# Realization and Testing of an In-Service Vibration Analysis System for Structural Health Monitoring

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**ABSTRACT**

Large lightweight structures like bridges are susceptible to vibrations due to operational and environmental loads. Since the excitation of structural resonances can effect in high vibration levels and in turn to fatigue damages, structural analyses are conducted which serve as a basis for the improvement of the design or the implementation of vibration control devices like tuned mass dampers. By regularly repeating those analyses, also structural damages can be detected in an early state in order to support condition based maintenance processes. In this paper, a system is introduced for the permanent instrumentation of structures in order to realize unattended long-term vibration analyses for structural health monitoring. Robust units are used for data acquisition on the structure under in-service conditions. Those units are distributed over the structure to collect vibration signals from a number of adjacently mounted sensors. Also, a first signal analysis for data compression to enable efficient communication of data via a protocol based network is performed on those units. To keep computational efforts moderate, the Random Decrement (RD) method is used to estimate auto- and cross correlation functions of vibration time signals from ambient excitation due to traffic or wind. The Random Decrement signatures are transmitted to a central processing unit, which performs the derivation of modal parameters, i.e. resonance frequencies and mode shapes of the structure, which can serve as input for damage detection algorithms. The developed system is tested on a pedestrian bridge. To this end, first an experimental modal analysis is performed with impulse hammer excitation. The results serve as a reference for assessment of the resonances and mode shapes identified by the operational modal analysis performed with the in-service vibration analysis system.

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## INTRODUCTION

The analysis of the dynamic characteristics of mechanical structures is useful for the validation of numerical models or the design of vibration control systems. By regularly repeating those analyses, also structural damages can be detected or the performance of the vibration control devices can be monitored [1].

In the past, plenty of algorithms for vibration based damage detection have been proposed and evaluated within research projects [2][3]. Mostly, a significant amount of data analysis is needed to implement reliable detection methods. Furthermore, it depends from the actual application, which is the most promising damage detection algorithm.

Considering a permanent instrumentation with a monitoring system, further issues arise: The cabling effort for connecting sensors to a central data acquisition unit seems rather impractical when dealing with large objects like bridges. Thus, sensor networks, either tethered or wireless have been proposed to alleviate the realization of SHM systems [1][4]. However, due to limited bandwidth of the communication channels, it is desirable to pre-process the acquired vibration signals for data compression and transmit a lower amount of data.

Moreover, the hardware should be implemented in a way to withstand harsh environmental conditions in order to enable the mounting directly on the structure adjacent to the vibration sensors.

In this work, the development of a data acquisition and analysis system is presented which aims at providing a platform for the flexible implementation of complex algorithms for structural analysis and damage detection, while using hardware for industrial environments. Also the realization with a distributed smart sensor network is considered.

As an application, the implementation of an autonomous operational modal analysis procedure for a pedestrian bridge is introduced. In continuation of previous work on distributed modal analysis [5], a two-stage approach is considered: First, the vibration signals are analyzed in order to estimate auto- and cross-correlation functions by the Random Decrement method [6]. Afterwards, the operational modal analysis is performed to determine mode shapes, resonance frequencies and damping coefficients.

As a target platform, a system is regarded, which has been successfully used for load monitoring in different challenging applications [7][8].

In the remainder of this paper, the system layout is introduced in detail. The implemented concepts for signal analysis and operational modal analysis are described. The system is first realized with a rapid-control-prototyping platform and tests on a pedestrian bridge are performed. After that, the system is integrated with industrial hardware and validated in a final test.

## SYSTEM LAYOUT

The idea behind the described monitoring system is to distribute the signal processing and analysis to different units (Figure 1). The concept is rather generic and can be implemented in different ways.

After data acquisition and A/D conversion, a first signal analysis is performed and the results are transmitted to the second unit. For the application of an operational

modal analysis, auto- and cross correlation functions are estimated. Since these are some kind of time-averaged data, the transmission of time samples between the units is avoided, i.e. no synchronous communication of large amounts of data is needed. Furthermore, the acquired time series are compressed by extracting the relevant information, thus the communication effort is reduced. This is especially interesting when wireless communication is considered. Generally, the first signal processing unit may be implemented by real-time capable micro controller platforms, e.g. smart sensor nodes.

The second unit is intended to implement the data analysis. Based on the information received from the first unit, algorithms for structural analysis or damage detection are used to estimate the relevant parameters. In the example at hand, this includes the dynamic characteristics of the mechanical structure. Algorithms for the determination of structural parameters are generally more complex, but don't use real-time measurements as input. Thus, more powerful platforms like PC or 32-bit microcontrollers may be used.
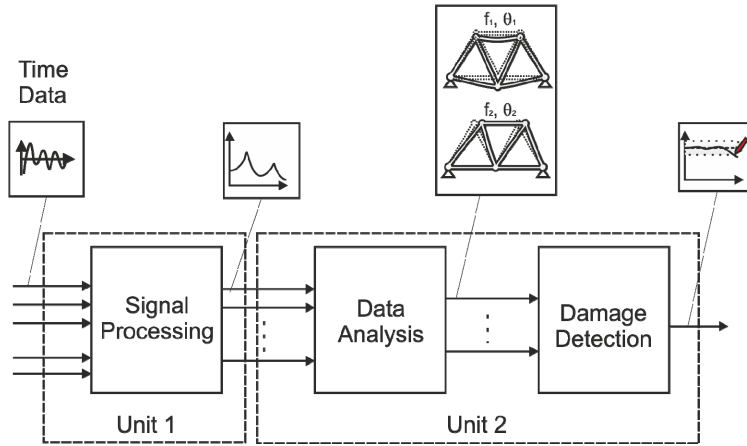


*Figure 1. System layout with stages for signal processing and data analysis.*

## SIGNAL PROCESSING

In order to estimate auto-and cross correlation functions, which later serve as input to the operational modal analysis, the Random Decrement (RD) method is used. This method is especially interesting due to its low computational effort, which enables the implementation on small low-power sensor nodes.

The basic idea of the RD method is to average triggered time series of a defined length. Due to the triggering, random parts of the vibration are removed and correlated parts remain. Commonly, trigger conditions like level crossing of the signal are applied. To estimate cross correlation functions between two channels, the trigger condition is taken from signal $x(t)$ while averaging time series of the signal $y(t)$:

$$D_{XX}(\tau) = \frac{1}{N} \sum_{n=1}^{N} x(t_n + \tau) \bigg| x(t_n) = a \qquad D_{YX}(\tau) = \frac{1}{N} \sum_{n=1}^{N} y(t_n + \tau) \bigg| x(t_n) = a$$

The Random Decrement signatures have to be scaled by a factor in order to derive the estimate of the correlation functions [9]. For the level crossing trigger condition, this factor reads:

$$R_{XX}(\tau) = D_{XX}(\tau)\frac{\sigma_X^2}{a}$$

The signal variance which is needed for proper scaling can simply be estimated with an AR1-process implemented in parallel to the RD estimation [10].

Obviously, the choice of the trigger level and trigger condition can influence the number of averages in a given time span. Lower levels will deliver more trigger events, but more averages will be needed; higher trigger levels will cause a few trigger events, but the estimation converges with less averages. According to [9], in the case of the level crossing trigger condition, the optimum trigger level can be calculated with respect to the variance of the signal:

$$a = \sqrt{2}\sigma_x$$

## DATA ANALYSIS

The determined estimations for auto- and cross correlation functions are used as input data for an autonomous operational modal analysis procedure. This is implemented on the second unit.

First, the matrices $\mathbf{R}$ of the correlation functions are evaluated. Afterwards, an intermediate step is needed before starting with the modal decomposition. Because the algorithms of frequency domain based OMA need a matrix $\mathbf{G}(f)$ of spectral densities as an input, a single block Discrete Fourier Transform (DFT) has to be applied to the correlation functions [12]. For the subsequent OMA, the FDD algorithm is used [12]. This algorithm is based on a Singular Value Decomposition (SVD) of the matrix $\mathbf{G}(f)$ For every frequency $f$, this process leads to two fully populated matrices $\mathbf{U}(f)$ and a diagonal matrix $\mathbf{S}(f)$ holding the spectra of the so-called singular values $\mathbf{S}_{ii}(f)$ in decreasing order:

$$\mathbf{G}(f) = \mathbf{U}(f)\mathbf{S}(f)\mathbf{U}^H(f)$$

The peak values of the first singular values are then interpreted as indicators for the systems' eigenfrequencies. Furthermore, using the FDD algorithm, it is possible to estimate the mode shapes for the found frequencies. The eigenvectors describing the mode shapes corresponding to the eigenfrequencies determined by the spectra of the singular values can be found in the corresponding columns of the matrix $\mathbf{U}(f)$.

## TEST STRUCTURE

A steel bridge for pedestrians is used for tests of the system (Figure **2**). The bridge is about 24 m long and 6 m high. First, an experimental modal analysis using ten three-axis-accelerometers and a modal hammer of 1.5 kg is conducted. Examples for derived eigenmodes are depicted in Figure **3**. The values for resonance frequencies and damping coefficients are summarized at the end of the paper together with the other results. The resulting eigenmodes below 20 Hz are listed in Table *1*.
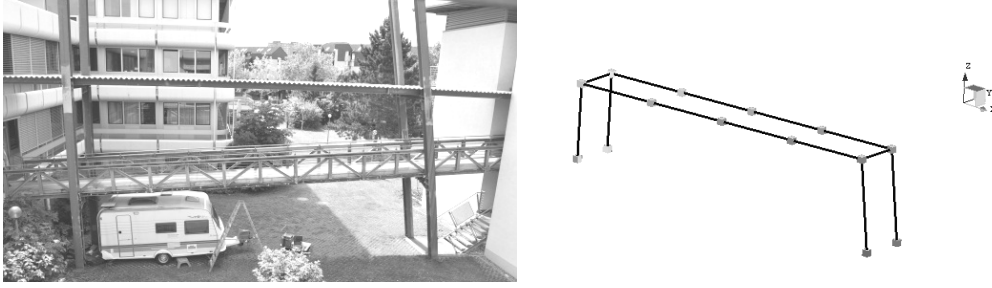
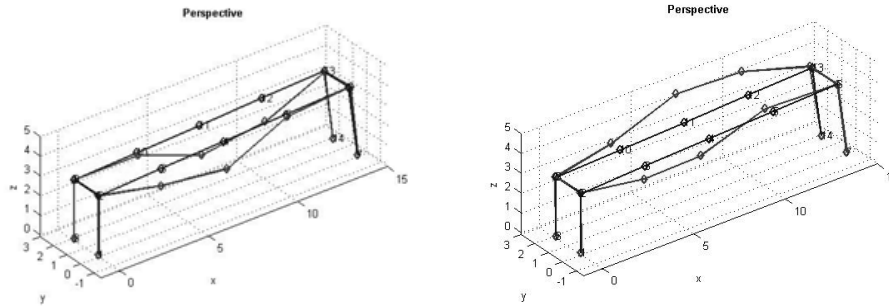Figure 2. Test structure (left) and geometry model for modal analysis.



Figure 3. Identified mode shapes – first bending mode (left) and first torsion (right).

| Frequency [Hz] | Damping [-] | Mode shape |
|---|---|---|
| 8,1 | 0,63 | Bending (horizontal) |
| 9,8 | 0,43 | Bending (vertical) |
| 15,1 | 1,23 | Torsion |

Table 1. Identified eigenmodes of the test structure.

## RAPID CONTROL PROTOTYPING

For the evaluation of the system concept in the framework of a model based development, a strategy similar to rapid control prototyping used for the development in the automotive or aerospace industry is applied. This includes the high-level programming of the signal processing and data analysis algorithms in a suitable environment. In this work, *Simulink* is used for the implementation of the real-time signal processing, i.e. the RD estimation, while *MATLAB* is used for programming of the operational modal analysis routine. This offers the possibility to conduct basic studies on the algorithms in simplified simulations.

The hardware platform for the experimental investigations in this prototyping stage consists of two embedded PCs, commonly used for complex control tasks in automation systems. One serves as a real-time platform, and is equipped with A/D conversion cards. Using automatic code generation, the *Simulink* models can be quickly implemented on this platform.

The second PC is set up with a common desktop operation system. Thus, the *MATLAB* routines for data analysis can be directly run. This PC communicates via

network connection with the real-time platform. Together with some auxiliary equipment, the PCs are mounted into a weatherproof aluminum case, so the rapid prototyping system can be deployed directly to the target application (Figure **4**).

The system uses a reduced number of 14 channels due to restrictions of memory and computational power of the real-time platform. The optimal choice of the reduced sensor set from the original one is performed using effective independence methods [13]. Long term tests over two weeks were performed in order to evaluate the system before final implementation on the target platform. Results are summarized at the end of the paper.
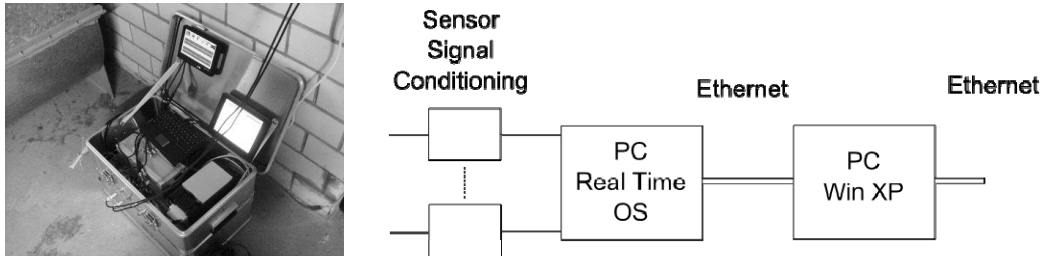


*Figure 4. Rapid prototyping system for evaluation of signal processing and data analysis (left) and its block diagram (right).*

## INTEGRATED SYSTEM

The final hardware implementation consists of a tethered smart sensor network connected to a central data analysis unit. Each network node consists of a microcontroller platform, data acquisition for eight ICP accelerometers and a CAN network connection; integrated into a rugged enclosure (Figure **5**). The central unit remains an embedded PC platform. This allows for the utilization of high level programming languages like *Octave* or *MATLAB* for the implementation of the algorithms. For the tests presented here, just one network node with eight channels was used. Due to reduced observability, the horizontal bending movements could not be identified with this set up.
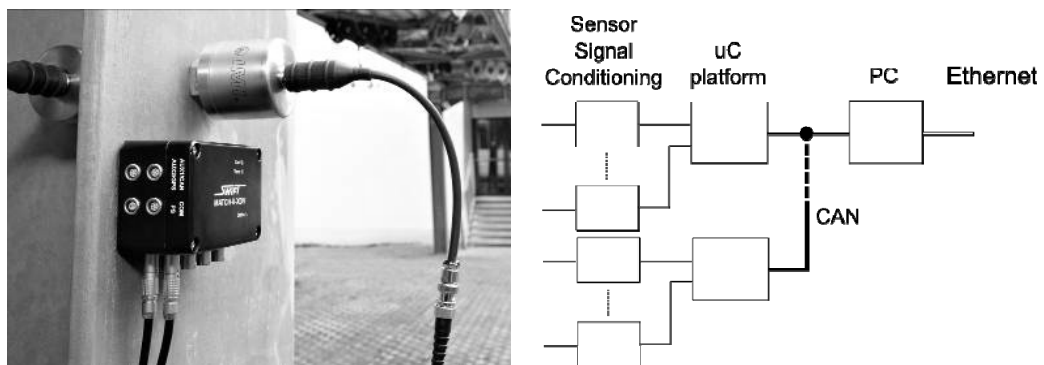


*Figure 5. Smart sensor node with seismic accelerometer.*

# RESULTS

The results of the tests conducted within the development are summarized here to enable a comparison between the reference measurement (EMA), the rapid prototyping system and the smart sensor. In Table *2*, system parameters and the first three identified resonance frequencies are listed. Obviously, all set ups deliver nearly identical results. Also the identified mode shapes were found to be consistent. The modal assurance criterion (MAC) for z-bending and torsion was calculated, and the values between the smart sensor set up and the reference EMA were derived to 92% and 73%.

| Test set up | Hardware | Channels used | 1st resonance (bending x) | 1st resonance (bending z) | 2nd resonance (torsion) |
|---|---|---|---|---|---|
| Reference | EMA system, LMS test lab | 32 | 8,1 Hz | 9,8 Hz | 15,1 Hz |
| Rapid prototyping | PC hardware | 14 | 7,8 Hz | 8,9 Hz | 14,6 Hz |
| Smart Sensor | μC network nodes, PC | 8 | not identified | 9,0 Hz (92% MAC with EMA) | 14,8 Hz (73% MAC with EMA) |

Table 2. Summary of results.

# SUMMARY AND CONCLUSIONS

In the presented work, the development of a vibration analysis system based on a system level approach was presented. By using model based development tools and rapid control prototyping systems, a fast way from the development to the evaluation of signal processing and data analysis algorithms in actual applications has been elaborated. In the future, the developed smart sensor network will have to be tested in a more complex configuration. Furthermore, the data analysis algorithms will be enhanced towards an autonomous tracking of parameters and the derivation of damage sensitive metrics.

# ACKNOWLEDGEMENTS

# REFERENCES

[1]    Brownjohn, J. M. W., Carden, E. P., Goddard, C. R., Oudin, G. , *Real-time performance monitoring of tuned mass damper system for a 183m reinforced concrete chimney*, Journal of Wind Engineering and Industrial Aerodynamics, Vol. 98, Nr. 3, pp. 169-179, March 2010.

[2]     Doebling, S. W., Farrar, C. R., Prime, M. B., Shevitz, D. W., *Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: A literature review*. Los Alamos National Lab., 1996.

[3]     Fan, W., Qiao, P., *Vibration-based Damage Identification Methods: A Review and Comparative Study*, Structural Health Monitoring, Vol. 10(1), 2010, pp. 83-111.

[4]     Zhuo Liu, Bingwen Wang, Wenjun Yang, *Design and Deployment of Bridge Structural Health Monitoring System Based on Wireless Sensor Network*, Proceedings of 6th International Conference on Wireless Communications Networking and Mobile Computing (WiCOM), 2010, pp. 1–4.

[5]     Friedmann, A., Mayer, D., Kauba, M., *An approach for decentralized mode estimation based on the Random Decrement method*, Shock and Vibration, Vol. 17, Nr. 4, pp. 579-588, Jan. 2010.

[6]     Cole, H., *On-line failure detection and damping measurement of aerospace structures by random decrement signatures*, Report NASA CR-2205, 1973

[7]     Stolze, F, Boller, C., Dornbusch, T., Uhse, W: *Simulation Based Health assessment of Engineering Structures,* Proceedings of the 3rd European Workshop Structural Health Monitoring, 2006, Granada, Spain, 2006, pp. 743-750.

[8]     Rupp, A., Masieri, A., Dornbusch, T., *Efficient Monitoring of Loads and Stresses Under Service and Test Conditions*, SAE Technical Paper 2005-01-3563, 2005.

[9]     Asmussen, J. C., *Modal Analysis Based on the Random Decrement Technique*: *Application to Civil Engineering Structures*, PhD-Thesis, University of Aalborg, Aalborg, 1998.

[10]    Friedmann, A., Koch, M., Mayer, D.: *Using the Random Decrement Method for the Decentralized Acquisition of Modal Data*, Proceedings of International Conference on Noise and Vibration Engineering (ISMA) 2010, Leuven, Belgium, 2010, pp. 3275 – 3286.

[11]    Xu, N. et. al., *A Wireless Sensor Network For Structural Monitoring*, Proceedings of SenSys'04, Baltimore, Maryland, USA, 2004.

[12]    Brincker, R., Zhang, L., Andersen, P., *Modal Identification from Ambient Response using Frequency Domain Decomposition*, Proceedings of the 18th IMAC, San Antonio, 2000, TX, USA, pp. 625–630.

[13]    Bartel, T., Buff, H., Kauba, M., Koch, M., et al.: *Experimental investigation of a Random decrement based modal estimation on a pedestrian bridge*. Proceedings of the 14th International Adaptronic Congress 2011, September 2011, Darmstadt, pp. 247–253.