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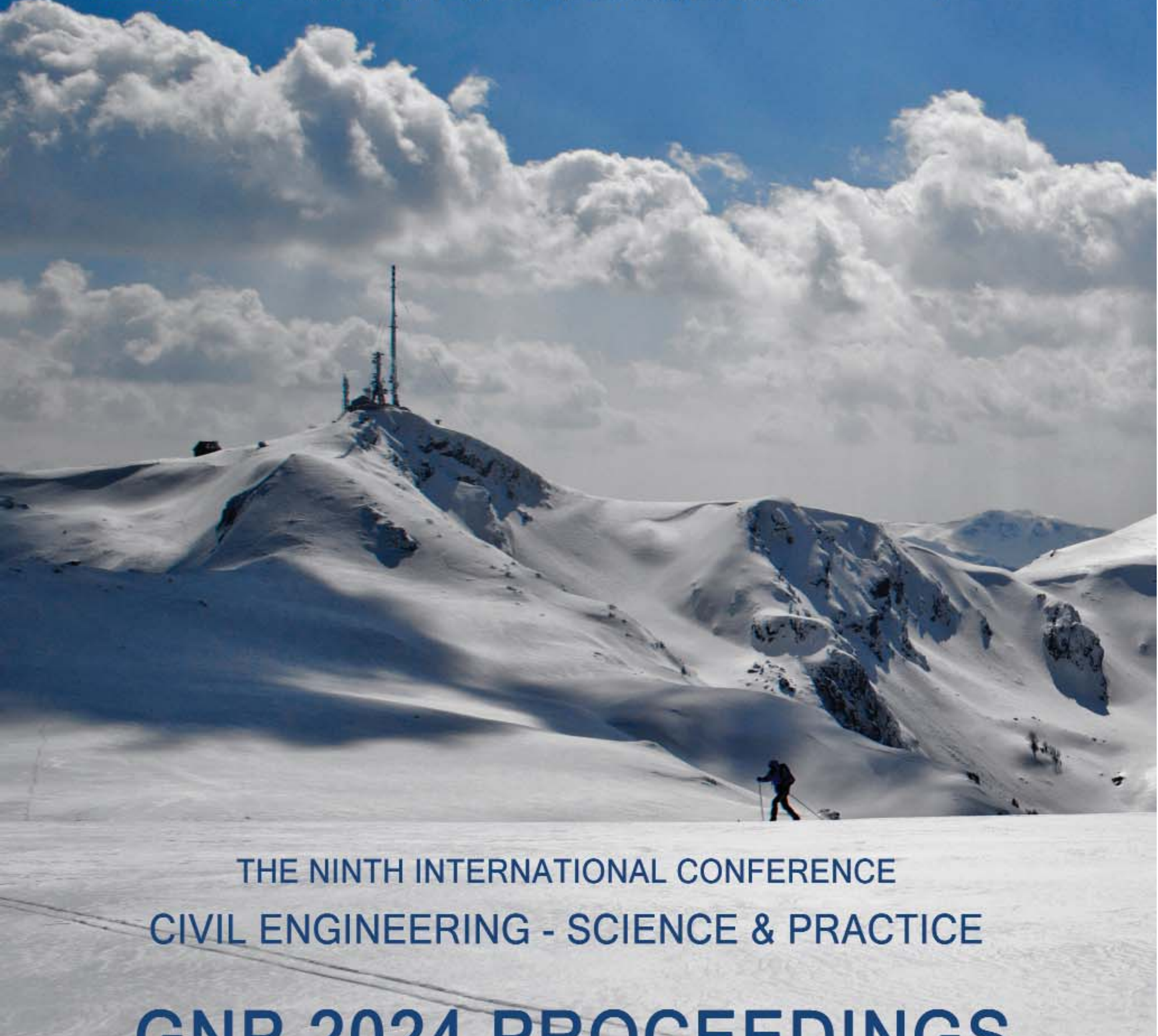

THE NINTH INTERNATIONAL CONFERENCE

CIVIL ENGINEERING - SCIENCE & PRACTICE

GNP 2024 PROCEEDINGS

Kolašin, March 2024

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DIRECT LASER DYNAMIC DISPLACEMENT MEASUREMENT OF STRUCTURAL RESPONSE DURING TESTING

Abstract

The paper presents part of the conducted research on laser-displacement sensors for the measurement of structural response in civil engineering applications. Usually, the level of displacement in laboratory or on-site testing is in small to mid-range levels of 1.00 to 25.00 mm and in the frequency range of up to 100 Hz. Appropriate sensors were selected and used according to performance in the sense of resolution/accuracy.

Experiments are conducted on steel model beam in the laboratory and on-site real bridge structure. In both analysed cases, data analysis was carried out in the sense of modal frequencies and damping estimation with comparison with numerically computed values.

Presented are the results of two experiments, a laboratory-tested model of steel beam and an on-site tested real bridge structure. In both cases have achieved good argument of test results, estimated modal frequencies and damping of tested model/structure.

Data analyses conducted used a developed *MATLAB script*, while the numerical computation conducted used *SAP2000_v14* FEM package for structural analysis.

Excellent agreement of extracted results was achieved in the case of the laboratory-tested structural model, as well as of extracted results of on-site tested real-world structure in the sense of extracted modal frequencies and modal damping.

Finally, the conclusion is that laser-displacement sensors are quite appropriate for small to mid-range of expected displacement and are quite appropriate for such applications according to the possibility of installation so that such sensors could be applied for structural testing, particularly for dynamic testing of such structures because of their possibility of high sampling frequency and high resolution/accuracy.

Keywords

Laser displacement measurement, structural testing, data reduction of test results

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1. INTRODUCTION

Displacement measurement is always one of the most important tasks during execution laboratory or on-site structural testing because it significantly reflects static or dynamic response. There are more methods with corresponding equipment for such applications, which are more / less applicable for particular study depending of expected range of displacement which has to be measured, as well as the character of displacement – static/dynamic and frequency range of interest.

Methods with corresponding equipment/sensors are characterized by several of the most important parameters that must be considered to determine which method is the most suitable for a specific application. The main parameters for assessing the suitability of the method and equipment/sensor are:

- *Resolution* – the smallest value of displacement which can be registered, for example $Res = 0.001 / 0.01 / 0.1 / 1.0 / 2.0 / 5.0 / 10.0$ mm for structural applications;
- *Accuracy* – accuracy of measured displacement, which is roughly within the limits $Acur = (2 \div 4) x Res$
- *Frequency maximum sampling* – system maximum frequency of measurement which has to be adequate to maximum frequency of interest for particular application. Theoretically, according to *Nyquist–Shannon sampling theorem* $F\_max\_samp \geq 2 \text{ x } \mathrm{F\_interest}$, but in practice usually used $\mathrm{F\_max\_sampl} \geq (5 \div 10) \text{ x } \mathrm{F\_interest}$ to avoid so-called aliased effects, as well to avoid applied filter distortions during post processing;

Also, some other parameters could be considered during the selection of a measurement method suitable for a particular application, such as *Level of noise*, etc.

Depending on resolution/accuracy, some methods are applicable for structural testing or material testing, and the choice has to be made for a particular application. The paper considers laboratory / on-site structural testing, so further consideration is restricted to such applications, with an accent on dynamic structural response.

The most commonly applied structural displacement measurement methods mainly can be classified:

- Application of *Geodetic level and tachymetry* [3];
- Application of *LVDT* (*Linear Variable Differential Transformer*) with appropriate acquisition system [10];
- Application of *GPS* (*Global Position System*) [5];
- Application of *Vision based systems* [6];
- Application of *Interferometry based systems* [2];

The suitability of each of the mentioned systems is assessed in the first place by considering the main, previously mentioned, characteristics on the basis of the suitability of the method for a specific application.

The research presented in the paper is oriented on practical application with small to mid - range level of displacement $Displ\_max \pm (1 \div 25)\, mm$ with appropriate resolution / accuracy in the range *of* frequency of interest $F\_interest \geq (0 \div 100)\, Hz$. According to assumed restrictions, research carried out using laser distance sensors which are commonly used in mechanical engineering applications for process control.

2. EXPERIMENTS USING LASER DISTANCE SENSORS

An innovative system for direct displacement measurement consists of laser distance displacement sensors made by *Micro*-Epsilon *GmbH & Co. KG* [7] type *optoNCDT 1220-50*, with a span of 50mm and analog AC of 4-20mA and 16-bits conversion using *AC* to *RS422USB* conversion of the same producer, Fig.1.

Figure 1. Sensors and data ACDC RS422 converter used in experiments

Such system satisfies requirements of the specified range of $Displ\_max \pm (1 \div 25)\ mm$, as well as sampling frequency $Freq\_sampling\ (1\ \text{kHz} / 0.5\ \text{kHz} / 0.25\ \text{kHz})$ which is selectable and quite suitable for frequency of interest $F\_interest = (100 \div 200)\ Hz$ and more. Producer specified *Reputably* of 0.005mm guarantees that could be achieved accuracy of $Acur = 0.15\ mm$. Should be noted that system has high level of shock and vibration resistance, low power consummation and it is IP65 protection class.

Using described system, carried out two experiments, one in laboratory on structural model and the second one on real bridge on-site.

2.1. LABORATORY EXPERIMENT ON SIMPLE STRUCTURAL MODEL

The first experiment using described inovate application *laser-direct-displacement measuring system* carried out on the simple structural model of steel beam with two overhangs, Fig.2.

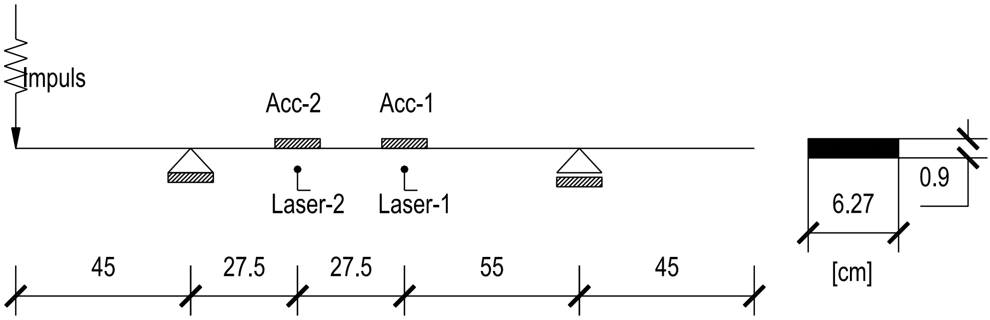
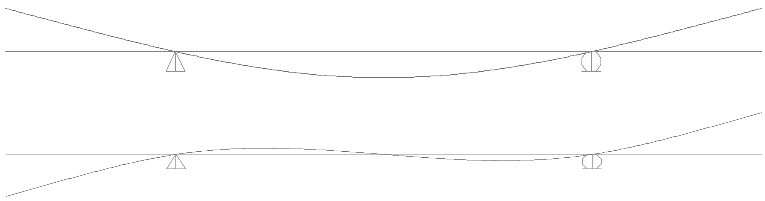


Figure 2. Layout of laboratory structural model and laser-direct-displacement sensors positions

Computational model of the steel beam tested in laboratory shown Fig. 2 developed in *SAP2000 v14* structural analysis *FEM* package using steel Young's module E_{steel} = 200 GPa and material mass density of m=7850 kg/m^3. First two mode shapes and corresponding frequencies are shown in Fig 3.



Mode 1
f_1 *=11.54 Hz*

Mode 2
f_2 *=21.45 Hz*

Figure 3. Computed first two of tested steel beam model and corresponding frequencies SAP2000_v14 structural analysis FEM package

Parallel with displacement measurement using *laser-direct-displacement measuring* underneath the beam, while on the top side of the beam model at the same positions were installed low-frequency sensitive accelerometers *model 2240* produced by Silicon Design Inc. [8], while the data acquisition carried out by 20-bit measuring amplifier *MGCplus* produced by *Hottinger Baldwin Messtechnik Gmbh*, Fig. 2. Photos of the conducted experiment are shown in Fig. 4.

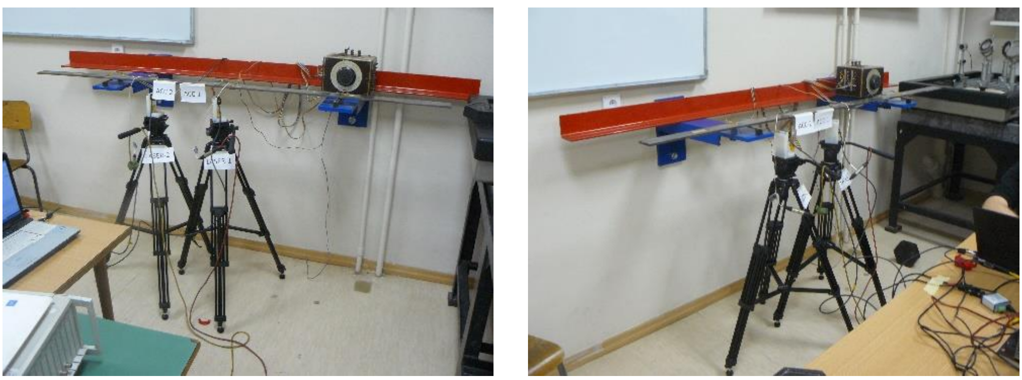


Figure 4. Photo of laboratory structural model experiment

Laser distance sensors were installed on stable professional tripods to be stable and possible for easy rectification to mid-distance respect the target of about 25mm. They were sampled with frequency of 500 Hz (0.5 kHz). Accelerometers were installed on the top of the beam and sampled with a frequency of 600 Hz. Sample frequencies chosen according to possibility/restrictions of applied acquisition systems for *laser displacement sensors* and *accelerometers*. Duration of recording of measured values, displacement and acceleration, was about 100 sec.

Fig. 5 shows the response of the beam after impulse load on end of the left overhang of the *Laser 2 displacement sensor* (upper left diagram) with maximum of recorded displacement of 0.55093mm.

Data analysis carried out by developed *MATLAB script* by *FFT analysis* for determination the modal frequencies of the beam according to registries displacement (upper right diagram Fig. 5) and the first two frequencies which were recognized. Also, on the same figure (lower diagram Fig.5) is showed diagram of analysis of results used for damping estimation based on conducted measurement on *Laser-2* position, but using part of displacement record where *free-decay* recorded.

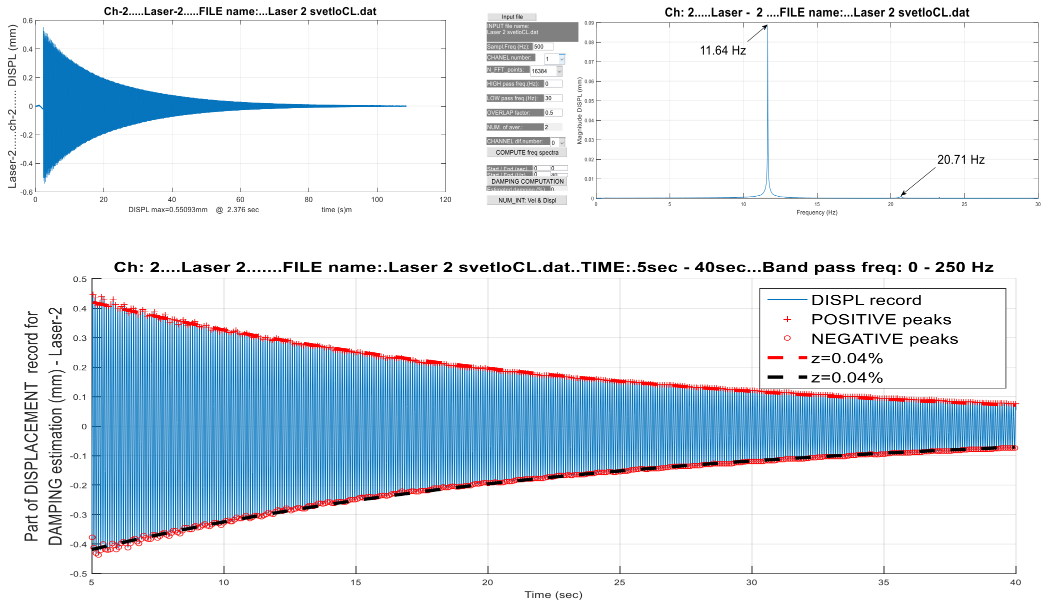


Figure 5. Response of the beam tested in laboratory at position of Laser-2 displacement sensor respect to beam loaded by an impulse on end of left overhang with results of data analysis

Beside to direct displacement measurements, the acceleration response of the beam at the position of *Laser-2* was measured acceleration response of accelerometer *Acc-2*, practically at the same position of *laser displacement sensor*. Records of acceleration, as well as corresponding data analysis are shown in Fig. 6.

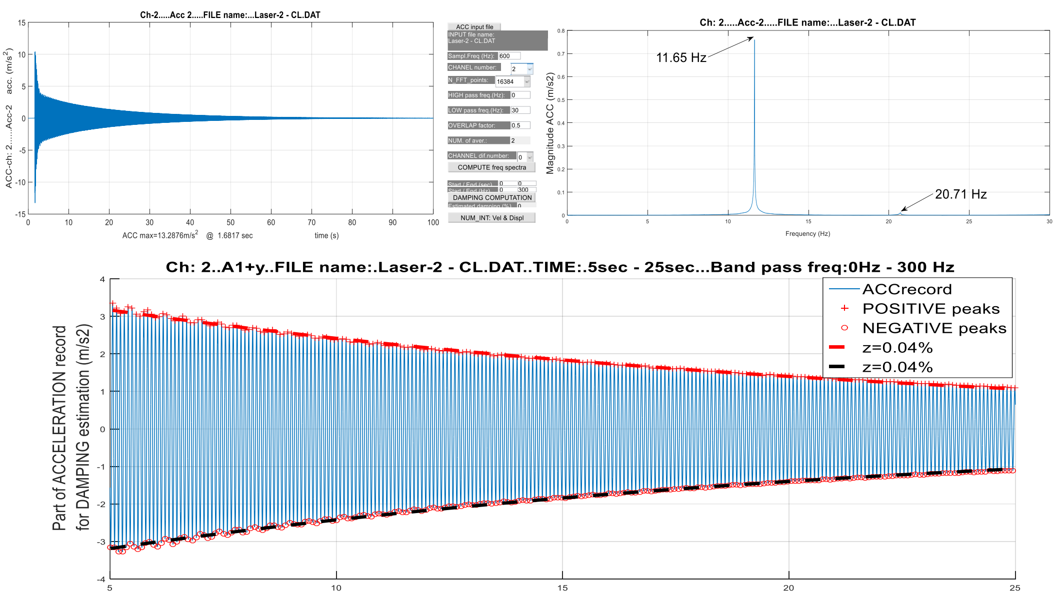


Figure 6. Response of the beam tested in laboratory at position of Acc-2 sensor respect to beam loaded by impulse on end of left overhang with results of data analysis

Data analysis was carried out by developed by the same *MATLAB script* by *FFT analysis* for determination of the modal frequencies of the beam according to recorded acceleration and during analysis of results used for damping estimation based on conducted measurement on *Acc-2* position using part of recorded acceleration where *free-decay* recorded.

In Table 1 are summarized results of estimated parameters by laser displacement measurement and corresponding acceleration measurement at the same position.

Table 1. Comparison of results of estimation properties of the laboratory tested beam model

Estimated	**Mode-1 *f(Hz)***	**Mode-2 *f(Hz)***	**Damping *f(%)***
Laser - 2	11.64	21.71	0.04
Acc - 2	11.65	21.71	0.04
Computed	11.54	21.45	-

2.2. ON-SITE EXPERIMENT ON BRIDGE STRUCTURE

The second experiment using *laser-direct-displacement measuring system* carried out on railway bridge structure *M1* consists of a row of simple supported beams with span of L=11.70m. Fig.7. Tested conducts on span S4-S5, with *laser displacement measurement* and *accelerations*.

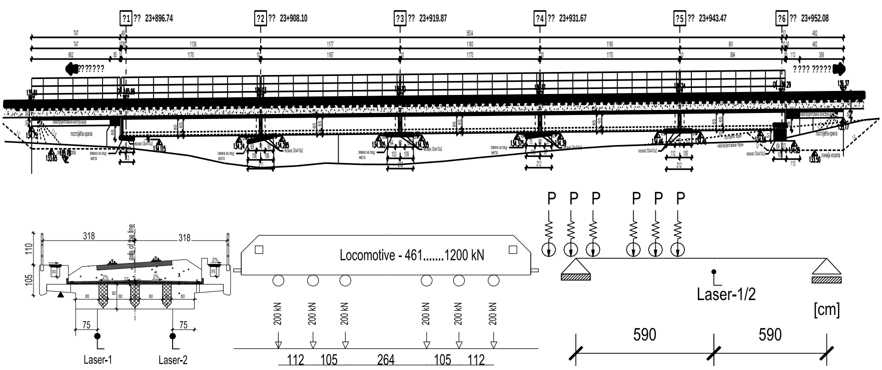


Figure 7. Layout of on-site experiment of bridge structure M1 of rehabilitated railway line Jajinci – Mala Krsna – Serbia with load applied for static and dynamic testing

In Fig. 8 are shown photos during span S4-S5 testing of the span S4-S5 of the bridge M1 structure1with installed of *laser-displacement sensors* and *accelerometers* at same positions.

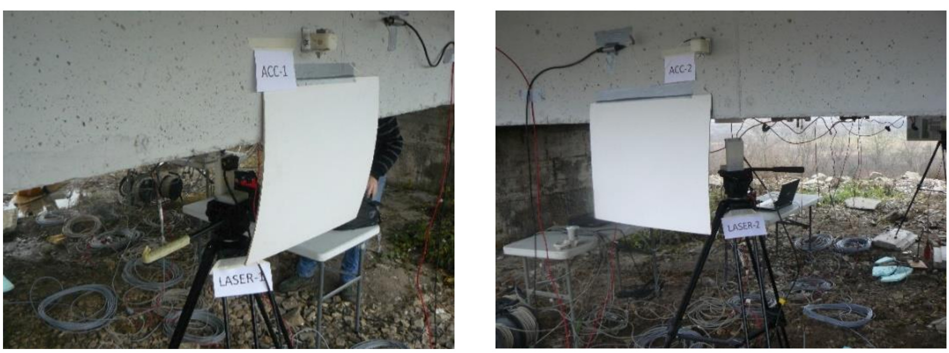


Figure 8. Photos of on-site experiment of bridge structure M1 of rehabilitated railway line Jajinci – Mala Krsna – Serbia with load applied for static and dynamic testing

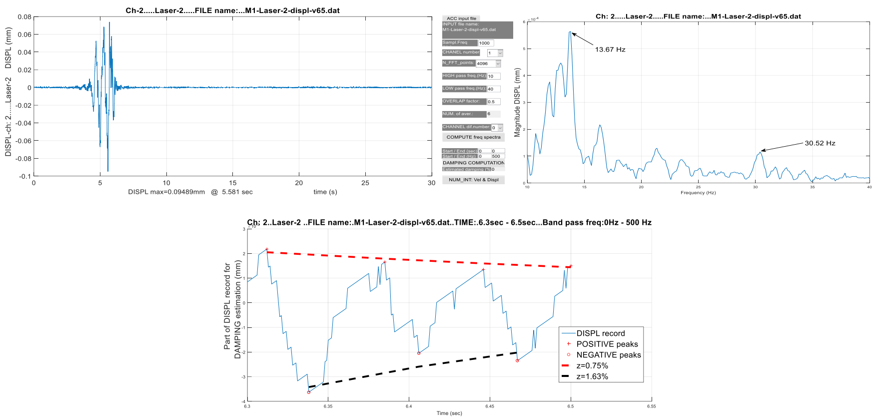


Figure 9. Response of the beam tested in laboratory at position of Laser-2 displacement sensor of tested M1 bridge structure with results of data analysis

Beside to direct displacement measurements, acceleration response at position of accelerometer *Acc-2*, practically at the same position of *laser displacement sensor*. Records of acceleration, as well as corresponding data analysis are shown in Fig. 10.

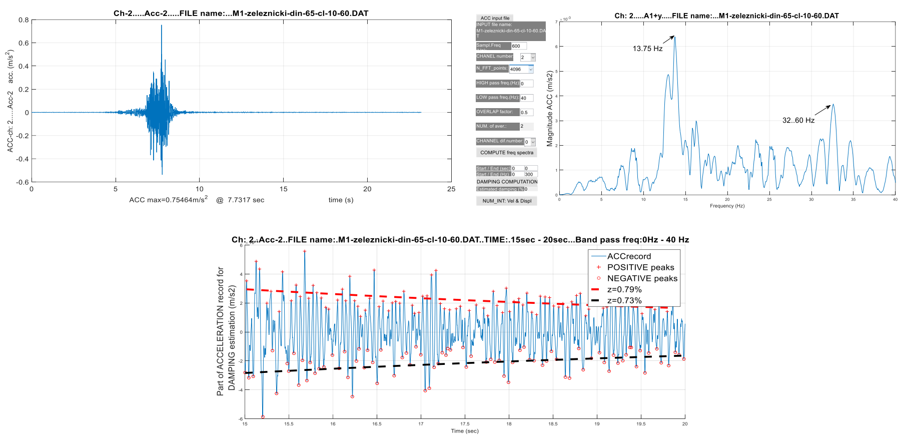
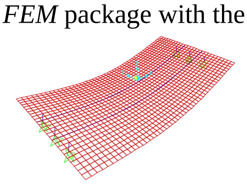
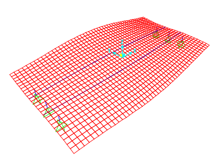


Figure 10. Response of the on-site tested bridge M1 at positions of Acc-2 sensor with results of data analysis

The computational model of the bridge suture developed in *SAP2000_v14* structural analysis *FEM* package with the first two mode shapes and corresponding frequencies are shown in Fig 11.



Mode 1 – bending
f_1 =10.13 Hz



Mode 2 - torsional
F_2 =32.47 Hz

Figure 11. Computed the first two modal shapes and corresponding frequencies of tested M1 bridge structure using SAP2000_v14 structural analysis FEM package

In Table 2 are summarized results of estimated parameters by *laser displacement sensor* and corresponding *acceleration measurement* at the same position of tested bridge structure M1.

Table 2. Comparison of results of estimation properties of the on-site tested M1 bridge structure

Estimated	Mode-1 *f(Hz)*	Mode-2 *f(Hz)*	Damping *f(%)*
Laser - 2	13.67	30.52	1.19
Acc - 2	13.75	32.60	0.76
Computed	10.13	32.47	-

3. CONCLUSION

The paper presents results of conducted measurements using laser-displacement sensors with comparison of results, recognized modal frequencies and damping of tested model and real bridge structure.

According to the presented results, it is evident that good argument is achieved in estimated modal frequencies and estimated damping values of tested model/structure. Finally, could be concluded that laser-displacement sensors could be efficiently used for structural testing application in the range of small to mid-range of level of displacement in the range of $Displ\_max \pm (1 \div 25)\, mm$, as well as possibility of adequate sampling rate for civil structural applications.

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