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Dynamic Tests for System Identification of Bridges

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ABSTRAKT

V predkladanej dizertačnej práci je venovaná pozornosť meraniam vibrácií využívajúc niektoré nedeštruktívne metódy monitorovania stavu konštrukcií (SHM) Významným prínosom autora je vývoj ovládacieho programu meracieho systému NI. V prostredí NI LabVIEW 2015 boli vytvorené tri rôzne programy na získavanie a spracovanie dát. V ďalšej fáze výskumu boli skúmané dva experimentálne nosníky v laboratóriu, na ktorých bola vykonaná systémová identifikácia (SI) a overené niektoré metódy SHM. Preto dôležitú časť práce tvorí identifikácia poškodenia na kompozitnom nosníku pomocou metódy aktualizácie MKP modelu. Vylepšený program bol na tento nosník úspešne aplikovaný. Nakoniec boli vykonané inicializačné merania na troch rôznych mostoch vystavených ambientným vibráciám, kde sa následne vykonala prevádzková modálna analýza. Výsledky SI mostných konštrukcií sú taktiež prezentované.

CONTENTS

1. Introduction

Nowadays, many scientists [7], [8], [22], [26], or [27] pay attention to different aspects of System Identification (SI) and following Structural Health Monitoring (SHM) to satisfy increasing demands for safety and the reduction of maintenance costs. In accordance with [12], another reason for paying greater attention to the monitoring of bridges is their gradual aging, which is the source of potential damage [18]. E.g. [3] noted that bridge structures in the USA are 43 years old on average. In accordance with [11], the average age of German bridges is about 45 years and over 65% of the structures are over the age of 30 years. Slovak bridges are about the same age on average as German bridges [19]. In many cases, the lack of long-term maintenance or periodic inspections can later result in expensive and complete reconstructions. The mentioned fact is confirmed by one of the most recent accidents from the USA, Pittsburgh. The 94-year-old Greenfield Bridge had to be demolished in 2015 and replaced by a new structure. SHM of bridges can help prevent this situation and the advantage of SHM is also less demanding maintenance (economically, but also time-saving), i.e. if damage is early detected, only minor repairs are required. It guarantees the sustainability of structures which will become an important aspect for the future.

Dynamic tests of structures are used in some non-destructive methods of the SHM. In laboratory conditions, it is possible to effectively pay attention to damage detection in detail. On the other hand, the application of damage assessment procedures for real structures has not been successful yet. The important step for their future application is represented by a precisely performed system identification.

2. Outline and Objectives of Dissertation

The thesis can be divided into the following objectives:

Assessment of stiffness change from experiments prepared and performed in the laboratory.

- Initial (alternatively repeated) dynamic tests of chosen bridges and SI of them. The preparation of the measurements includes:
    - programming the control code for the available measurement system in the NI LabVIEW environment;
    - FEM calculations;
    - sensor layout for measurements of dynamic response caused by ambient vibrations, or vibrations caused by various loads that can be quantified.
- Verification of some SHM methods applied on the selected bridges. Test of resonant excitation on diagonal members of truss bridges.
- Debugging and optimization of the code for calculation of stiffness changes using the method of FE model updating (or other methods).

Dissertation thesis corresponds with the aims of grant project no. APVV 0236-12 named as "Bridge Structural Health Monitoring via Repeated Dynamic Tests. "

The dissertation thesis consists of several sections. Section 3 describes the state-of-the-art of research and contains an overview of the used methods for SHM. Section 4 is devoted to the software developed by the author for a measurement system and its parts; Section 5 is devoted to measurements and appropriate results in the laboratory. Section 6 shows quite promising results of the damage detection. Section 7 deals with initialization in-situ measurements of three bridges and finally, the main conclusions are presented in Section 8. Section 9 is devoted to the Resumé in Slovak language which is a compulsory part of the thesis. Used references are at the end of Section 10. Section 11 shows the author's papers published during the doctoral study.

3. Literature Review

The state-of-the-art methods in Structural Health Monitoring (SHM) have been much advancing since 2000. Nowadays, there are many scientific teams in the world who have dedicated their research to SHM, especially SHM of bridges [4], [9], [15], [16], or [21]. There are several available methods how to monitor structures or to check operational conditions of structures. The introduction to SHM is described in [10].

Testing of structures and their components has a long history. The beginnings are dated to the early 20th century. Two main approaches are known. Testing can be destructive or non-destructive. Non-destructive methods (e.g. [14]) can be based on vibrations (Figure 3-1) or other types of waves [13], alternatively on radiation.

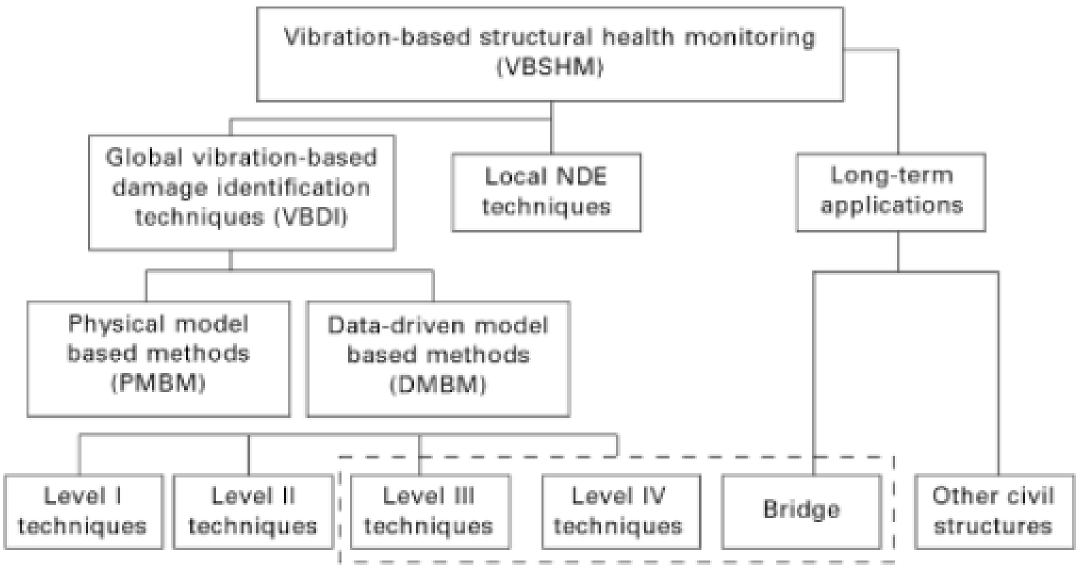


Figure 3-1 Overview of Vibration-based Methods.

Methods based on physical model are stated in the thesis. Methods based on natural frequencies, mode-shapes (MAC, COMAC) and FE model updating are described in more detail. The attention is also devoted to the basic description of sensors used for measurements (accelerometers, strain gauges, thermocouples) and the IBIS-S radar is briefly outlined. Finally, five examples of SHM applied around the world are presented. The described experiences and conclusions have been used in the dissertation. Reasons why the examples of SHM have been chosen are commented in the thesis.

4. Development of software for measuring system

it was necessary to programme a control code for a measurement system which allows to acquire, and to store data. The first variant of monitoring system represents the easiest composition of used devices. The code was prepared by the author to acquire data and to process them immediately. The device NI cDAQ 9171 with NI 9234 module has 4 channels for measurement of accelerations. The input data are the length of a measured record in seconds, sampling rate, which depends directly on the used NI 9234 module. Data wires from DAQ Assistant were branched to subVI which allows to save measured data to computer file, then to plot actual graphs of acceleration amplitudes. Filtration of the measured signals was chosen as a type of pre-processing. Owing to that, it is possible to filter unwanted frequencies. The band pass filter or low pass filter was used. The limits of filters are also the input data placed on the front panel. Besides that, the code calculates the frequency response spectrum to simply determine frequencies measured in the data. There is a possibility to set input parameters of measurements. Moreover, it is possible to read and examine the measured data. The user can choose if the measured data should be saved. The variant A can be used for quick data acquisition during bridge inspections to define basic dynamic characteristics. It can be also used in a laboratory or for measurement of smaller real structures.

The second variant is more complex. The device NI cRIO 9067 or the device NI cRIO 9074 represent the core of the system. The programming consisted of three steps: programming of an FPGA chip, programming of a Real Time target and finally, programming of a user interface placed on the host PC. The embedded monitoring architecture was considered in variant B in accordance with NI LabVIEW for CompactRIO developer's guide [17]. FPGA VI was programmed using the NI LabVIEW FPGA module. This module allows adapting an FPGA chip, according to specific requirements. The FPGA chip is built into the chassis. FPGA VI is synthesized directly down to physical hardware, which contains logic blocks, input-output blocks and programmable interconnects are used for connections. The FPGA VI is fully functional after the whole process of synthesizing. Seven NI 9234 modules are implemented into the code. Various other changes had to be done. Because of the compilation process, the process of modification was also time-consuming. When the FPGA VI was finished, the next step in the development was represented by the programming of the RT target VI. The VI works on the RT processor of the cRIO device. Using the FPGA chip provided a more reliable code with highest determinism and parallelism.

The user interface (UI) was also modified according to the requirements. The modified VI template gives an opportunity to create a configuration file in XML format. The created XML file consists of the number of measured channels, sampling rate, number of all samples acquired in one record and number of records. In accordance with the recommendation of NI, the used sampling rate should be at least 10 times bigger than the frequency of sampled signal. The XML file also contains information about triggering. The trigger can be switched on at a given time or after exceeding the specified limit. Finally, the XML file contains information about the sensitivity of used sensors. The UI allows to watch live data – measured acceleration of one chosen channel. It also allows to start acquisition manually. Acquired data are saved as a TDMS file, which can be additionally processed in NI LabVIEW, in MS Office Excel, or in NI DIAdem, or in ModalVIEW software. It can be also opened in other software that supports TDMS files. This composition is used mainly in laboratory tasks. The variant B can be possibly used for small measurements of bridges and footbridges with short spans.

The variant C represents the most complex system, which was developed as the last one. All available equipment and sensors were included in this composition. The most powerful device – cRIO 9067 was chosen as the master. The cRIO 9074 device was parallelly programmed to the master. Devices NI 9144 were connected in series to the master. The UI in variant C allows to choose suitable architecture before measurements. The network switch Edimax ES-3305P V2 allows to connect the whole system together. The mentioned cRIO devices are connected by FTP network cables or by using Wi-Fi antennas. Both possibilities were tested. The network switch is placed at the same place as the master device cRIO 9067. The connection between the master and the NI 9144 devices is designed differently. The NI 9144 supports the Ether CAT standard, so it can be easily connected to the master or between each other by FTP cable with a length up to 100 m. This length was tested, and it provides sufficient results. FPGA chips had to be programmed and compiled on both devices. Up to five NI 9234 modules, two NI 9237 modules and two NI 9211 modules can be put into the free slots of the master device. On the other hand, up to three NI 9234 modules can be used in the device cRIO 9074. The slave chassis can use up to two NI 9234 modules in this developed system. All data from the used modules are saved to the memory of the master device. The saved data are also in TDMS format. The master device (cRIO 9067) has the most complex code of VI, because it communicates with all other devices and with the UI which runs on the host PC. The code for the cRIO 9074 device is easier and it reads only data from the NI 9234 modules and then it sends them to the master device using Network Stream. Additionally, it can receive commands from the master. At the first,

Three tests have been done during the development of Variant C. Network Stream had to be tested for the functionality and speed of the sent data. The results from the test show that the sampling rate must be smaller than 5120 samples per second. If we use higher sampling rates, it is not possible to ensure a reliable transfer between the cRIO 9067 and cRIO 9074 devices. The slave chassis have also their own FPGA chips. Nevertheless, they could not be programmed in the same way as the other cRIO devices. The reason is that the NI 9144 devices do not have their own processor and reading of data from FPGA chips cannot be so quickly performed by the master device. The above-mentioned SCAN mode of FPGA chip has been used. The setup of SCAN mode must also be tested. The performed test was based on detecting how many samples per second the master device could read. SCAN mode was set up to a minimum period (488 µs) of the loop cycle. The maximum sampling rate was detected at the level of 3012 samples per second. Besides that, the connection between the NI 9074 device and the slave chassis was tested but it appeared that it was not possible to use a direct connection between them. This sampling rate is sufficient for measurement of bridge structures. The connection between the master device and the slave chassis) via Ether CAT technology allows that standard network FTP cables with length up to 100 m can be used. Tests have proved that the cables up to 100 m work without any trouble and the best achieved sampling rate according to the SCAN mode period is 2438 samples per second. The third test was devoted to synchronizing triggers of all used devices. At first, the solution for the synchronization appeared that the Shared Variable Engine is suitable. Afterwards, it has been found out during the development and tests that the mechanism is not so fast as needed, and it did not lead to synchronize the devices accurately. Deviation of the synchronized starts was not deterministic. Finally, the synchronization was reliably established through a TCP/IP protocol. Because of that solution, the initialization of the system must be done before triggering of the measurement. It causes a slowdown of measurement initiation, but on the other hand, the most accurate synchronization was achieved. Deviation was only up to two samples when 5120 samples per second was used as the sampling rate. This value of deviation is negligible. Method of the synchronization was tested in two situations. Firstly, the connection was established via Wi-Fi antennas and secondly, via standard network cable. The deviation did not depend on the type of used connection.

The designed UI contains a configuration window, a window with live data and a window which shows the state of individual devices during measurements. The configuration panel allows to set up the required architecture, number of NI 9234 modules, sampling rate used in NI 9234 modules, possibility to measure strain (YES or NO). The recommended sampling rate for measurement when the whole system is used is 2438 samples per second. The measurement trigger consists of two phases. The first is configuration when the synchronization progresses and the second is the start of a measurement. This variant C was prepared because of measurement of a longer type of bridge in Bratislava. Other possible alternatives of architecture developed in the variant C can be used for measurement of smaller bridges or also footbridges. The system can be extended in the future.

A separate VI was developed for pre-processing of data for system variant B and C. Data must be copied from the hard disk of the master device to the host PC. Variant B is prepared mainly for laboratory use, so the copying of data is sufficient. After that, the pre-processing such as filtering is possible, where it is possible to set up limits for the band-pass filter. On the other hand, continuously monitoring of real bridge structures requires an automatic transfer of data between the master device and the host PC. It will be developed in the nearest future. The VI allows to save calibrated data, filtered data or review individual channels. The FFT spectra can be also prepared to perform quick analysis. The next steps of processing were done in the ModalVIEW software, programmed in the NI DIAdem software or MATLAB, alternatively in MS Office Excel. The ModalVIEW system is the software developed in NI LabVIEW by ABSignal company for Modal Analysis [1] and [2]. The OMA was mainly performed. The basics of the OMA are outlined in [5] and Stochastic Subspace Method is described in [6], [20]. In accordance with them, the method is suitable when only the output signal is known. It is an example of ambient vibration analysis.

5. Dynamic Tests in Laboratory

Tests using the system described in Section 4 have been performed yet. Two laboratory specimens were analysed in the last four years. The first and long-term measurement was the test of a composite beam. After that, a steel truss model of the bridge was measured.

The first experimental model was made from wood and plasterboards. Three wooden boards were used for the main beam. The deck was 300 mm wide, and it was made of three plasterboard layers. The whole length of the experimental model was 4,000 mm, and a simply supported beam was assumed. The joint supports were realized using steel bars with a diameter of 12 mm located in the centre of gravity of the cross-section through holes drilled in the wooden boards. Firstly, an initial FEM model was done, then the first data were measured. After that, Verification & Validation (V&V) of the FEM model were performed. Finally, the comparison of natural frequencies (measured, calculated - Table 5-1), Cross-MAC values, mode-shapes (Figure 5-1) are depicted in the thesis. It shows good conformity. Tested techniques of SHM have been verified. The preparation of the FEM model met our expectations and it made the measurements easier.

Table 5-1 Comparison of the Dynamic Characteristics (the composite beam).

No. of the mode-shape (direction)	Experimental model (A) [Hz]	Standard Deviation σ [Hz]	Numerical model (B) [Hz]	Error $\frac{(A-B)}{\max(A,B)}$ [%]
1st – in *z* direction	10.74	±0.08	10.54	+1.89
2nd – around *x* axis	12.88	±0.13	13.13	-1.90

a) b)

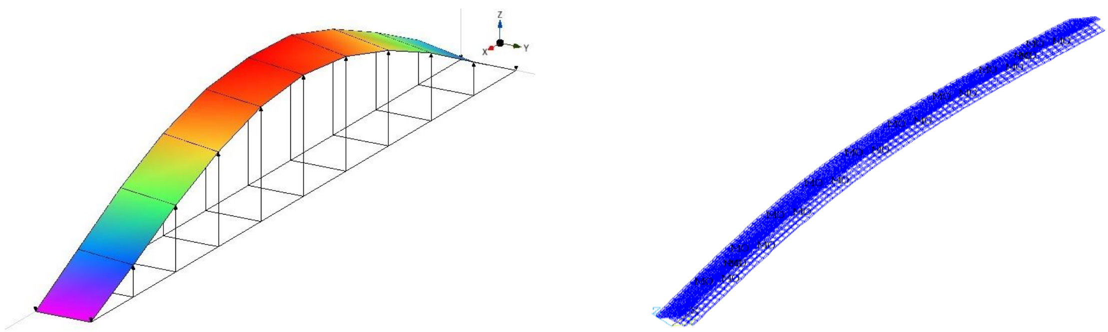


Figure 5-1 The 1st Mode-shape of the Composite Beam a) Measurement b) FEM Model.

Besides that, the truss bridge with bolts was investigated. As the first step again, a FEM model was created. The documentation was not available, therefore, cross-section dimensions and other characteristics of elements of the system were carefully measured. The boundary conditions of the experimental model were considered variously. The first setup was a cantilever beam with a length of 1,890 mm. The second type of assumed boundary condition has been a simply supported beam. The span was 2,520 mm long. The cross-sections were the same for both variants. It was a closed section with a width of 230 mm and a height of about 320 mm. The procedures were similar as for the composite beam. Subsequently, the comparison of natural frequencies (measured, calculated after procedures of V&V - Table 5-2), Cross-MAC values, mode-shapes (Figure 5-2) are depicted for both variants of supports.

Table 5-2 Comparison of the Dynamic Characteristics (the truss cantilever).

No. of the global mode-shape (direction)	Experimental model (A) [Hz]	Standard Deviation σ [Hz]	Numerical model (B) [Hz]	Error $\frac{(A-B)}{\max(A,B)}$ [%]
1st – in Y direction	14.84	±0.05	14.71	+0.88
2nd – in Z direction	25.42	±0.11	25.08	+1.34

a) b)

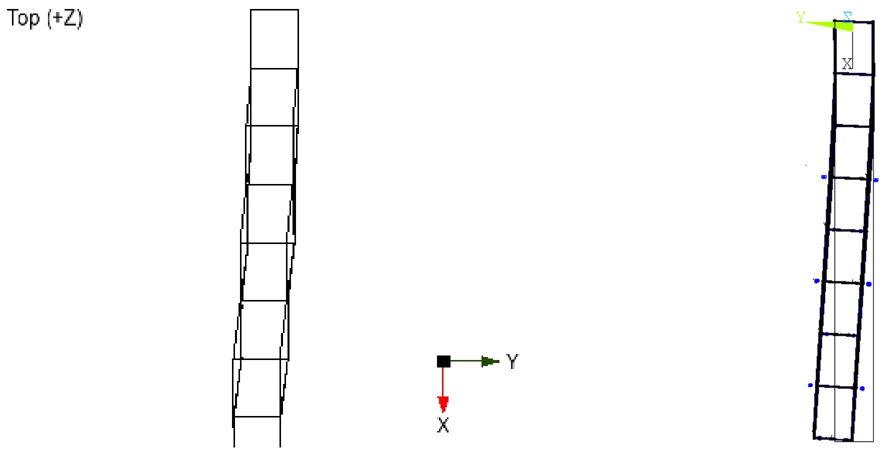


Figure 5-2 The 1st Mode-shape of the Truss Cantilever a) Measurement b) FEM Model.

After the successful system identification of two different structures, identification of artificial damage was tested in Section 6.

6. Damage Detection

In the case of the truss model, damage detection was completed by using the method based on the comparison of natural frequencies. Identification has been only done on the simply supported beam.

More powerful tool to find a damage is represented by the simple code developed by the Department of Structural Mechanics (Slovak University of Technology, Faculty of Civil Engineering) and it has been optimized by the author of the thesis. A parametric study is described in the thesis in more detail because the code uses more input parameters. The parameters affect the accuracy of the results and the time consumption of calculations. The modal analysis of the steel beam was done in the FEM software, and the results were used as the input data for the parametric study. Specified changes of stiffness were applied for the 35 elements in case of the modal analysis and for damage detection. The length of the used element was 100 mm, so the length of the investigated beam was 3,500 mm. The calculations were prepared in such a way that one element (1,200 mm from the right side of the beam) had a changed height of the cross-section. The optimized input parameters of the code were used in the other damage identifications.

The experimental model (Section 5), as well as the measured accelerations, was assumed in accordance with Venglár and Sokol [25]. The change of stiffness was simulated with an added stiffener (Figure 6-1). The stiffener was located 1400 mm from the right side of the specimen and its length was 200 mm. It was added or taken away. The real bending stiffness EI with the stiffener was approximately 274 kNm^2. Only the first mode-shape was applied to the damage detection code (with damage and without damage), and it was smoothed in accordance with an original procedure from [23].

In comparison with Venglár and Sokol [25], a satisfactory degree of accuracy of the identification was achieved in this way. The difference in the identified stiffness was reduced. The optimized input values of the parameters for the calculations led to more accurate results, but the identification was still not good enough.

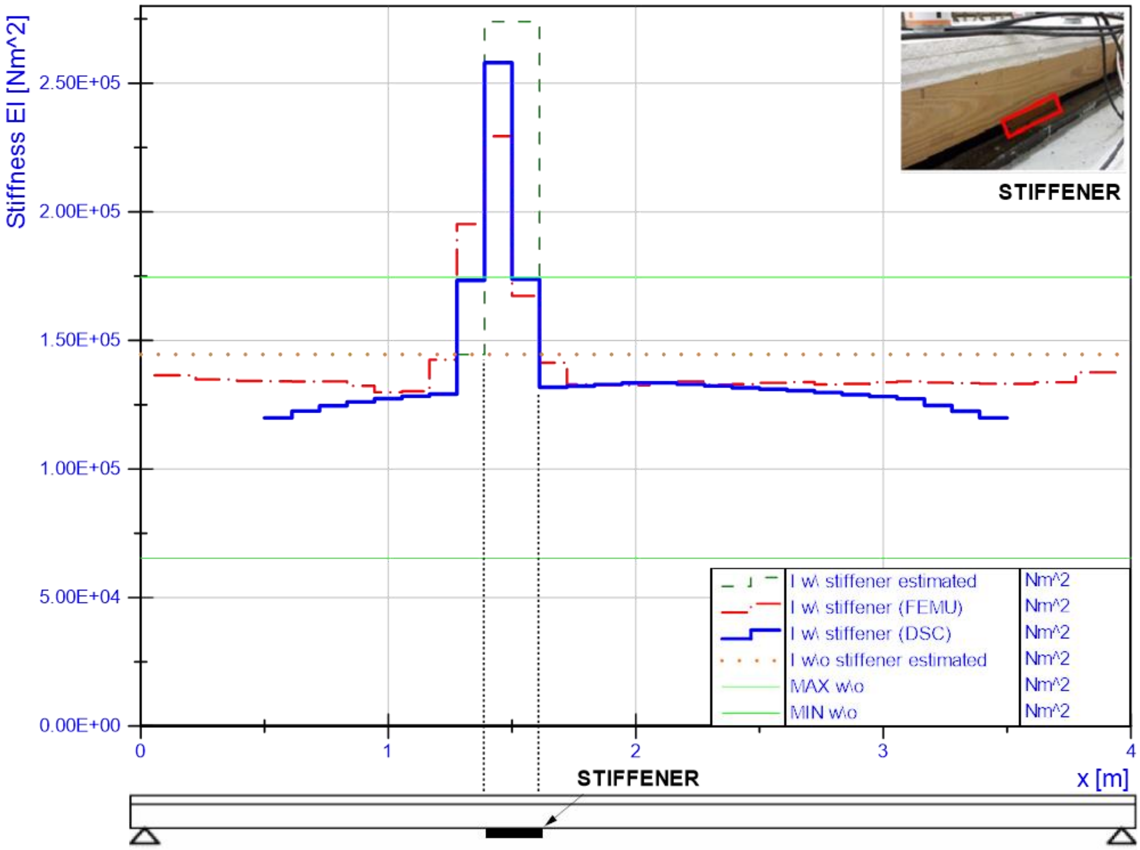


Figure 6-1 Comparison of the Identification Method Applied: FEMU Method (calculation Accuracy 6) and DSC Method.

The damage of a shear connection has also been investigated on the composite beam. The damage was assumed as the bolts near the left support were loosened in two stages: four bolts were unscrewed in the first stage; another four bolts were unscrewed in the next stage.

After comparing the natural frequencies and the MAC values for the damage detection, a code optimized by the author was applied for the damage assessment. All the data acquired were foremost smoothed by approximation functions using the software Mathematica before the data were directly used in the code as the input data. In the numerical calculations, more elements and nodes were needed than those points where the sensors had been applied. So, smoothing of the data was necessary to get more accurate results.

The mode-shape without a change in the stiffness of the structure was recalculated at the beginning with the above-mentioned program. The estimated stiffness of the entire cross-section was applied to the developed program as the input value and is marked with a dotted line (see Figure 6-2). The solid line represents the identified stiffness of the intact structure.

Afterwards, the calculations continued with the data for the damaged beam. As mentioned before, the first damaged stage represents a loosening of four bolts, which is represented by the dot-dashed line in Figure 6-2. During the second stage, another four bolts were loosened, i.e. the dashed line in Figure 6-2.

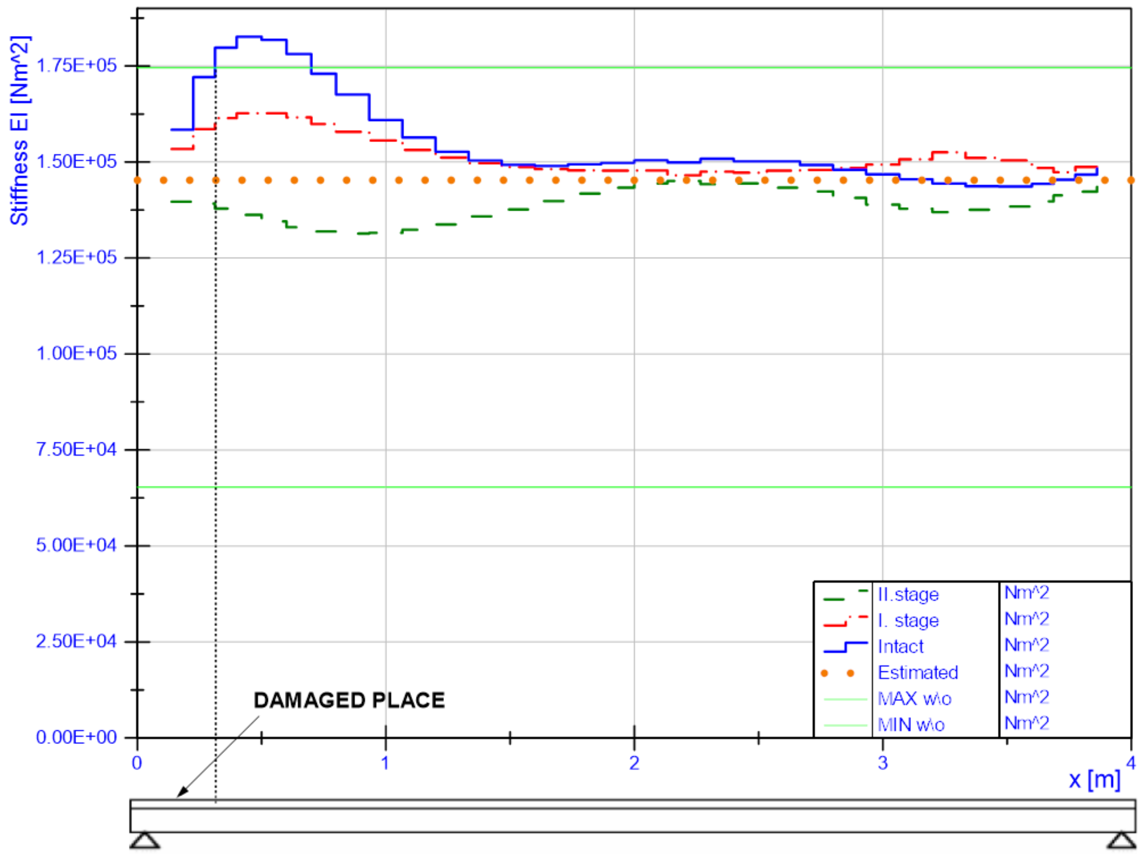


Figure 6-2 Damage Detection of the Shear Connection.

Even though the change in stiffness is not that significant, the damage was successfully identified in both stages; however, the site identified is a bit larger than that of the real structure. A small inaccuracy was identified at a site 3.4 m from the left support for the first stage of damage. It could have been caused by the sparsely placed accelerometers or by the smoothening function, but the achieved values are still acceptable.

7. Initial In-situ Measurements

A steel truss bridge in the city of Nové Mesto nad Váhom was measured in 2016. The control software developed by the author of the thesis for the measurement system was also successfully tested on more complicated bridge structures. The second presented bridge - “SNP” Bridge was measured repeatedly, in one-year period. Tests of the most used bridge in Slovakia – The “Prístavný” Bridge were performed twice (in 2015 and 2017).

Table 7-1 Comparison of Dynamic Characteristics (truss bridge).

No.	Mode-shape (direction)	Frequency [Hz]		
		Measurement 2016	Standard Deviation	Numerical model
1	Global in Y direction	2.75	N/A	2.82
2	Global in Z direction	3.01	±0.02	3.04

a) b)

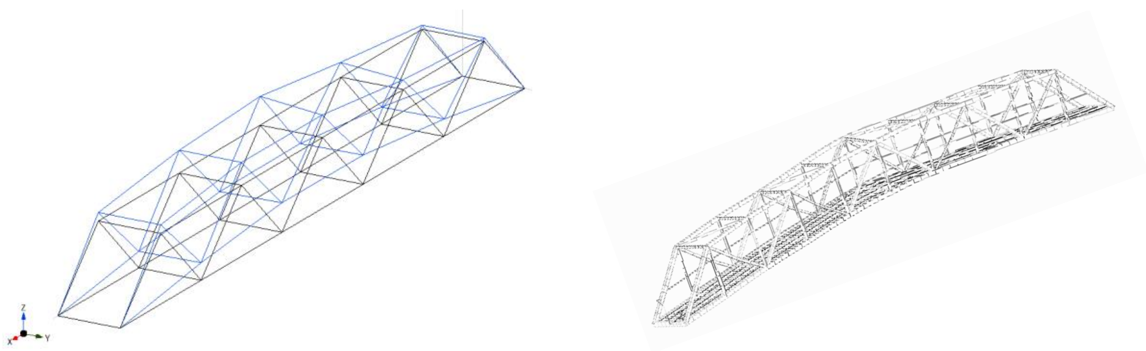
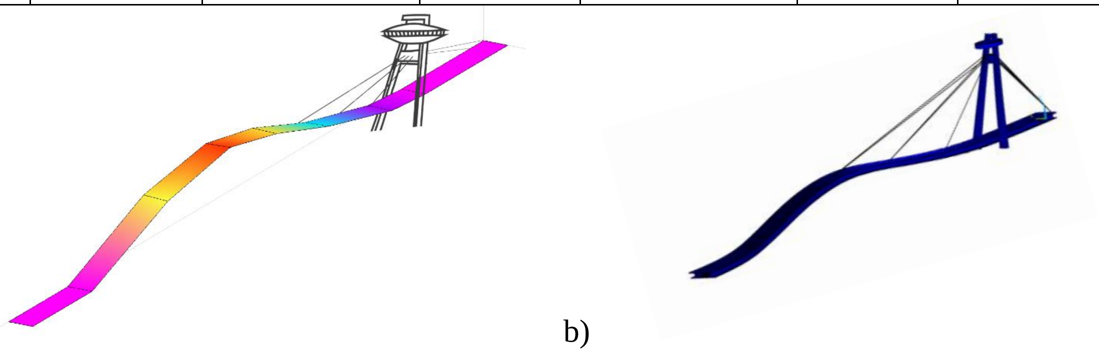


Figure 7-1 The 2nd Mode-shape of the Truss Bridge a) Measurement in 2016 b) FEM Model.

Figure 7-1 and Table 7-1 shows some results of SI performed from data acquired on the truss bridge in Nové Mesto nad Váhom. The first measurement was done in 2016. An FEM model was prepared without documentation, and only the cross-sections were measured that were within the reach of the hand. Small inaccuracies between measured frequencies and calculated natural frequencies are caused by the fact that the presented numerical model is only initial. Complete comparison is depicted and described in the thesis.

Table 7-2 Comparison of Dynamic Characteristics (“SNP“ Bridge).

No.	Mode-shape (direction)	Natural Frequency [Hz]				
		Measurement (2016)	Standard Deviation	Measurement (2017)	Standard Deviation	Numerical model
1	Global in Z direction	0.451	±0.007	0.467	±0.007	0.43
2	Global in Y direction	0.579	N/A	0.572	N/A	0.59



a) b)

Figure 7-2 The 1st Mode-shape of the “SNP” Bridge a) Measurement in 2016 b) FEM Model.

The first measurement of “SNP” Bridge was done in 2016, the second one was in 2017. Operational modal analysis using Stochastic Subspace Identification has been done. The first two natural frequencies from measurements and numerical model are shown in Table 7-2. It partly represents the results of SI. Complete comparison is depicted in the thesis. Prepared MAC values and direct comparison of mode-shapes, also Figure 7-2 show good conformity between measured and calculated mode-shapes.

Table 7-3 Comparison of Dynamic Characteristics (“Prístavný“ Bridge).

No.	Mode-shape (direction)	Natural Frequency [Hz]				
		Measurement (2015)	Standard Deviation	Measurement (2017)	Standard Deviation	Numerical model
1	Global in Z direction	0.894	±0.006	0.892	±0.002	0.79
2	Global in Y direction	0.76	±0.025	0.77	±0.020	0.81

a) b)

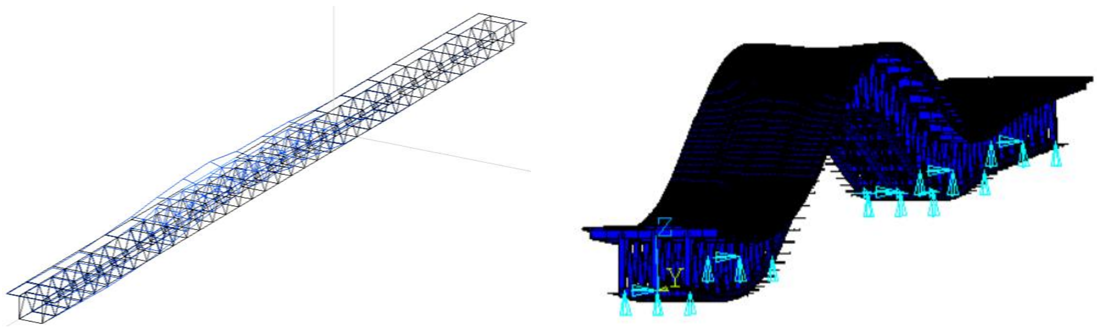


Figure 7-3 The 1st Mode-shape of the "Prístavný" Bridge a) Measurement in 2016 b) FEM Model.

The results of the tests and the initial numerical model were partially in Table 7-3. Besides the 1st mode-shape (Figure 7-3), other identified mode-shapes are depicted in the thesis with the whole comparison.

8. Conclusions

The research described in this thesis contributes to the dynamic tests of bridges for SI in a way that totally or partly fulfilled the specified goals in Section 2.

The author developed a software for controlling of the measuring system. The measuring system was built-up and optimized during the preparation of the dissertation, see Section 4. This system was tested repeatedly on various structures, mainly on two large bridges in Bratislava. These structures represent the most complex structures in Slovakia. Because of that, the system can be implemented on almost all bridges in Slovakia. The measuring polygon can reach up to 800 m. The advantage of the system is also that it was not necessary to stop the traffic during the measurements, and the used sensors were suitable for measurements of ambient vibrations. Another excitation was not needed. Operational Modal Analysis (OMA) was performed for processing the measured data. In the case of uncertain data, application of approximation functions in accordance with Sokol et al. [23] is recommended. The results of initialization tests were described in Section 7. The comparison between two measurements, the FEM model was commonly prepared for all real structures (the truss bridge in Nové Mesto nad Váhom, the "SNP" Bridge and the "Prístavný" Bridge in Bratislava). Presented work confirmed that development of FEM models is a helpful part of the SHM and the accurate FEM model after the V&V can be used for damage scenario simulation. Besides that, the presented work in the field of in-situ tests and their analysis showed other themes suitable for future investigation:

- Preparation of measurements also with strain gauges;
- Temperature impact on the dynamic characteristics of the mentioned structures;

- Application of the Bayesian approach in order to evaluate the economic advantages of Structural Health Monitoring in comparison to modernization (economic evaluation of the decision of the infrastructure administrator).

The results of the tests performed in the laboratory were shown in Section 5. Two types of structures were analysed (the steel truss structure with bolts and the composite beam). Many measurements forewent to the damage assessment, then three approaches (method based on natural frequencies, MAC values and FEMU method) were successfully applied and Section 6 was devoted to the presentation of simulation and identification of the damage. The code was optimized to achieve better results of quantification. The presented parametric study justified the required improvement. Moreover, previously analysed data were applied to the optimized code, and it gave also better results. The mentioned laboratory specimens were successfully subjected to the damage detection. The method based on natural frequencies was applied to the truss bridge model. Damage of the joints (the change in number of the bolts) was assessed. Then, damage scenarios of the shear connection were simulated on the composite beam. The damage scenarios have been identified using all mentioned methods. In addition, other topics for further research have emerged, e.g.:

- The use of Frequency Response Function (FRF) for better results in a case of measurable excitation;
- The next development of the damage detection code.

The following papers have been published during the PhD. study of the author: [25], [29] up to [56].

9. References[1]

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