cDAQ 9171)	1
5	Computer with Labview and Matlab	2	13	Low sensitivity accelerometers (PCB 353B34)	4
6	Coaxial extension cables 50 m + reel	16	14	Strain gauge connector blocks (100 PCS/box)	1
7	Magnets ITN-25	15	15	Strain gauge installation kit (+ box)	1
8	High sensitivity accelerometers (PCB 393B12)	10	16	Strain gauge cable (150 m)	4

Measurement Process

This section shows the initial configuration (Fig. 2) proposed to perform the measurement. The following shows how that initial proposal was adapted for the construction of the bridge geometry using the Beams command in MACEC 3.3. Figure 2 provides an overview of the measurement setups.

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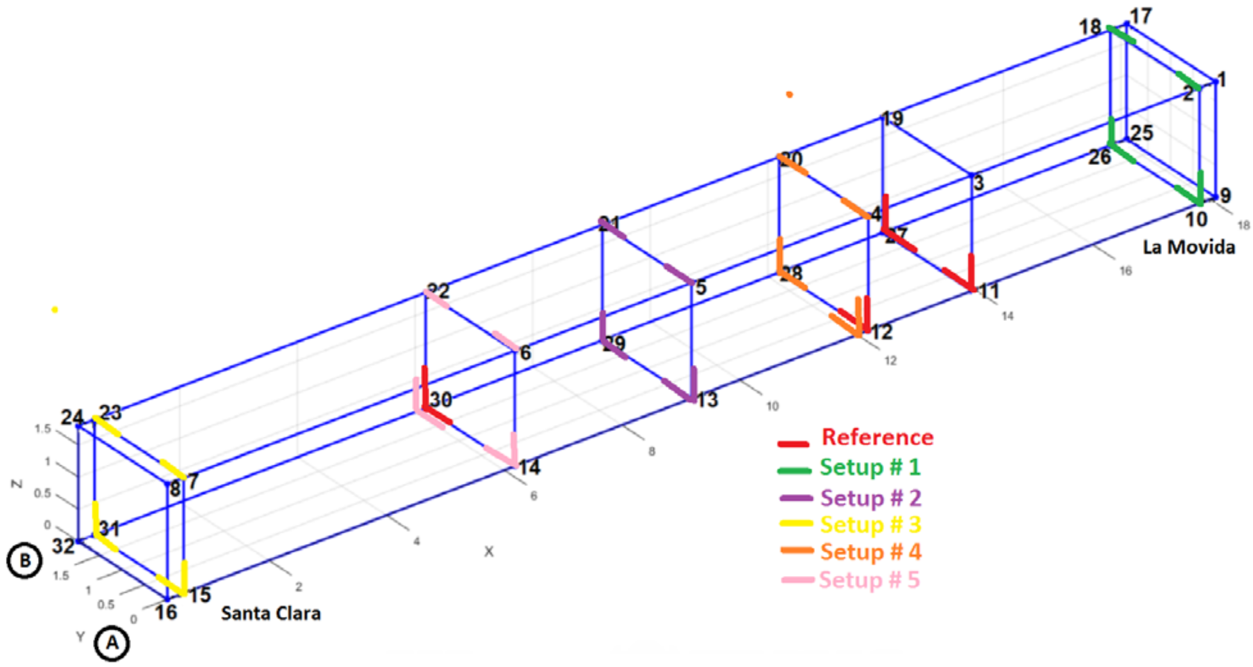

Figures 2 Overview of the measurement setups

In order to obtain dynamic parameters (natural frequencies, mode shapes and damping ratios) of the study case selected: railroad bridge "La Ceniza", two types of measurements were performed: 1) Operational modal analysis (OMA), performed using ambient excitation and only structure output was measured. 2) Experimental modal analysis (OMAX) of the structure, performed using field hammer excitation, imposed vertically and horizontally along the Y-direction and Z-direction, at the top and bottom of the two beans of the structure.

The response of the structure to the hammer/ambiance excitations is measured using accelerometers at each position, using 5 setups per each direction of hammer excitation hitting. During OMA and OMAX measurements, 14 acceleration channel were used. After processing, results were combined with the multi-setup techniques.

In order to obtain static (strains), one types of measurements were performed, strain measurements using strain gauges located at several positions at the top and the bottom flanges of bridge beams.

Data acquisition

This section describes the data acquisition process by the (NI) cDAQ 9181 USB chassis, in combination with LabVIEW by means of the NI-DAQmx drivers. The different modules of the cDAQ chassis are synchronized in LabVIEW by means of drivers. In the time synchronization, one of the NI 9234 modules is chosen to provide the time reference. This module exports its internal sample clock to be used by the other modules. The internal sample clock is equivalent to the data rate configured for the NI 9234 reference module and in this case, corresponds to a sampling frequency $f_s = 1651.6\,Hz$. The corresponding Nyquist frequency is 825.8 Hz.

The data are stored in a file with a duration of 5 minutes each. In order to avoid problems with disk access, the data acquisition and the data storage are split up in LabVIEW by using two separate loops that are connected using a queue. The data obtained from the data acquisition are stored in a RAM memory queue, which allows LabVIEW to store these data at the fastest possible rate, without jeopardizing the data acquisition by possible delays in the disk access.

The acceleration measurements on the bridge are performed by means of ten uniaxial accelerometers of type PCB 393B12. The channels labels are denoted by ***#-β-γ***, where # refers to the number of the measurement axis along the longitudinal direction (1-14, Fig. 2), β refers to the label of the measurement line along the lateral direction (A or B, Fig.3), and γ refers to the measurement direction (x, y or z). The sensors are installed at the bottom and top of the main bridge girders. Twelve accelerometers measurement the motion of the bridge in the vertical (z) direction and twenty-two accelerometers measurement the motion of the bridge in the vertical (y) direction. Accelerometers for measurements in vertical direction (z) were installed just at the bottom of the main girder. Unlike, accelerometers for measurements in horizontal direction were installed at the top (10) and at the bottom (12) of the main girder. (See Fig. 2). The accelerometers were connected to the structure using a pot magnet.

In addition, all the information for the setup 1 is summarized in Table 3. In total, 34 different positions, for the 5 setups (4 others not showed) is shown, including:

- ✓ Setup number
- ✓ Setup designations proposed by Belgian Professors
- ✓ Channel numbering and designation for reference (R) or hammer (H) position
- ✓ Accelerometer number
- ✓ Node and direction
- ✓ Last three columns for node coordinates, in meters.

Table 3: Position of accelerometers and reflectors by setup

Setup No.	Designation	Channel(CH) / Ref.	No. Accel.	Dir/ Node	X (m)	Y (m)	Z (m)
1	6-A-By	1 / R	601	+Y/12	12.191	0	0
	6-A-Bz	2 / R	609	+Z/12	12.191	0	0
	9-B-By	3 /R	610	-Y/30	6.179	1.975	0
	9-B-Bz	4 / R	611	+Z/30	6.179	1.975	0

2-A-By	5	622	+Y/10	17.82	0	0
2-A-Bz	6	623	+Z/10	17.82	0	0
2-A-Ty	7	624	+Y/2	17.82	0	1.798
2-B-By	8	625	-Y/26	17.82	1.975	0
2-B-Bz	9	657	+Z/26	17.82	1.975	0
2-B-Ty	10	658	-Y/18	17.82	1.975	1.798
5-A-By, 5-A-Bz, 5-B-By, 5-B-Bz	11 / H	HAMMER	**	**	**	**
5-A-By	12 / R	A226	+Y/11	13.951	0	0
5-A-Bz	13 / R	A305	+Z/11	13.951	0	0
5-B-By	14 / R	A923	-Y/27	13.951	1.975	0
5-B-Bz	15 / R	A925	+Z/27	13.951	1.975	0

System identification

The signals are processed with MACEC 3.3 (Reynders, Schevenels, et al. 2014) and using the reference-based stochastic subspace identification (SSI-ref) algorithm (Peeters and De Roeck 2001). Half the number of block rows in the correlation matrix is taken as 300. For the construction of the stabilization diagram, a model order range from 2 to 120 in increments of 2 was considered. Nine accelerations outputs are employed as reference outputs in the algorithm.

At this stage a series of adjustments are made in all setups:

- ✓ The double-sided PSD parameters are adjusted for 66% corresponding to a 33% overlap with the immediate upper and lower frequencies.
- ✓ A time adjustment is made in the (Time Window) to discard the initial and final times where there was no excitation or the damping was over. The time intervals used are shown in table 4.

Table 4 Time intervals applied to the original signal by “Time-Window”

Setup	1	2	3	4	5
Time windows applied to the original signal	0 s - 352.6 s (not required)	50 s - 220 s	220 s - 412 s	(not required)	(not required)

- ✓ A decimate factor equal to 20 is applied, its operation is to filter the low frequencies of the data and resample them at a lower rate. The Decimate Factor (DF) is calculated by the expression:

$$DF = 0.4 \times \frac{f_s}{f_{máx}} = 0.4 \times \frac{1651}{33} = 20$$

Where fs = 1651 Hz which is the sampling frequency, $f_{máx}$ = 33 Hz is the highest expected frequency to identify, which corresponds to mode 60 of the model.
This maximum frequency is obtained from displaying the frequency content of the PSD of the channel signal, and from displaying the frequency of the highest mode that is expected to be identified from a finite element model performed in SAP 2000.

- ✓ A "remove offset" command is applied then, for all channels of the 5 setups, with signal shifting.
- ✓ Later it is decided to eliminate the corresponding channels in each of the setups. This step will be shown individually in the processing of each setup.
- ✓ It was not necessary to remove the electricity peaks at 60 Hz,

The next step is to add the degree of freedom (DOF), where the lateral directions (Y) are positive for all accelerometers at nodes from 1 to 16 and negative for nodes from 17 to 32. In the case of vertical directions (Z), they are all positive since in all setups the sensors were placed in the bottom.

The next step is to select the identification method, for which we take the SSI (Stochastic Subspace Identification) since it is a type of operational modal analysis (OMA). The details of each setup are shown separately.

During the processing of this setup the following channels were eliminated:

- ✓ Delete ch_4(Acc # 611, reference),
- ✓ ch_11(Hammer),
- ✓ ch_12,13,14,15(low sensivity accelerometers).

Figure 3 shows the time history of the signal and was transformed into the frequency domain for channel n. ° 1, a process which was performed for the nine channels of this setup.

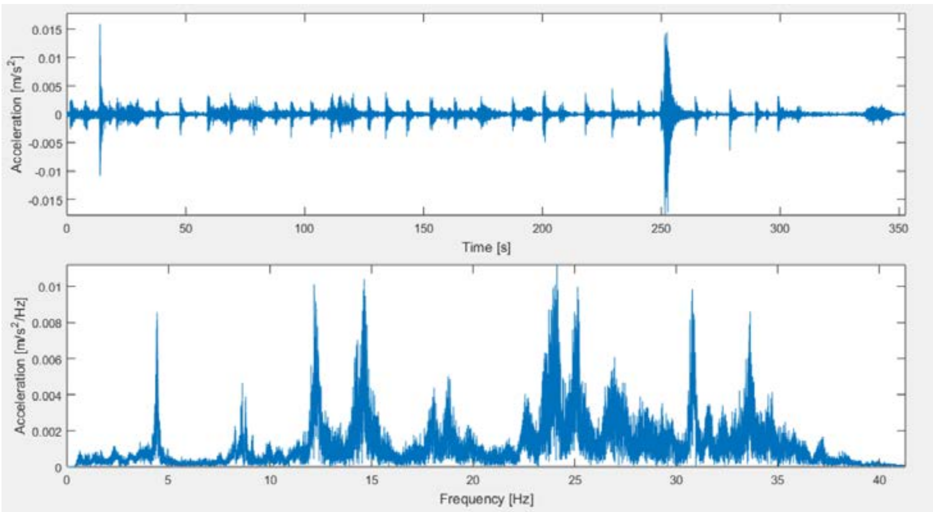

Fig. 3: Time history of the signal and transformed to the frequency domain for channel 1

After performing this procedure for the nine channels, the following degrees of freedom (DOF) were added to the nodes and addresses indicated in Table 5.

Table 5: DOF for setup # 1		
No. channel	Direction	Node(MACEC)
Ch_1	Y(+)	12
Ch_2	Z(+)	12
Ch_3	Y(-)	30
Ch_4	Y(+)	10

Ch_5	Z(+)	10
Ch_6	Y(+)	2
Ch_7	Y(-)	26
Ch_8	Z(+)	26
Ch_9	Y(-)	18

After selecting the SSI (stochastic Subspace Identification) identification method, the modal analysis was performed with MACEC allowing the stabilization diagram and the PSD to be displayed for this setup (see Fig. 4)

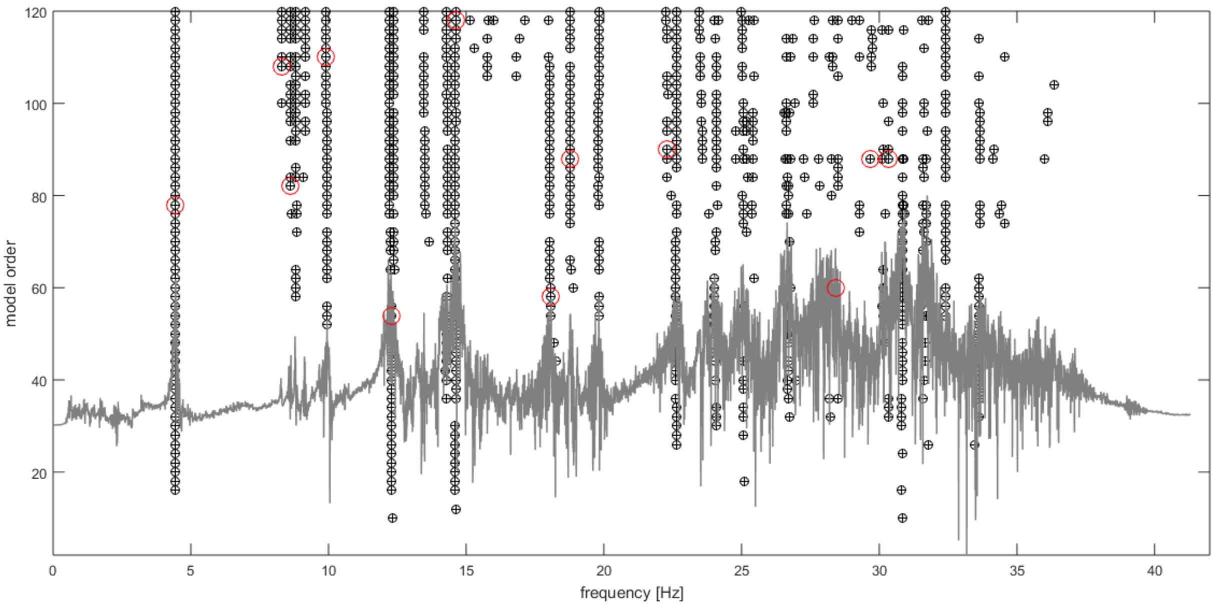

Fig. 4: Stabilization diagram and PSD for Setup 1

After performing for this setup the System Identification and Modal Analysis are summarized in table 6: natural frequencies, MPD(mean phase deviation), MP(mean phase), MPC(modal phase collinearity) and modal damping ratios.

Table 6: Identified modes data (setup 1)					
No.	Frecuency	MPD [°]	MP[°]	MPC[−]	Damping(%)
1	4.42837	1.3332	0.070278	0.99914	0.62976
2	8.30379	4.19	0.042028	0.98594	0.41879
3	8.62379	1.6419	-0.38142	0.99763	0.59041
4	9.91922	3.3987	-1.9464	0.98767	0.87207
5	12.2765	1.5548	0.26956	0.99835	0.83573
6	14.6166	0.37062	-0.05981	0.99988	0.82017
7	18.059	4.3046	-6.7956	0.97406	1.0142
8	18.7683	5.4886	0.6016	0.96457	0.7583
9	22.2807	5.3326	-0.46959	0.97085	0.87172
10	28.4318	3.9953	0.27117	0.98294	0.35369
11	29.6607	6.3398	-0.45931	0.94054	0.74246
12	30.3215	5.2792	2.2057	0.96754	0.68544

The process described above was repeated for all setups.

3. Results and Discussion

This section presents all the preparation of the results obtained in the System Identification stage with the verification of the modal assurance criterion (MAC). It also shows all the necessary programming in Matlab to combine the Setup and show the modal shapes corresponding to the identified modes.

Verification using Modal Assurance Criterion (MAC)

To verify the correspondence between the modal coordinates of the same supposed mode of one setup with respect to the modal coordinates of the same mode in another setup, MAC criterion was used. In addition, this comparison was made between (setup 1 and setup 3), (setup 1 and setup 4) and (setup 1 and setup 5). The MAC graphics for all comparisons are shown below (See Fig. 6).

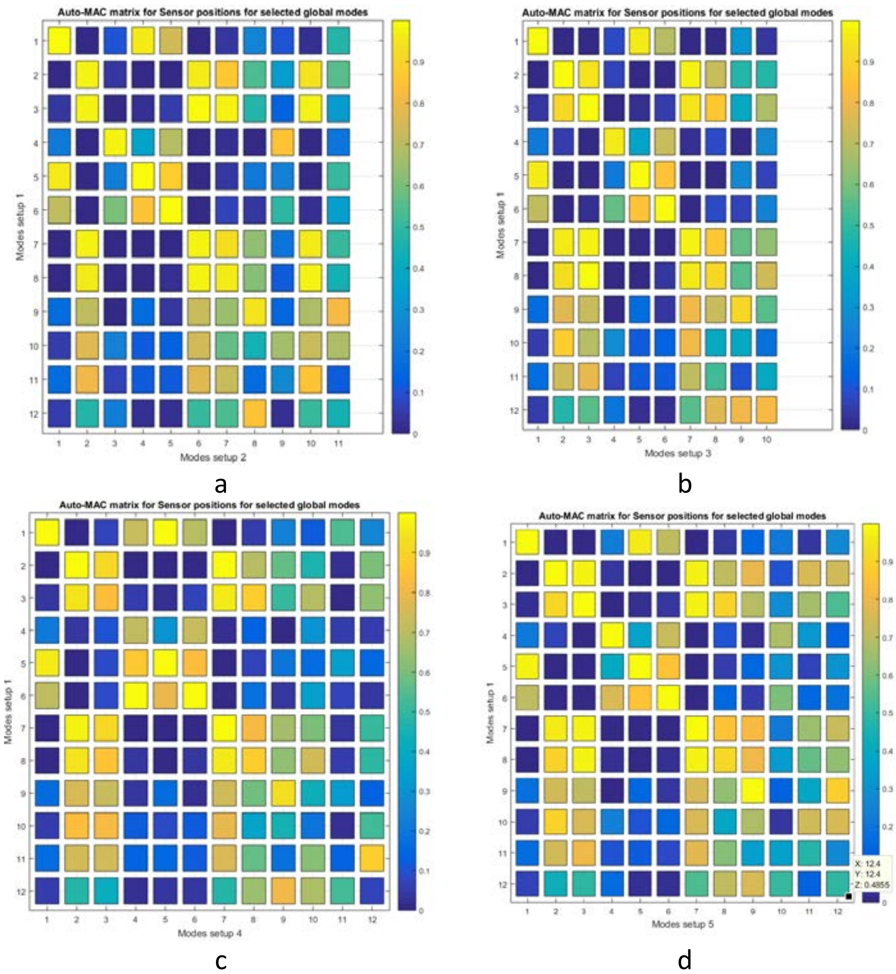

Fig. 6: Display of MAC_12 (a), MAC_13 (b), MAC_14 (c), MAC_15 (d)

After visualizing each comparison, a table was made for the MAC_max values corresponding to the main diagonal in each setup (See Fig. 7)

MAC	Setup 1	Setup 2	Setup 3	Setup 4	Setup 5
1	1.00	1.00	1.00	1.00	1.00
2	1.00	__	0.99	1.00	1.00
3	1.00	0.97	0.99	0.84	0.99
4	1.00	0.97	0.96	0.71	0.99
5	1.00	1.00	1.00	0.99	1.00
6	1.00	1.00	1.00	1.00	1.00
7	1.00	0.98	0.98	0.99	1.00
8	1.00	0.95	0.91	0.88	0.92
9	1.00	0.95	0.92	0.93	0.99
10	1.00	0.65	__	0.19	0.03
11	1.00	0.86	0.18	0.14	0.47
12	1.00	0.44	__	0.07	0.49

Legend(MAC)
Delete value
Excellent value
Good value
Acceptable value

Fig. 7: MAC values for each setup

Next, the modes that will be combined according to the MAC values are selected. Following this criterion, it can be affirmed that the modes corresponding to MAC_2, MAC_10, and MAC_12 were eliminated as they did not present information in all setups. For the mode corresponding to MAC_11, it was decided to delete although it had information in all modes since as of the third set up the MAC values are not good to be accepted by the Modal Assurance Criterion (MAC)

Combine Setups

To combine the setup correctly, modes that previously met the modal guarantee criteria (MAC), were selected. In our case there were 8 modes in each setup. The example we will give is from the first setup, but this applies to the remaining four.

After performing this process for 5 setups, setups are combined with MACEC, since each setup now has the same number of frequencies and the value of the frequencies is the same.

The results of this combination are shown in Table 15, where the modal characteristics obtained after combining the setups are the following: $f_{id.}$ (Hz): natural frequencies, $\xi_{id.}$: modal damping ratios, MPC: modal phase collinearity of the modal shape, MP: mean phase of the mode shape after scaling to unit modal displacement, and MPD: mean phase deviation of the mode shape. Figures 8 to 15 show the corresponding modes shapes.

Table 15: Identified modal characteristic obtained from multi-setup stochastic subspace identification

No.	$f_{id.}$ (Hz)	$\xi_{id.}$ (%)	MPC[−]	MP[°]	MPD [°]
1	4.39531	0.67921	0.9994	-0.3102	0.70887
2	8.61433	0.72869	0.99071	-1.1558	2.8768
3	9.84505	0.72004	0.93255	-0.96629	6.3362
4	12.1518	0.71096	0.99831	-1.081	1.3567
5	14.667	0.83204	0.98521	-1.4605	2.8469
6	17.9049	0.73627	0.97568	0.48094	4.3732
7	18.7641	0.77799	0.90197	-1.0286	8.5854
8	22.4993	0.58028	0.87965	0.87385	8.5678

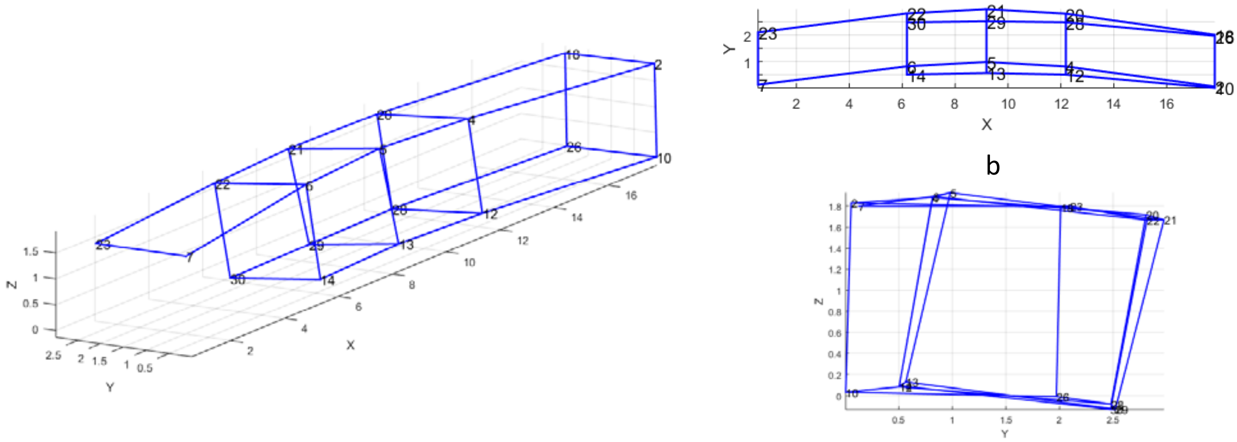

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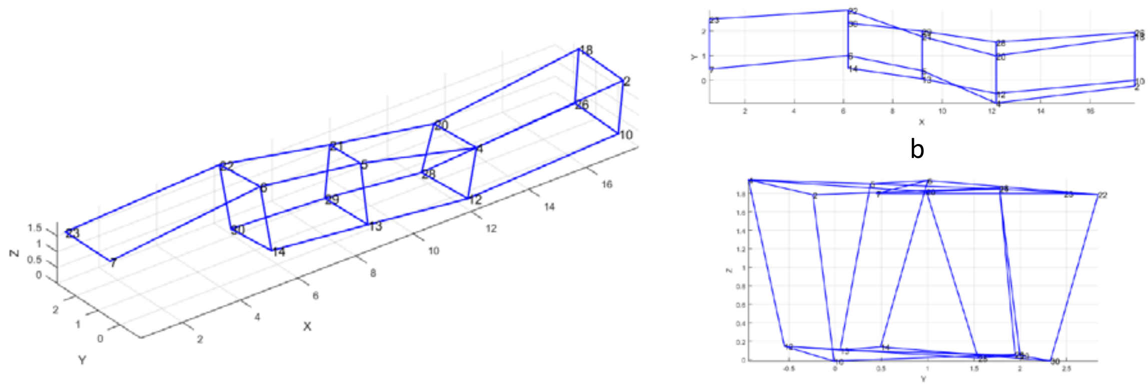
Fig.8: (a) Three-dimensional view, (b) top view and (c) longitudinal view of mode 1, f_{id}=4.4 Hz



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zFig.9: (a) Three-dimensional view, (b) top view and (c) longitudinal view of mode 2, f_{id}=8.61 Hz

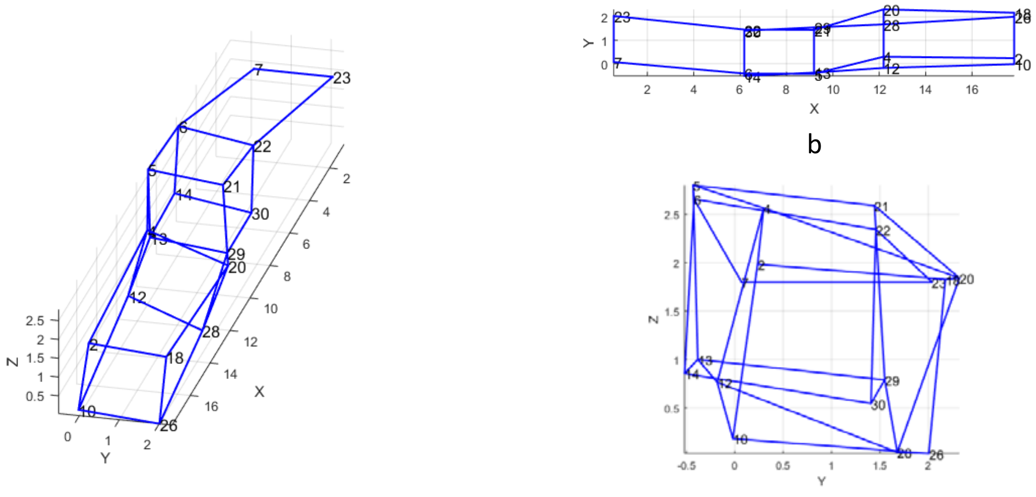

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Fig.10: (a) Three-dimensional view, (b) top view and (c) longitudinal view of mode 3, f_{id}=9.85 Hz

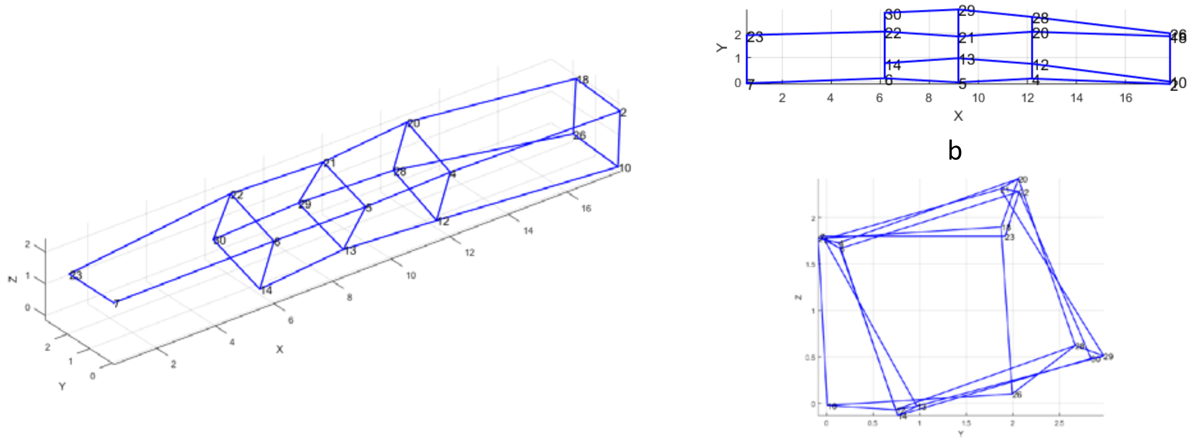

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Fig.11: (a) Three-dimensional view, (b) top view and (c) longitudinal view of mode 4, f_{id}=12.15 Hz

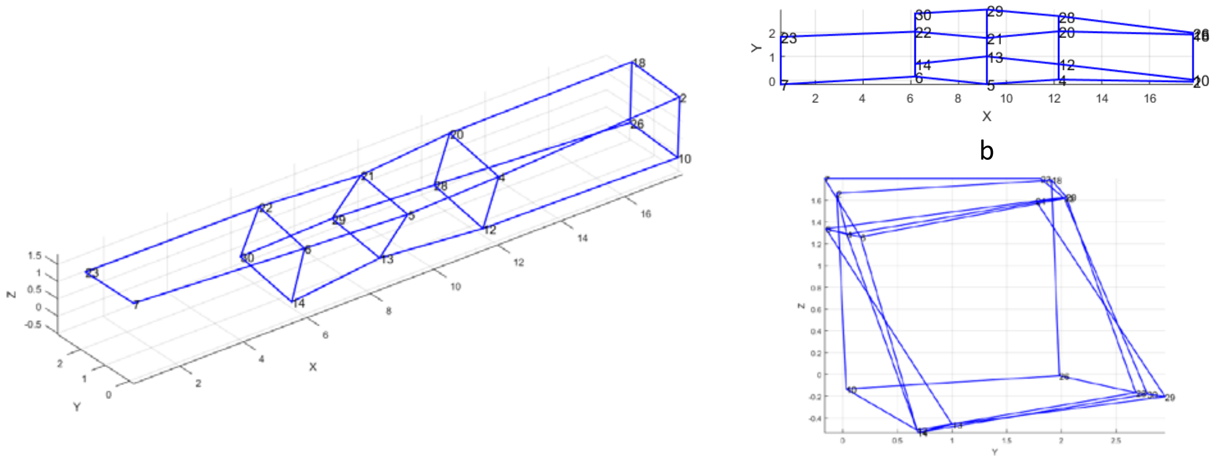

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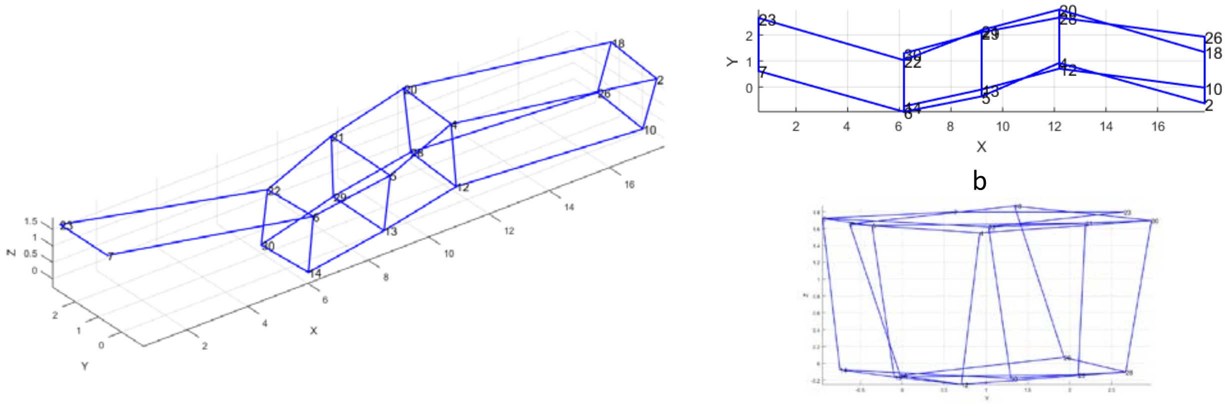
Fig.12: (a) Three-dimensional view, (b) top view and (c) longitudinal view of mode 5, f_{id}=14.67 Hz



a c

Fig.13: (a) Three-dimensional view, (b) top view and (c) longitudinal view of mode 6, f_{id}=17.9 Hz

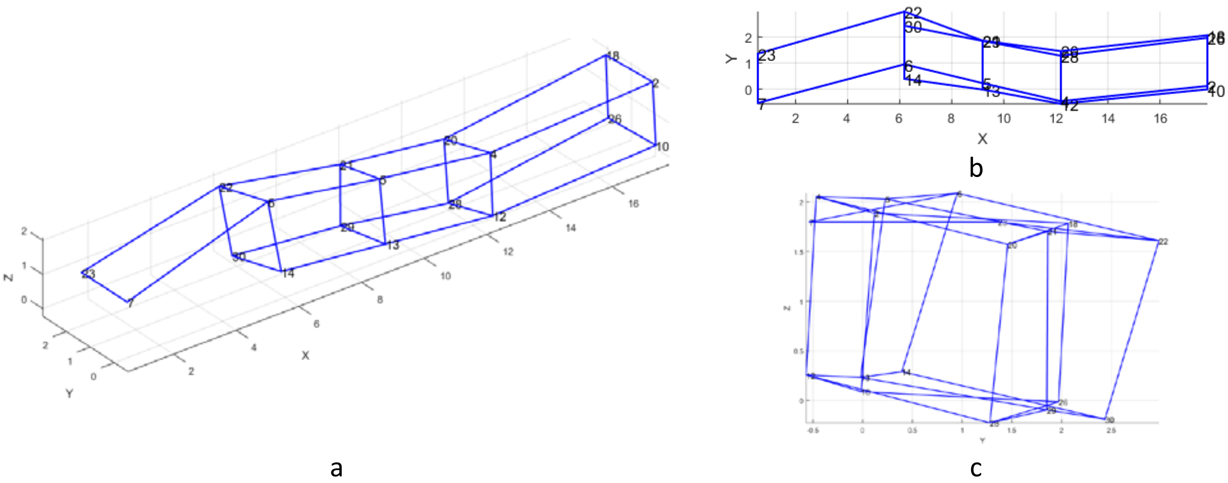


Fig.14: (a) Three-dimensional view, (b) top view and (c) longitudinal view of mode 7, f_{id}=18.76 Hz

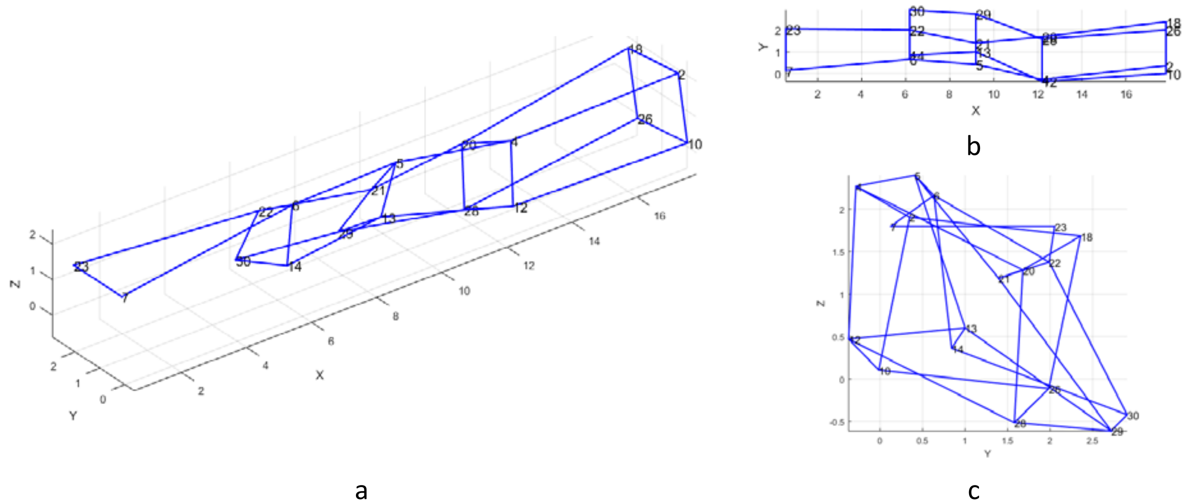


Fig.15: (a) Three-dimensional view, (b) top view and (c) longitudinal view of mode 8, f_{id}=22.5 Hz

4. Conclusions

1. During the measurement process, it is crucial for subsequent identification, the optimal positioning of the sensors, which then allows a correct identification.
2. The Modal Assurance Criterion is an important tool in correctly identifying which modes correspond to which among the different setups.
3. The multi-setup technique and the combination of the results of their measurements, requires that there be reference sensors in the process, which allow them to be combined.
4. As can be seen from the results, some modes are not completed in the graphic representation, so it is necessary to improve the "slaving" process and other techniques which allow its completion.

5. However, the previous shortcomings, the global information identified from the values of the frequencies and the information provided by the modal shapes identified, is of great interest and enough for the two fundamental foreseen applications in this case: the model updating of the bridge and the damage detection during bridge assessment.

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